Chapter 4: Strengthening and implementing the global response

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Date of Draft: 04 June 2018

Notes: TSU compiled version
# Table of Content

**Executive Summary**  ........................................................................................................................................... 5

4.1 Accelerating the Global Response to Climate Change ................................................................. 10

4.2 Pathways Compatible with 1.5°C: Starting Points for Strengthening Implementation 11

4.2.1 Implications for Implementation of 1.5°C-consistent Pathways ............................................. 11

4.2.1.1 Challenges and Opportunities for Mitigation Along the Reviewed Pathways ............. 12

4.2.1.1.1 Greater scale, speed and change in investment patterns ............................................. 12

4.2.1.1.2 Greater policy design and decision-making implications .............................................. 13

4.2.1.1.3 Greater sustainable development implications .......................................................... 13

4.2.1.2 Implications for Adaptation Along the Reviewed Pathways ........................................... 14

4.2.2 System Transitions and Rates of Change ......................................................................................... 14

4.2.2.1 Mitigation: Historical Rates of Change and State of Decoupling ................................. 14

4.2.2.2 Transformational Adaptation ......................................................................................... 15

4.2.2.3 Disruptive Innovation ..................................................................................................... 16

4.3 Systemic Changes for 1.5°C-Consistent Pathways ....................................................................... 17

4.3.1 Energy System Transitions ........................................................................................................... 17

4.3.1.1 Renewable Electricity: Solar and Wind ........................................................................ 17

4.3.1.2 Bioenergy and Biofuels ............................................................................................... 18

4.3.1.3 Nuclear Energy ............................................................................................................. 19

4.3.1.4 Energy Storage ........................................................................................................... 20

4.3.1.5 Options for Adapting Electricity Systems to 1.5°C ................................................... 20

4.3.1.6 Carbon Dioxide Capture and Storage in the Power Sector .................................... 21

4.3.2 Land and Ecosystem Transitions ................................................................................................. 22

4.3.2.1 Agriculture and Food ................................................................................................ 22

4.3.2.2 Forests and Other Ecosystems .................................................................................. 25

4.3.2.3 Coastal Systems ......................................................................................................... 27

4.3.3 Urban and Infrastructure System Transitions ............................................................................ 27

4.3.3.1 Urban Energy Systems ............................................................................................... 28

4.3.3.2 Urban Infrastructure, Buildings and Appliances ......................................................... 28

4.3.3.3 Urban Transport and Urban Planning ....................................................................... 29

4.3.3.4 Electrification of Cities and Transport ...................................................................... 30

4.3.3.5 Shipping, Freight and Aviation .................................................................................. 31

4.3.3.6 Climate-Resilient Land Use ....................................................................................... 32

4.3.3.7 Green Urban Infrastructure and Ecosystem Services ............................................... 32

4.3.3.8 Sustainable Urban Water and Environmental Services ............................................ 33

4.3.4 Industrial Systems Transitions .................................................................................................... 33

4.3.4.1 Energy Efficiency ....................................................................................................... 34

4.3.4.2 Substitution and Circularity ....................................................................................... 35

4.3.4.3 Bio-Based Feedstocks ............................................................................................... 35

4.3.4.4 Electrification and Hydrogen ..................................................................................... 35

4.3.4.5 CO₂ Capture, Utilisation and Storage in Industry ....................................................... 36

4.3.5 Overarching Adaptation Options Supporting Adaptation Transitions ................................ 36

4.3.5.1 Disaster Risk Management (DRM) ........................................................................... 36

4.3.5.2 Risk Sharing and Spreading ....................................................................................... 36
4.3.5.3 Education and Learning ................................................................. 37
4.3.5.4 Population Health and Health System Adaptation Options .......... 37
4.3.5.5 Indigenous Knowledge ............................................................... 37
4.3.5.6 Human Migration .................................................................. 37
4.3.5.7 Climate Services .................................................................... 38

Cross-Chapter Box 9: Risks, Adaptation Interventions, and Implications for Sustainable Development and Equity Across Four Social-Ecological Systems: Arctic, Caribbean, Amazon, and Urban .......................................................... 39

4.3.6 Short Lived Climate Forcers ...................................................... 42

4.4 Carbon Dioxide Removal (CDR) .................................................. 44

4.4.3.1 Bioenergy with carbon capture and storage (BECCS) .......... 44
4.4.3.2 Afforestation and Reforestation (AR) ..................................... 47
4.4.3.3 Soil Carbon Sequestration and Biochar .................................. 47
4.4.3.4 Enhanced Weathering (EW) and Ocean Alkalisation .......... 48
4.4.3.5 Direct Air Carbon Dioxide Capture and Storage (DACCS) .. 49
4.4.3.6 Ocean Fertilisation ............................................................... 50

4.4.8 Solar Radiation Modification (SRM) .......................................... 52

4.4.8.1 Governance and Institutional Feasibility .............................. 53
4.4.8.2 Economic and Technological Feasibility ......................... 54
4.4.8.3 Social Acceptability and Ethics ............................................ 54

Cross-Chapter Box 10: Solar Radiation Modification in the Context of 1.5°C Mitigation Pathways ................................................................. 55

4.4 Implementing Far-Reaching and Rapid Change ............................ 58

4.4.1 Enhancing Multi-Level Governance ........................................ 58

4.4.1.1 Institutions and their Capacity to Invoke Far-Reaching and Rapid Change .............................................................. 58
4.4.1.2 International Governance .................................................... 59
4.4.1.3 Sub-National Governance ................................................... 61
4.4.1.4 Interactions and Processes for Multi-Level Governance .. 61

Box 4.1: Multi-Level Governance in the EU Covenant of Mayors: Example of the Provincia di Foggia ................................................................. 62

Box 4.2: Watershed Management in a 1.5°C World ............................. 63

Cross-Chapter Box 11: Consistency Between Nationally Determined Contributions and 1.5°C Scenarios ............................................................................. 64

4.4.2 Enhancing Institutional Capacities ............................................ 67

4.4.2.1 Capacity for Policy Design and Implementation ................... 68

Box 4.3: Indigenous Knowledge and Community Adaptation .............. 68

Box 4.4: Manizales, Colombia: Supportive National Government and Localised Planning and Integration as an Enabling Condition for Managing Climate and Development Risks ............................................. 69

4.4.2.2 Monitoring, Reporting, and Review Institutions ................. 70
4.4.2.3 Financial Institutions ............................................................ 70
4.4.2.4 Co-Operative Institutions and Social Safety Nets .......... 71

4.4.3 Enabling Lifestyle and Behavioural Change .............................. 71

4.4.3.1 Factors Related to Climate Actions ........................................ 74
4.4.3.1.1 Ability to engage in climate action ................................... 74
4.4.3.1.2 Motivation to engage in climate action ............................. 75
4.4.3.1.3 Habits, heuristics and biases ............................................ 76

Do Not Cite, Quote or Distribute 4-3 Total pages: 198
4.4.3.2 Strategies and Policies to Promote Actions on Climate Change ........................................ 77
Box 4.5: How Pricing Policy has Reduced Car Use in Singapore, Stockholm and London .... 77
Box 4.6: Bottom-up Initiatives: Adaptation Responses Initiated by Individuals and Communities ................................................................. 79
4.4.3.3 Acceptability of Policy and System Changes ................................................................. 80
4.4.4 Enabling Technological Innovation .................................................................................. 81
4.4.4.1 The Nature of Technological Innovations ...................................................................... 81
4.4.4.2 Technologies as Enablers of Climate Action ................................................................. 82
4.4.4.3 The Role of Government in 1.5°C-Consistent Climate Technology Policy .................. 83
Box 4.7: Bioethanol in Brazil: Innovation and Lessons for Technology Transfer ..................... 84
4.4.4.4 Technology Transfer in the Paris Agreement ............................................................... 85
4.4.5 Strengthening Policy Instruments and Enabling Climate Finance .................................. 86
4.4.5.1 The Core Challenge: Cost Efficiency, Coordination of Expectations and Distributive Effects .................................................. 86
Box 4.8: Investment Needs and the Financial Challenge of Limiting Warming to 1.5°C ........ 86
Box 4.9: Emerging cities and ‘peak car use’: Evidence of decoupling in Beijing ............. 90
4.4.5.2 Carbon Pricing: Necessity and Constraints ................................................................. 91
4.4.5.3 Regulatory measures and information flows ............................................................... 92
4.4.5.4 Scaling-up Climate Finance and De-Risking Low-Emission Investments .................. 93
4.4.5.5 Financial Challenge for Basic Needs and Adaptation Finance ................................ 95
4.4.5.6 Towards Integrated Policy Packages and Innovative Forms of Financial Cooperation 96
4.5 Integration and Enabling Transformation .......................................................................... 97
4.5.1 Assessing Feasibility of Options for Accelerated Transitions ..................................... 97
4.5.2 Implementing Mitigation ................................................................................................. 98
  4.5.2.1 Assessing of Mitigation Options for Limiting Warming to 1.5°C Against Feasibility Dimensions ................................................................. 98
  4.5.2.2 Enabling Conditions for Implementation of Mitigation Options Towards 1.5°C .... 103
4.5.3 Implementing Adaptation ............................................................................................... 103
  4.5.3.1 Feasible Adaptation Options ..................................................................................... 104
  4.5.3.2 Monitoring and Evaluation ...................................................................................... 108
4.5.4 Synergies and Trade-Offs Between Adaptation and Mitigation .................................. 108
Box 4.10: Bhutan: Synergies and Trade-Offs in Economic Growth, Carbon Neutrality and Happiness ................................................................................. 109
4.6 Knowledge Gaps and Key Uncertainties ......................................................................... 111
Frequently Asked Questions ................................................................................................. 119
FAQ 4.1: What transitions could enable limiting global warming to 1.5°C? ..................... 119
FAQ 4.2: What are Carbon Dioxide Removal and negative emissions? ......................... 121
FAQ 4.3: Why is adaptation important in a 1.5°C warmer world? ................................. 123
References .............................................................................................................................. 125
Executive Summary

Limiting warming to 1.5°C would require transformative systemic change, integrated with sustainable development. Such change would require the upscaling and acceleration of the implementation of far-reaching, multi-level and cross-sectoral climate mitigation and addressing barriers. Such systemic change would need to be linked to complementary adaptation actions, including transformational adaptation, especially for pathways that temporarily overshoot 1.5°C (Chapter 2, Chapter 3, 4.2.1, 4.4.5, 4.5) (medium evidence, high agreement). Current national pledges on mitigation and adaptation are not enough to stay below the Paris Agreement temperature limits and achieve its adaptation goals. While transitions in energy efficiency, carbon intensity of fuels, electrification and land use change are underway in various countries, limiting warming to 1.5°C will require a greater scale and pace of change to transform energy, land, urban and industrial systems globally. {4.3, 4.4, Cross-Chapter Box CB9 in this Chapter}

Although multiple communities around the world are demonstrating the possibility of implementation consistent with 1.5°C pathways (Boxes 4.1-4.10), very few countries, regions, cities, communities or businesses can currently make such a claim (high confidence). To strengthen the global response, almost all countries would need to significantly raise their level of ambition. Implementation of this raised ambition would require enhanced institutional capabilities in all countries, including building the capability to utilise Indigenous and local knowledge (medium evidence, high agreement). In developing countries and for poor and vulnerable people, implementing the response would require financial, technological and other forms of support to build capacity, for which additional local, national and international resources would need to be mobilised (high confidence). However, public, financial, institutional and innovation capabilities currently fall short of implementing far-reaching measures at scale in all countries (high confidence). Transnational networks that support multi-level climate action are growing, but challenges in their scale-up remain. {4.4.1, 4.4.2, 4.4.4, 4.4.5, Box 4.1, Box 4.2, Box 4.7}

Adaptation needs will be lower in a 1.5°C world compared to a 2°C world (high confidence) (Chapter 3; Cross-Chapter Box CB11 in this Chapter). Learning from current adaptation practices and strengthening them through adaptive governance {4.4.1}, lifestyle and behavioural change {4.4.3} and innovative financing mechanisms {4.4.5} can help their mainstreaming within sustainable development practices. Preventing maladaptation, drawing on bottom-up approaches {Box 4.6} and using Indigenous knowledge {Box 4.3} would effectively engage and protect vulnerable people and communities. While adaptation finance has increased quantitatively, significant further expansion would be needed to adapt to 1.5°C. Qualitative gaps in the distribution of adaptation finance, readiness to absorb resources and monitoring mechanisms undermine the potential of adaptation finance to reduce impacts. {Chapter 3, 4.4.2, 4.4.5, 4.6}

System transitions

The energy system transition that would be required to limit global warming to 1.5°C is underway in many sectors and regions around the world (medium evidence, high agreement). The political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies has improved dramatically over the past few years, while that of nuclear energy and Carbon Dioxide Capture and Storage (CCS) in the electricity sector have not shown similar improvements. {4.3.1}

Electrification, hydrogen, bio-based feedstocks and substitution, and in several cases carbon dioxide capture, utilisation and storage (CCUS), would lead to the deep emissions reductions required in energy-intensive industry to limit warming to 1.5°C. However, those options are limited by institutional, economic and technical constraints, which increase financial risks to many incumbent firms (medium evidence, high agreement). Energy efficiency in industry is more economically feasible and an enabler of industrial system transitions but would have to be complemented with Greenhouse Gas (GHG)-neutral processes or Carbon Dioxide Removal (CDR) to make energy-intensive industry consistent with 1.5°C (high confidence). {4.3.1, 4.3.4}

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Global and regional land-use and ecosystems transitions and associated changes in behaviour that would be required to limit warming to 1.5°C can enhance future adaptation and land-based agricultural and forestry mitigation potential. Such transitions could, however, carry consequences for livelihoods that depend on agriculture and natural resources [4.3.2, Cross-Chapter Box CB6 in chapter 3]. Alterations of agriculture and forest systems to achieve mitigation goals could affect current ecosystems and their services and potentially threaten food, water and livelihood security. While this could limit the social and environmental feasibility of land-based mitigation options, careful design and implementation could enhance their acceptability and support sustainable development objectives (medium evidence, medium agreement). [4.3.2, 4.5.3]

Changing agricultural practices can be an effective climate adaptation strategy. A diversity of adaptation options exists, including mixed crop-livestock production systems which can be a cost-effective adaptation strategy in many global agriculture systems (robust evidence, medium agreement). Improving irrigation efficiency could effectively deal with changing global water endowments, especially if achieved via farmers adopting new behaviour and water-efficient practices rather than through large-scale infrastructure (medium evidence, medium agreement). Well-designed adaptation processes such as community-based adaptation can be effective depending upon context and levels of vulnerability. [4.3.2, 4.5.3]

Improving the efficiency of food production and closing yield gaps have the potential to reduce emissions from agriculture, reduce pressure on land and enhance food security and future mitigation potential (high confidence). Improving productivity of existing agricultural systems generally reduces the emissions intensity of food production and offers strong synergies with rural development, poverty reduction and food security objectives, but options to reduce absolute emissions are limited unless paired with demand-side measures. Technological innovation including biotechnology, with adequate safeguards, could contribute to resolving current feasibility constraints and expand the future mitigation potential of agriculture. [4.3.2, 4.4.4]

Dietary choices towards foods with lower emissions and requirements for land, along with reduced food loss and waste, could reduce emissions and increase adaptation options (high confidence). Decreasing food loss and waste and behavioural change around diets could lead to effective mitigation and adaptation options (high confidence) by reducing both emissions and pressure on land, with significant co-benefits for food security, human health and sustainable development [4.3.2, 4.4.5, 4.5.2, 4.5.3, 5.4.2], but evidence of successful policies to modify dietary choices remains limited.

Mitigation and Adaptation Options and other Measures

A mix of mitigation and adaptation options implemented in a participatory and integrated manner can enable rapid, systemic transitions in urban and rural areas that are necessary elements of an accelerated transition to 1.5°C worlds. Such options and changes are most effective when aligned with economic and sustainable development, and when local and regional governments are supported by national governments (4.3.3, 4.4.1, 4.4.3). Various mitigation options are expanding rapidly across many geographies. Although many have development synergies, not all income groups have so far benefited from them. Electrification, end-use energy efficiency and increased share of renewables, amongst other options, are lowering energy use and decarbonising energy supply in the built environment, especially in buildings. Other rapid changes needed in urban environments include demotorisation and decarbonisation of transport, including the expansion of electric vehicles, and greater use of energy-efficient appliances (medium evidence, high agreement). Technological and social innovations can contribute to limiting warming to 1.5°C, e.g. by enabling the use of smart grids, energy storage technologies and general-purpose technologies, such as Information and Communication Technology (ICT) that can be deployed to help reduce emissions. Feasible adaptation options include green infrastructure, resilient water and urban ecosystem services, urban and peri-urban agriculture, and adapting buildings and land use through regulation and planning (medium evidence, medium to high agreement). [4.3.3]
Synergies can be achieved across systemic transitions through several overarching adaptation options in rural and urban areas. Investments in health, social security and risk sharing and spreading are cost-effective adaptation measures with high potential for scaling-up (medium evidence, medium to high agreement). Disaster risk management and education-based adaptation have lower prospects of scalability and cost-effectiveness (medium evidence, high agreement) but are critical for building adaptive capacity. {4.3.5, 4.5.3}

Converging adaptation and mitigation options can lead to synergies and potentially increase cost effectiveness, but multiple trade-offs can limit the speed of and potential for scaling up. Many examples of synergies and trade-offs exist in all sectors and system transitions. For instance, sustainable water management (high evidence, medium agreement) and investment in green infrastructure (medium evidence, high agreement) to deliver sustainable water and environmental services and to support urban agriculture are less cost-effective but can help build climate resilience. Achieving the governance, finance and social support required to enable these synergies and to avoid trade-offs is often challenging, especially when addressing multiple objectives, and appropriate sequencing and timing of interventions. {4.3.2, 4.3.4, 4.4.1, 4.5.2, 4.5.3, 4.5.4}

Though CO₂ dominates long-term warming, the reduction of warming Short-Lived Climate Forcers (SLCFs), such as methane and black carbon, can in the short term contribute significantly to limiting warming to 1.5°C. Reductions of black carbon and methane would have substantial co-benefits (high confidence), including improved health due to reduced air pollution. This, in turn, enhances the institutional and socio-cultural feasibility of such actions. Reductions of several warming SLCFs are constrained by economic and social feasibility (low evidence, high agreement). As they are often co-emitted with CO₂, achieving the energy, land and urban transitions necessary to limit warming to 1.5°C would see emissions of warming SLCFs greatly reduced. {2.3.3.2, 4.3.6}

Most CDR options face multiple feasibility constraints, that differ between options, limiting the potential for any single option to sustainably achieve the large-scale deployment in 1.5°C-consistent pathways in Chapter 2 (high confidence). Those 1.5°C pathways typically rely on Bioenergy with Carbon Capture and Storage (BECCS), Afforestation and Reforestation (AR), or both, to neutralise emissions that are expensive to avoid, or to draw down CO₂ emissions in excess of the carbon budget (Chapter 2). Though BECCS and AR may be technically and geophysically feasible, they face partially overlapping yet different constraints related to land use. The land footprint per tonne CO₂ removed is higher for AR than for BECCS, but in the light of low current deployment, the speed and scales required for limiting warming to 1.5°C pose a considerable implementation challenge, even if the issues of public acceptance and missing economic incentives were to be resolved (high agreement, medium evidence). The large potentials of afforestation and their co-benefits if implemented appropriately (e.g. on biodiversity, soil quality) will diminish over time, as forests saturate (high confidence). The energy requirements and economic costs of Direct Air Carbon Capture and Storage (DACCS) and enhanced weathering remain high (medium evidence, medium agreement). At the local scale, soil carbon sequestration has co-benefits with agriculture and is cost-effective even without climate policy (high confidence). Its potential global feasibility and cost effectiveness appears to be more limited. {4.3.7}

Uncertainties surrounding Solar Radiation Modification (SRM) measures constrain their potential deployment. These uncertainties include: technological immaturity; limited physical understanding about their effectiveness to limit global warming; and a weak capacity to govern, legitimise, and scale such measures. Some recent model-based analysis suggests SRM would be effective but that it is too early to evaluate its feasibility. Even in the uncertain case that the most adverse side-effects of SRM can be avoided, public resistance, ethical concerns and potential impacts on sustainable development could render SRM economically, socially and institutionally undesirable (low agreement, medium evidence). {4.3.8, Cross-Chapter Box CB10 in this Chapter}
Enabling Rapid and Far-reaching Change

The speed and scale of transitions and of technological change required to limit warming to 1.5°C has been observed in the past within specific sectors and technologies [4.2.2.1]. But the geographical and economic scales at which the required rates of change in the energy, land, urban, infrastructure and industrial systems would need to take place, are larger and have no documented historic precedent (limited evidence, medium agreement). To reduce inequality and alleviate poverty, such transformations would require more planning and stronger institutions (including inclusive markets) than observed in the past, as well as stronger coordination and disruptive innovation across actors and scales of governance. [4.3, 4.4]

Governance consistent with limiting warming to 1.5°C and the political economy of adaptation and mitigation can enable and accelerate systems transitions, behavioural change, innovation and technology deployment (medium evidence, medium agreement). For 1.5°C-consistent actions, an effective governance framework would include: accountable multi-level governance that includes non-state actors such as industry, civil society and scientific institutions; coordinated sectoral and cross-sectoral policies that enable collaborative multi-stakeholder partnerships; strengthened global-to-local financial architecture that enables greater access to finance and technology; and addresses climate-related trade barriers; improved climate education and greater public awareness; arrangements to enable accelerated behaviour change; strengthened climate monitoring and evaluation systems; and reciprocal international agreements that are sensitive to equity and the Sustainable Development Goals (SDGs). System transitions can be enabled by enhancing the capacities of public, private and financial institutions to accelerate climate change policy planning and implementation, along with accelerated technological innovation, deployment and upkeep. [4.4.1, 4.4.2, 4.4.3, 4.4.4]

Behaviour change and demand-side management can significantly reduce emissions, substantially limiting the reliance on CDR to limit warming to 1.5°C (Chapter 2, 4.4.3). Political and financial stakeholders may find climate actions more cost-effective and socially acceptable, if multiple factors affecting behaviour are considered, including aligning them with people’s core values (medium evidence, high agreement). Behaviour- and lifestyle-related measures and demand-side management have already led to emission reductions around the world and can enable significant future reductions (high confidence). Social innovation through bottom-up initiatives can result in greater participation in the governance of systems transitions and increase support for technologies, practices and policies that are part of the global response to 1.5°C. [Chapter 2, 4.4.1, 4.4.3, Figure 4.3]

This rapid and far-reaching response required to keep warming below 1.5°C and enhance the adaptive capacity to climate risks needs large investments in low-emission infrastructure and buildings that are currently underinvested, along with a redirection of financial flows towards low-emission investments (robust evidence, high agreement). An estimated annual incremental investment of 1% to 1.5% of global Gross Fixed Capital Formation (GFCF) for the energy sector is indicated; and 1.7% to 2.5% of global GFCF for other development infrastructure that could also address SDG implementation. Though quality policy design and effective implementation may enhance efficiency, they cannot substitute for these investments. [2.5.2, 4.2.1]

Enabling this investment requires the mobilisation and better integration of a range of policy instruments that include: the reduction of socially inefficient fossil fuel subsidy regimes and innovative price and non-price national and international policy instruments and would need to be complemented by de-risking financial instruments and the emergence of long-term low-emission assets. These instruments would aim to reduce the demand for carbon-intensive services and shift market preferences away from fossil fuel-based technology. Evidence and theory suggest that carbon pricing alone, in the absence of sufficient transfers to compensate their unintended distributional cross-sector, cross-nation effects, cannot reach the levels needed to trigger system transitions (robust evidence, medium agreement). But, embedded in consistent policy-packages, they can help mobilise incremental resources and provide flexible mechanisms that help reduce the social and economic costs of the triggering phase of the transition (robust evidence, medium agreement). [4.4.3, 4.4.4, 4.4.5]
Increasing evidence suggests that a climate-sensitive realignment of savings and expenditure towards low-emission, climate-resilient infrastructure and services requires an evolution of global and national financial systems. Estimates suggest that, in addition to climate-friendly allocation of public investments, a potential redirection of 5% to 10% of the annual capital revenues\(^1\) is necessary \(\{4.4.5, \text{Table 1 in Box 4.8}\}\). This could be facilitated by a change of incentives for private day-to-day expenditure and the redirection of savings from speculative and precautionary investments, towards long-term productive low-emission assets and services. This implies the mobilisation of institutional investors and mainstreaming of climate finance within financial and banking system regulation. Access by developing countries to low-risk and low-interest finance through multilateral and national development banks would have to be facilitated (\textit{medium evidence, high agreement}). New forms of public-private partnerships may be needed with multilateral, sovereign and sub-sovereign guarantees to de-risk climate-friendly investments, support new business models for small-scale enterprises and help households with limited access to capital. Ultimately, the aim is to promote a portfolio shift towards long-term low-emission assets, that would help redirect capital away from potential stranded assets (\textit{medium evidence, medium agreement}). \(\{4.4.5\}\)

\textbf{Knowledge Gaps}

Knowledge gaps around implementing and strengthening the global response to climate change would need to be urgently resolved if the transition to 1.5°C worlds is to become reality. Remaining questions include: how much can be realistically expected from innovation, behaviour and systemic political and economic change in improving resilience, enhancing adaptation and reducing GHG emissions? How can rates of changes be accelerated and scaled up? What is the outcome of realistic assessments of mitigation and adaptation land transitions that are compliant with sustainable development, poverty eradication and addressing inequality? What are life-cycle emissions and prospects of early-stage CDR options? How can climate and sustainable development policies converge, and how can they be organised within a global governance framework and financial system, based on principles of justice and ethics (including Common But Differentiated Responsibilities and Respective Capabilities (CBDR-RC)), reciprocity and partnership? To what extent limit warming to 1.5°C needs a harmonisation of macro-financial and fiscal policies, that could include financial regulators such as central banks? How can different actors and processes in climate governance reinforce each other, and hedge against the fragmentation of initiatives? \(\{4.1, 4.4.1, 4.3.7, 4.4.5, 4.6\}\)

\(^1\) FOOTNOTE: Annual capital revenues are the paid interests plus the increase of the asset value.
4.1 Accelerating the Global Response to Climate Change

This chapter discusses how the global economy and socio-technical and socio-ecological systems can transition to 1.5°C-consistent pathways and adapt to warming of 1.5°C. In the context of systemic transitions, the chapter assesses adaptation and mitigation options, including Carbon Dioxide Removal (CDR), and potential Solar Radiation Modification (SRM) remediable measures (Section 4.3), as well as the enabling conditions that would facilitate implementing the rapid and far-reaching global response (Section 4.4), and render the options more or less feasible (Section 4.5).

The impacts of 1.5°C warmer worlds, while less than in a 2°C warmer world, would require complementary adaptation and development action, typically at local and national scale. From a mitigation perspective, 1.5°C-consistent pathways require immediate action on a greater and global scale so as to achieve net-zero emissions by mid-century, or earlier (Chapter 2). This chapter and Chapter 5 highlight the potential that combined mitigation, development and poverty reduction offer for accelerated decarbonisation.

The global context is an increasingly interconnected world, with the human population growing from the current 7.6 billion to over 9 billion by mid-century (UN, 2017). There has been a consistent growth of global economic output, wealth and trade with a significant reduction in extreme poverty. These trends could continue for the next few decades (Burt et al., 2014), potentially supported by new and disruptive information and communication, and nano- and bio-technologies. They however co-exist with rising inequality (Piketty, 2014), exclusion and social stratification, and regions locked in poverty traps (Deaton, 2013) that could fuel social and political tensions.

The aftermath of the 2008 financial crisis generated a challenging environment on which leading economists have issued repeated alerts about the ‘discontents of globalisation’ (Stiglitz, 2002), ‘depression economics’ (Krugman, 2009), an excessive reliance of export-led development strategies (Rajan, 2011), and risks of ‘secular stagnation’ due to the ‘saving glut’ that slows down the flow of global savings towards productive 1.5°C-consistent investments (Summers, 2016). Each of these impacts the implementation of both 1.5°C-consistent pathways and sustainable development (Chapter 5).

The range of mitigation and adaptation actions that can be deployed in the short run are well-known: for example, low-emission technologies, new infrastructure, energy efficiency measures in buildings, industry and transport; transformation of fiscal structures; reallocation of investments and human resources towards low-emission assets; sustainable land and water management, ecosystem restoration, enhancement of adaptive capacities to climate risks and impacts, disaster risk management; research and development; and mobilisation of new, traditional and Indigenous knowledge.

The convergence of short-term development co-benefits of mitigation and adaptation to address ‘everyday development failures’ (e.g., institutions, market structures and political processes) (Hallegatte et al., 2016; Pelling et al., 2018) could enhance the adaptive capacity of key systems at risk (e.g., water, energy, food, biodiversity, urban, regional and coastal systems) to 1.5°C climate impact (Chapter 3). The issue is whether aligning 1.5°C-consistent pathways with the Sustainable Development Goals (SDGs) will secure support for accelerated change and a new growth cycle (Stern, 2013, 2015). It is difficult to imagine how a 1.5°C world would be attained unless the SDG on cities and sustainable urbanisation is attained in developing countries (Revi, 2016), or without reforms in the global financial intermediation system.

Unless affordable and environmentally and socially acceptable CDR become feasible and available at scale well before 2050, 1.5°C-consistent pathways will be difficult to realise, especially in overshoot scenarios. The social costs and benefits of 1.5°C-consistent pathways depend on the depth and timing of policy responses and their alignment with short term and long-term development objectives, through policy packages that bring together a diversity of policy instruments, including public investment (Campiglio 2016; Winkler and Dubash 2015; Grubb et al. 2014).

Whatever its potential long-term benefits, a transition to a 1.5°C world may suffer from a lack of broad political and public support, if it exacerbates existing short-term economic and social tensions, including

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4-10

Total pages: 198
unemployment, poverty, inequality, financial tensions, competitiveness issues and the loss of economic value of carbon-intensive assets (Mercure et al., 2018). The challenge is therefore how to strengthen climate policies without inducing economic collapse or hardship, and to make them contribute to reducing some of the ‘fault lines’ of the world economy (Rajan, 2011).

This chapter reviews literature addressing the alignment of climate with other public policies (e.g., fiscal, trade, industrial, monetary, urban planning, infrastructure, innovation) and with a greater access to basic needs and services, defined by the SDGs. It also reviews how de-risking low-emission investments and the evolution of the financial intermediation system can help reduce the ‘savings glut’ (Arezki et al., 2016) and the gap between cash balances and long-term assets (Aglietta et al., 2015b) to support more sustainable and inclusive growth.

As the transitions associated with 1.5°C-consistent pathways require accelerated and coordinated action, in multiple systems across all world regions, they are inherently exposed to risks of freeriding and moral hazards. A key governance challenge is how the convergence of voluntary domestic policies can be organised via aligned global, national and sub-national governance, based on reciprocity (Ostrom and Walker, 2005) and partnership (UN, 2016), and how different actors and processes in climate governance can reinforce each other to enable this (Gupta, 2014; Andonova et al., 2017). The emergence of polycentric sources of climate action and transnational and subnational networks that link these efforts (Abbott et al., 2012) offer the opportunity to experiment and learn from different approaches, thereby accelerating approaches led by national governments (Cole, 2015; Jordan et al., 2015).

Section 4.2 of this chapter outlines existing rates of change and attributes of accelerated change. Section 4.3 identifies global systems, and their components, that offer options for this change. Section 4.4 documents the enabling conditions that influence the feasibility of those options, including economic, financial and policy instruments that could trigger the transition to 1.5°C-consistent pathways. Section 4.5 assesses mitigation and adaptation options for feasibility, strategies for implementation and synergies and trade-offs between mitigation and adaptation.

4.2 Pathways Compatible with 1.5°C: Starting Points for Strengthening Implementation

4.2.1 Implications for Implementation of 1.5°C-consistent Pathways

The 1.5°C-consistent pathways assessed in Chapter 2 form the basis for the feasibility assessment in section 4.3. A wide range of 1.5°C-consistent pathways from both Integrated Assessment Modelling (IAM), supplemented by other literature, are assessed by Chapter 2 (Sections 2.1, 2.3, 2.4, and 2.5). The most common feature shared by these pathways is their requirement for faster and more radical changes compared to 2°C and higher warming pathways.

A variety of 1.5°C-consistent technological options and policy targets is identified in the assessed modelling literature (Sections 2.3, 2.4, 2.5). These technology and policy options include energy demand reduction, greater penetration of low-emission and carbon-free technologies as well as electrification of transport and industry, and reduction of land-use change. Both the detailed integrated modelling pathway literature and a number of broader sectoral and bottom-up studies provide examples of how these sectoral technological and policy characteristics can be broken down sectorally for 1.5°C-consistent pathways (see Table 4.1).

Both the integrated pathway literature and the sectoral studies agree on the need for rapid transitions in the production and use of energy across various sectors, to be consistent with limiting global warming to 1.5°C. The pace of these transitions are particularly significant for the supply mix and electrification, with sectoral studies projecting a higher pace of change compared to IAMs (Table 4.1). These trends and transformation patterns create opportunities and challenges for both mitigation and adaptation (Sections 4.2.1.1 and 4.2.1.2), and have significant implications for the assessment of feasibility and enablers, including governance, institutions, and policy instruments addressed in Sections 4.3 and 4.4.
Table 4.1: Sectoral indicators of the pace of transformation in 1.5°C-consistent pathways, based on selected integrated pathways assessed in Chapter 2 (from the scenario database) and sectoral studies reviewed in Chapter 2 that assess mitigation transitions consistent with limiting warming to 1.5°C. Values for ‘1.5C low OS’ and ‘1.5C high OS’ indicate the median and the interquartile ranges for 1.5°C scenarios distinguishing high and low overshoot. S1, S2, S5 and LED represent the four illustrative pathway archetypes selected for this assessment (see Section 2.1 and Supplementary Material 4.A for detailed description).

<table>
<thead>
<tr>
<th>Energy</th>
<th>Buildings</th>
<th>Transport</th>
<th>Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Share of renewable in primary energy [%]</td>
<td>Share of renewable in electricity [%]</td>
<td>Change in energy demand for buildings (2010 baseline) [%]</td>
<td>Share of low carbon fuels (electricity, hydrogen and biofuel) in transport [%]</td>
</tr>
<tr>
<td>1.5C low OS</td>
<td>1.5C high OS</td>
<td>IAM Pathways 2030</td>
<td>Sectorial studies 2030</td>
</tr>
<tr>
<td>S1</td>
<td>29 (35; 25)</td>
<td>58</td>
<td>-8</td>
</tr>
<tr>
<td>S2</td>
<td>29 (27; 20)</td>
<td>43 (54; 37)</td>
<td>-17 (-12; -20)</td>
</tr>
<tr>
<td>S5</td>
<td>14 (25)</td>
<td>30</td>
<td>NA</td>
</tr>
<tr>
<td>LED</td>
<td>37 (60)</td>
<td>30</td>
<td>NA</td>
</tr>
<tr>
<td>1.5C low OS</td>
<td>58 (67; 50)</td>
<td>76 (85; 69)</td>
<td>-19 (2; -37)</td>
</tr>
<tr>
<td>1.5C high OS</td>
<td>62 (68; 47)</td>
<td>82 (88; 64)</td>
<td>-37 (-13; -51)</td>
</tr>
<tr>
<td>S1</td>
<td>58 (67; 50)</td>
<td>63 (74)</td>
<td>-21</td>
</tr>
<tr>
<td>S2</td>
<td>53 (60; 24)</td>
<td>63 (74)</td>
<td>-25</td>
</tr>
<tr>
<td>S5</td>
<td>67 (70)</td>
<td>63 (74)</td>
<td>NA</td>
</tr>
<tr>
<td>LED</td>
<td>73 (77)</td>
<td>45</td>
<td>NA</td>
</tr>
<tr>
<td>1.5C low OS</td>
<td>100</td>
<td>100</td>
<td>98</td>
</tr>
<tr>
<td>1.5C high OS</td>
<td>100</td>
<td>100</td>
<td>98</td>
</tr>
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</table>

4.2.1.1 Challenges and Opportunities for Mitigation Along the Reviewed Pathways

4.2.1.1.1 Greater scale, speed and change in investment patterns
There is agreement in the literature reviewed by Chapter 2 that staying below 1.5°C would entail significantly greater transformation in terms of energy systems, lifestyles and investments patterns compared to 2°C-consistent pathways. Yet there is limited evidence and low agreement regarding the magnitudes and costs of the investments (Sections 2.5.1, 2.5.2 and 4.4.5). Based on the IAM literature reviewed in Chapter 2, climate policies in line with limiting warming to 1.5°C would require a marked upscaling of supply-side energy system investments between now and mid-century, reaching levels of between 1.6–3.8 trillion USD.
Not only the level of investment but also the type and speed of sectoral transformation would be impacted by the transitions associated with 1.5°C-consistent pathways. IAM literature projects that investments in low-emission energy will overtake fossil-fuel investments globally by 2025 in 1.5°C-consistent pathways (Section 2.5.2). The projected low-emission investments in electricity generation allocations over the period 2016–2050 are: solar (0.09–1.0 trillion USD yr\(^{-1}\)), wind (0.1–0.35 trillion USD yr\(^{-1}\)), nuclear (0.1–0.25 trillion USD yr\(^{-1}\)), and transmission, distribution, and storage (0.3–1.3 trillion USD yr\(^{-1}\)). In contrast, investments in fossil-fuel extraction and unabated fossil electricity generation along a 1.5°C-consistent pathway are projected to drop by 0.3–0.85 trillion USD yr\(^{-1}\) over the period 2016–2050, with investments in unabated coal generation projected to halt by 2030 in most 1.5°C-consistent pathways (Section 2.5.2). Estimates of investments in other infrastructure are currently unavailable, but they could be considerably larger in volume than solely those in the energy sector (Section 4.4.5).

4.2.1.1.2 Greater policy design and decision-making implications

1.5°C-consistent pathways raise multiple challenges for effective policy design and responses to address the scale, speed, and pace of mitigation technology, finance and capacity building needs. They also need to deal with their distributional implications, while addressing adaptation to residual climate impacts (see Chapter 5). The available literature indicates that 1.5°C-consistent pathways would require robust, stringent and urgent transformative policy interventions targeting the decarbonisation of energy supply, electrification, fuel switching, energy efficiency, land-use change, and lifestyles (Sections 2.5, 4.4.2, 4.4.3). Examples of effective approaches to integrate mitigation with adaptation in the context of sustainable development and to deal with distributional implications proposed in the literature include the utilisation of dynamic adaptive policy pathways (Haasnoot et al., 2013; Mathy et al., 2016) and transdisciplinary knowledge systems (Bendito and Barrios, 2016).

Yet, even with good policy design and effective implementation, 1.5°C-consistent pathways would incur higher costs. Projections of the magnitudes of global economic costs associated with 1.5°C-consistent pathways and their sectoral and regional distributions from the currently assessed literature are scant, yet suggestive. For example, IAM simulations assessed in Chapter 2 project (with a probability greater than 50%) that marginal abatement costs, typically represented in IAMs through a carbon price, would increase by about threefold by 2050 under a 1.5°C-consistent pathway compared to a 2°C-consistent pathway (Section 2.5.2, Figure 2.26). Managing these costs and distributional effects would require an approach that takes account of unintended cross-sector, cross-nation, and cross-policy trade-offs during the transition (Droste et al., 2016; Stiglitz et al., 2017; Pollitt, 2018; Sands, 2018; Siegmeier et al., 2018).

4.2.1.1.3 Greater sustainable development implications

Few studies address the relations between the Shared Socioeconomic Pathways (SSPs) and the Sustainable Development Goals (SDGs) (O’Neill et al., 2015; Riahi et al., 2017). Nonetheless, literature on potential synergies and trade-offs between 1.5°C-consistent mitigation pathways and sustainable development dimensions is emerging (Sections 2.5.3, 5.4). Areas of potential trade-offs include reduction in final energy demand in relation to SDG 7 (the universal clean energy access goal) and increase of biomass production in relation to land use, water resources, food production, biodiversity and air quality (Sections 2.4.3, 2.5.3). Strengthening the institutional and policy responses to deal with these challenges are discussed in Section 4.4 together with the linkage between disruptive changes in the energy sector and structural changes in other infrastructure (transport, building, water and telecommunication) sectors. A more in-depth assessment of the complexity and interfaces between 1.5°C-consistent pathways and sustainable development is presented in Chapter 5.
4.2.1.2  Implications for Adaptation Along the Reviewed Pathways

Climate variability and uncertainties in the underlying assumptions in Chapter 2’s IAMs as well as in model comparisons complicate discerning the implications for climate impacts, adaptation options and avoided adaptation investments at the global level of 2°C compared to 1.5°C warming (James et al., 2017; Mitchell et al., 2017).

Incremental warming from 1.5°C to 2°C would lead to significant increases in temperature and precipitation extremes in many regions (Section 3.3.2, 3.3.3). Those projected changes in climate extremes under both warming levels, however, depend on the emissions pathways, as they have different greenhouse gas (GHG)/aerosol forcing ratios. Impacts are sector-, system- and region-specific, as described in Chapter 3. For example, precipitation-related impacts reveal distinct regional differences (Sections 3.3.3, 3.3.4, 3.3.5, 3.4.2). Similarly, regional reduction in water availability and the lengthening of regional dry spells have negative implications for agricultural yields depending on crop types and world regions (see for example Sections 3.3.4, 3.4.2, 3.4.6).

Adaptation helps reduce impacts and risks. However, adaptation has limits. Not all systems can adapt, and not all impacts can be reversed (Cross-Chapter Box 12 in Chapter 5). For example, tropical coral reefs are projected to be at risk of severe degradation due to temperature-induced bleaching (Box 3.4).

4.2.2  System Transitions and Rates of Change

Society-wide transformation involves socio-technical transitions and social-ecological resilience (Gillard et al., 2016). Transitional adaptation pathways would need to respond to low-emission energy and economic systems, and the socio-technical transitions for mitigation involve removing barriers in social and institutional processes that could also benefit adaptation (Pant et al., 2015; Geels et al., 2017; Ickowitz et al., 2017). In this chapter, transformative change is framed in mitigation around socio-technical transitions, and in adaptation around socio-ecological transitions. In both instances, emphasis is placed on the enabling role of institutions (including markets, and formal and informal regulation). 1.5°C-consistent pathways and adaptation needs associated with warming of 1.5°C imply both incremental and rapid, disruptive and transformative changes.

4.2.2.1  Mitigation: Historical Rates of Change and State of Decoupling

Realising 1.5°C-consistent pathways would require rapid and systemic changes on unprecedented scales (see Chapter 2 and Section 4.2.1). This section examines whether the needed rates of change have historical precedents and are underway.

Some studies conduct a de-facto validation of IAM projections. For CO₂ emission intensity over 1990–2010, this resulted in the IAMs projecting declining emission intensities while actual observations showed an increase. For individual technologies (in particular solar energy), IAM projections have been conservative regarding deployment rates and cost reductions (Creutzig et al., 2017), suggesting that IAMs do not always impute actual rates of technological change resulting from influence of shocks, broader changes and mutually reinforcing factors in society and politics (Geels and Schot, 2007; Daron et al., 2015; Sovacool, 2016; Battiston et al., 2017).

Other studies extrapolate historical trends into the future (Höök et al., 2011; Fouquet, 2016), or contrast the rates of change associated with specific temperature limits in IAMs (such as those in Chapter 2) with historical trends to investigate plausibility of emission pathways and associated temperature limits (Wilson et al., 2013; Gambhir et al., 2017; Napp et al., 2017). When metrics are normalised to Gross Domestic Product (GDP; as opposed to other normalisation metrics such as primary energy), low-emission technology deployment rates used by IAMs over the course of the coming century are shown to be broadly consistent with past trends, but rates of change in emission intensity are typically overestimated (Wilson et al., 2013;
Loftus et al., 2014; van Sluijsveld et al., 2015). This bias is consistent with the findings from the ‘validation’ studies cited above, suggesting that IAMs may under-report the potential for supply-side technological change assumed in 1.5°C-consistent pathways, but may be more optimistic about the systemic ability to realise incremental changes in reduction of emission intensity as a consequence of favourable energy efficiency payback times (Wilson et al., 2013). This finding suggests that barriers and enablers other than costs and climate limits play a role in technological change, as also found in the innovation literature (Hekkert et al., 2007; Bergek et al., 2008; Geels et al., 2016b).

One barrier to a greater rate of change in energy systems is that economic growth in the past has been coupled to the use of fossil fuels. Disruptive innovation and socio-technical changes could enable the decoupling of economic growth from a range of environmental drivers, including the consumption of fossil fuels, as represented by 1.5°C-consistent pathways (UNEP, 2014; Newman, 2017). This may be relative decoupling due to rebound effects that see financial savings generated by renewable energy used in the consumption of new products and services (Jackson and Senker, 2011; Gillingham et al., 2013), but in 2015 and 2016 total global GHG emissions have decoupled absolutely from economic growth (IEA, 2017g; Peters et al., 2017). A longer data trend would be needed before stable decoupling can be established. The observed decoupling in 2015 and 2016 was driven by absolute declines in both coal and oil use since the early 2000s in Europe, in the past seven years in the United States and Australia, and more recently in China (Newman, 2017). In 2017, decoupling in China reversed by 2% due to a drought and subsequent replacement of hydropower with coal-fired power (Tollefson, 2017), but this reversal is expected to be temporary (IEA, 2017c). Oil consumption in China is still rising slowly, but absolute decoupling is ongoing in megacities like Beijing (Gao and Newman, 2018) (see Box 4.9).

4.2.2.2 Transformational Adaptation

In some regions and places, incremental adaptation would not be sufficient to mitigate the impacts of climate change on social-ecological systems (see Chapter 3). Transformational adaptation would then be required (Bahadur and Tanner, 2014; Pant et al., 2015; Gillard, 2016; Gillard et al., 2016; Colloff et al., 2017; Termeer et al., 2017). Transformational adaptation refers to actions aiming at adapting to climate change resulting in significant changes in structure or function that go beyond adjusting existing practices (Dowd et al., 2014; IPCC, 2014a; Few et al., 2017), including approaches that enable new ways of decision-making on adaptation (Colloff et al., 2017). Few studies have assessed the potentially transformative character of adaptation options (Pelling et al., 2015; Rippke et al., 2016; Solecki et al., 2017), especially in the context of warming of 1.5°C.

Transformational adaptation can be adopted at a large scale, can lead to new strategies in a region or resource system, transform places and potentially shifts locations (Kates et al., 2012). Some systems might require transformational adaptation at 1.5°C. Implementing adaptation policies in anticipation of 1.5°C would require transformation and flexible planning of adaptation (sometimes called adaptation pathways) (Rothman et al., 2014; Smucker et al., 2015; Holland, 2017; Gajjar et al., 2018), an understanding of the varied stakeholders involved and their motives, and knowledge of less visible aspects of vulnerability based on social, cultural, political, and economic factors (Holland, 2017). Transformational adaptation would seek deep and long-term societal changes that influence sustainable development (Chung Tiam Fook, 2017; Few et al., 2017).

Adaptation requires multidisciplinary approaches integrating scientific, technological and social dimensions. For example, a framework for transformational adaptation, and the integration of mitigation and adaptation pathways can transform rural indigenous communities to address risks of climate change and other stressors (Thornton and Comberti, 2017). In villages in rural Nepal, transformational adaptation has taken place with villagers changing their agricultural and pastoralist livelihood strategies after years of lost crops due to changing rain patterns and degradation of natural resources (Thornton and Comberti, 2017). Instead, they are now opening stores, hotels, and tea shops. In another case, the arrival of an oil pipeline altered traditional Alaskan communities’ livelihoods. With growth of oil production, investments were made for rural development. A later drop in oil production decreased these investments. Alaskan Indigenous populations
are also dealing with impacts of climate change, such as sea level rise, which is altering their livelihood sources. Transformational adaptation is taking place by changing the energy matrix to renewable energy, in which indigenous people apply their knowledge to achieve environmental, economic, and social benefits (Thornton and Comberti, 2017).

4.2.2.3 Disruptive Innovation

Demand-driven disruptive innovations that emerge as the product of political and social changes across multiple scales can be transformative (Seba, 2014; Christensen et al., 2015; Green and Newman, 2017a). Such innovations would lead to simultaneous, profound changes in behaviour, economies and societies (Seba, 2014; Christensen et al. 2015), but are difficult to predict in supply-focused economic models (Geels et al., 2016a; Pindyck, 2017). Rapid socio-technical change has been observed in the solar industry (Creutzig et al. (2017). Similar changes to socio-ecological systems can stimulate adaptation and mitigation options that lead to more climate-resilient systems (Adger et al., 2005; Ostrom, 2009; Gillard et al., 2016) (see the Alaska and Nepal examples in Section 4.2.2.2). The increase in roof-top solar and energy storage technology as well as the increase in passive housing and net zero-emissions buildings are further examples of such disruptions (Green and Newman, 2017b). Both roof-top solar and energy storage have benefitted from countries’ economic growth strategy and associated price declines in photovoltaic technologies, particularly in China (Hsu et al., 2017; Shrivastava and Persson, 2018), as well as from new information and communication technologies (Koomey et al., 2013), rising demand for electricity in urban areas, and global concern regarding greenhouse gas emissions (Azoteiro et al., 2017; Lutz and Muttarak, 2017; Wamsler, 2017).

System co-benefits can create the potential for mutually enforcing and demand-driven climate responses (Jordan et al., 2015; Hallegatte and Mach, 2016; Pelling et al., 2018), and rapid and transformational change (Cole, 2015; Geels et al., 2016b; Hallegatte and Mach, 2016; Peters et al., 2017). Examples of co-benefits include gender equality, agricultural productivity (Nyantakyi-Frimpong and Bezner-Kerr, 2015), reduced indoor air pollution (Satterthwaite and Bartlett, 2017), flood buffering (Colenbrander et al., 2017), livelihood support (Shaw et al., 2014; Ürge-Vorsatz et al., 2014), economic growth (GCEC, 2014; Stiglitz et al., 2017), social progress (Steg et al., 2015; Hallegatte and Mach, 2016) and social justice (Ziervogel et al., 2017; Patterson et al., 2018).

Innovations that disrupt entire systems may leave firms and utilities with stranded assets as the transition can happen very quickly (IPCC, 2014b; Kossoy et al., 2015). This may have consequences for fossil fuels that are rendered ‘unburnable’ (McGlade and Ekins, 2015) and fossil fuel-fired power and industry assets that would become obsolete (Caldecott, 2017; Farfan and Breyer, 2017). The presence of multiple barriers and enablers operating in a system implies that rapid change, whether the product of many small changes (Sterling et al., 2017; Termmer et al., 2017) or large-scale disruptions, is seldom an insular or discrete process. This finding informs the multi-dimensional nature of feasibility in Cross-Chapter Box 3 in Chapter 1 which is applied in Section 4.5. Climate responses that are aligned with multiple feasibility dimensions and combine adaptation and mitigation interventions with non-climate benefits can accelerate change and reduce risks and costs (Fazey et al., 2018). Also political, social and technological influences on energy transitions, for example, can accelerate them faster than narrow techno-economic analysis suggests is possible (Kern and Rogge, 2016), but could also introduce new constraints and risks (Geels et al., 2016b; Sovacool, 2016; Eyre et al., 2018).

Disruptive innovation and technological change may play a role in mitigation and in adaptation. The next section assesses mitigation and adaptation options in energy, land and ecosystem, urban and infrastructure and industrial systems.
4.3 Systemic Changes for 1.5°C-Consistent Pathways

Section 4.2 emphasises the importance of systemic change for 1.5°C-consistent pathways. This section translates this into four main system transitions: energy, land and ecosystem, urban and infrastructure, and industrial system transitions. This section assesses the mitigation, adaptation and carbon dioxide removal options that offer the potential for such change within those systems, based on options identified by Chapter 2 and risks and impacts in Chapter 3.

The section puts more emphasis on those adaptation options (Sections 4.3.1-4.3.5) and mitigation options (Sections 4.3.1-4.3.4, 4.3.6 and 4.3.7) that are 1.5°C-relevant and have developed considerably since AR5. They also form the basis for the mitigation and adaptation feasibility assessments in Section 4.5. Section 4.3.8 discusses solar radiation modification methods.

This section emphasises that no single solution or option can enable a global transition to 1.5°C-consistent pathways or adapting to projected impacts. Rather, accelerating change, much of which is already starting or underway, in multiple global systems, simultaneously and at different scales, could provide the impetus for these system transition. The feasibility of individual options as well as the potential for synergies and reduce trade-offs will vary according to context and the local enabling conditions. These are explored at a high level in Section 4.4. Policy packages that bring together multiple enabling conditions can provide building blocks for a strategy to scale-up implementation and intervention impacts.

4.3.1 Energy System Transitions

This section discusses the feasibility of mitigation and adaptation options related to the energy system transition. As only options relevant to 1.5°C and with significant changes since AR5 are discussed, which means that for options like hydropower and geothermal energy, the chapter refers to AR5 and does not provide a discussion. Socio-technical inertia of energy options for 1.5°C-consistent pathways are increasingly being surmounted as fossil fuels start to be phased out. Supply-side mitigation and adaptation options, energy demand-side options, including energy efficiency in buildings and transportation, are discussed in Section 4.3.3, options around energy use in industry are discussed in Section 4.3.4.

Section 4.5 assesses the feasibility in a systematic manner based on the approach outlined in Cross-Chapter Box 3 in Chapter 1.

4.3.1.1 Renewable Electricity: Solar and Wind

All renewable energy options have seen considerable advances over the years since AR5, but solar energy and both onshore and offshore wind energy have had dramatic growth trajectories. They appear well underway to contribute to 1.5°C-consistent pathways (REN21, 2012; IEA, 2017c; IRENA, 2017b).

The largest growth driver for renewable energy since AR5 has been the dramatic reduction in the cost of solar PV (REN21, 2012). This has made rooftop solar competitive in sunny areas between 45° north and south (Green and Newman, 2017b), though IRENA (2018) suggests it is cost effective in many other places too. Solar Photovoltaics (PV) with batteries have been cost effective in many rural and developing areas (Pueyo and Hanna, 2015; Szabó et al., 2016; Jimenez, 2017), for example 19 million people in Bangladesh now have solar-battery electricity in remote villages and are reporting positive experiences on safety and ease of use (Kabir et al., 2017). Small-scale distributed energy projects are being implemented in developed and developing cities where residential and commercial rooftops offer potential for consumers becoming producers (called prosumers) (ACOLA, 2017; Kotilainen and Saari, 2018). Such prosumers could contribute significantly to electricity generation in sun-rich areas like California (Kurdgelashvili et al., 2016) or Sub-Saharan Africa in combination with micro-grids and mini-grids Bertheau et al. (2017). It could also contribute to universal energy access (SDG 7) as shown by (IEA, 2017c).
The feasibility of renewable energy options depends to a large extent on geophysical characteristics of the area where the option is implemented. However, technological advances and policy instruments make renewable energy options increasingly attractive in other areas. For example, solar PV is deployed commercially in areas with low solar insolation, like North-Western Europe (Nyholm et al., 2017). Feasibility also depends on grid adaptations (e.g., storage, see below) as renewables grow (IEA, 2017c). For regions with high energy needs, such as industrial areas (see section 4.3.4), high-voltage DC transmission across long distances would be needed (MacDonald et al., 2016).

Another important factor affecting feasibility is public acceptance, in particular for wind energy and other large-scale renewable facilities (Yenneti and Day, 2016; Rand and Hoen, 2017; Gorayeb et al., 2018) that raise landscape management (Nadaï and Labussière, 2017) and distributional justice (Yenneti and Day, 2016) challenges. Research indicates that financial participation and community engagement can be effective in mitigating resistance (Brunes and Ohlhorst, 2011; Rand and Hoen, 2017) (see Section 4.4.3).

Bottom-up studies estimating the use of renewable energy in the future, either at the global or at the national level, are plentiful, especially in the grey literature. It is hotly debated whether a fully renewable energy or electricity system, with or without biomass, is possible (Jacobson et al., 2015, 2017) or not (Clack et al., 2017; Heard et al., 2017), and by what year. Scale-up estimates vary with assumptions about costs and technological maturity, as well as local geographical circumstances and the extent of storage used (REN21, 2012; Ghorbani et al., 2017). Several countries have adopted targets of 100% renewable electricity (IEA, 2017c) as this meets multiple social, economic and environmental goals and contribute to mitigation of climate change (REN21, 2012).

4.3.1.2 Bioenergy and Biofuels

Bioenergy is renewable energy from biomass. Biofuel is biomass-based energy used in transport. Chapter 2 suggests that pathways limiting warming to 1.5°C would enable supply of 67–150 EJ yr⁻¹ (see Table 2.8) from biomass. Most scenarios find that Bioenergy is combined with Carbon Dioxide Capture and Storage (CCS, BECCS) if it is available but also find robust deployment of bioenergy independent of the availability of CCS (see Section 2.3.4.2 and 4.3.7 for a discussion of BECCS). Detailed assessments indicate that deployment is similar for 2°C-consistent pathways (Chum et al., 2011; P. Smith et al., 2014; Creutzig et al., 2015). There is however high agreement that the sustainable bioenergy potential in 2050 would be restricted to around 100 EJ yr⁻¹ (Slade et al., 2014; Creutzig et al., 2015b). Sustainable deployment at this or higher levels envisioned by 1.5°C-consistent pathways may put significant pressure on available land, food production and prices (Popp et al., 2014b; Persson, 2015; Kline et al., 2017; Searchinger et al., 2017), preservation of ecosystems and biodiversity (Creutzig et al., 2015b; Holland et al., 2015; Santangeli et al., 2016) as well as potential water and nutrient constraints (Gerbens-Leenes et al., 2009; Gheewala et al., 2011; Bows and Smith, 2012; Smith and Torn, 2013; Bonsch et al., 2016; Lampert et al., 2016; Mouriadou et al., 2016; Smith et al., 2016b; Wei et al., 2016; Mathioudakis et al., 2017); but there is still low agreement on these interactions (Robledo-Abad et al., 2017). Some of the disagreement on the sustainable capacity for bioenergy stems from global versus local assessments. Global assessments may mask local dynamics that exacerbate negative impacts and shortages while at the same time niche contexts for deployment may avoid trade-offs and exploit co-benefits more effectively. In some regions of the world (e.g., the case of Brazilian ethanol, see Box 4.7, where land may be less of a constraint, the use of bioenergy is mature and the industry is well developed), land transitions could be balanced with food production and biodiversity to enable a global impact on CO₂ emissions (Jaiswal et al., 2017).

The carbon intensity of bioenergy, key for both bioenergy as an emission-neutral energy system and BECCS as a Carbon Dioxide Removal (CDR) measure, is still a matter of debate (Buchholz et al., 2016; Liu et al., 2018) and depends on management (Pyörälä et al., 2014; Torssonen et al., 2016; Baul et al., 2017; Kilpeläinen et al., 2017); direct and indirect land use change emissions (Plevin et al., 2010; Schulze et al.,

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Biofuels are a part of the transport sector in some cities and countries, and may be deployed as a mitigation option for aviation, shipping and freight transport (see Section 4.3.3.5) as well as industrial decarbonisation (IEA, 2017g) (Section 4.3.4) though only Brazil has mainstreamed ethanol as a substantial, commercial option. Lower emissions and reduced urban air pollution have been achieved there by use of ethanol and biodiesel as fuels (Hill et al., 2006; Salvo et al., 2017) (see Box 4.7).

4.3.1.3 Nuclear Energy

Many scenarios in Chapter 2 and in AR5 (Bruckner et al., 2014) project an increase in the use of nuclear power, while others project a decrease. The increase can be realised through existing mature nuclear technologies or new options (generation III/IV reactors, breeder reactors, new uranium and thorium fuel cycles, small reactors or nuclear cogeneration).

Even though historically scalability and speed of scaling of nuclear plants have been high in many nations, such rates are currently not achieved anymore. In the 1960s and 1970s, France implemented a programme to rapidly get 80% of its power from nuclear in about 25 years (IAEA, 2018), but the current time-lag between the decision date and the commissioning of plants is observed to be 10-19 years (Lovins et al., 2018). The current deployment pace of nuclear energy is constrained by social acceptability in many countries due to concerns over risks of accidents and radioactive waste management (Bruckner et al., 2014). Though comparative risk assessment shows health risks are low per unit of electricity production (Hirschberg et al., 2016), and land requirement is lower than that of other power sources (Cheng and Hammond, 2017), the political processes triggered by societal concerns depend on the country-specific means of managing the political debates around technological choices and their environmental impacts (Gregory et al., 1993). Such differences in perception (Kim and Chung, 2017) explain why the 2011 Fukushima incident resulted in a confirmation or acceleration of phasing out nuclear energy in five countries (Roh, 2017) while 30 other countries have continued using nuclear energy, amongst which 13 are building new nuclear capacity including China, India and the United Kingdom (IAEA, 2017; Yuan et al., 2017).

Costs of nuclear power have increased over time in some developed nations, principally due to market conditions where increased investment risks of high-capital expenditure technologies have become significant. ‘Learning by doing’ processes often failed to compensate for this trend because they were slowed down by the absence of standardisation and series effects (Grubler, 2010). What are and have been the costs of nuclear power is debated in the literature (Lovering et al., 2016; Koomey et al., 2017). Countries with liberalised markets that continue to develop nuclear employ de-risking instruments through long-term contracts with guaranteed sale prices (Finon and Roques, 2013). For instance, the United Kingdom works with public guarantees covering part of the upfront investment costs of newly planned nuclear capacity. This dynamic differs in countries such as China and South Korea, where monopolistic conditions in the electric system allow for reducing investment risks, deploying series effects and enhancing the engineering capacities of users due to stable relations between the security authorities and builders (Schneider et al., 2017).

The safety of nuclear plants depends upon the public authorities of each country. However, because accidents affect worldwide public acceptance of this industry, questions have been raised about the risk of economic and political pressures weakening the safety of the plants (Finon, 2013; Budnitz, 2016). This raises the issue of international governance of civil nuclear risks and reinforced international cooperation involving governments, companies and engineering (Walker and Lönnroth, 1983; Thomas, 1988; Finon, 2013), based

2 FOOTNOTE: While there is high agreement that indirect Land Use Change (iLUC) could occur, there is low agreement about the actual extent of iLUC (P. Smith et al., 2014; Verstegen et al., 2015; David, 2017)
on the experience of the International Atomic Energy Agency.

4.3.1.4 **Energy Storage**

The growth in electricity storage for renewables has been around Grid Flexibility Resources (GFR) that would enable several places to source more than half their power from non-hydro renewables (Komarnicki, 2016). Ten types of GFRs within smart grids have been developed largely since AR5 as renewables have tested grid stability (Blaabjerg et al., 2004; IRENA, 2013; IEA, 2017d; Majzooob and Khodaei, 2017) though demonstrations of how to do this without hydro or natural gas-based power back-up are still needed. Pumped hydro comprised 150 GW of storage capacity in 2016, and grid-connected battery storage just 1.7 GW, but the latter grew between 2015 to 2016 by 50% (REN21, 2012). Battery storage has been the main growth feature in energy storage since AR5 (Breyer et al., 2017). This appears to the result of significant cost reductions due to mass production for Electric Vehicles (EVs) (Nykvist and Nilsson, 2015; Dhar et al., 2017). Although costs and technical maturity look increasingly positive, the feasibility of battery storage is challenged by concerns over the availability of resources and the environmental impacts of its production (Peters et al., 2017). Lithium, a common element in the earth’s crust, does not appear to be restricted and large increases in production have happened in recent years with eight new mines in Western Australia where most lithium is produced (GWA, 2016). Emerging battery technologies may provide greater efficiency and recharge rates (Belmonte et al., 2016) but remain significantly more expensive due to speed and scale issues compared to lithium ion batteries (Dhar et al., 2017; IRENA, 2017a).

Research and demonstration of energy storage in the form of thermal and chemical systems continues, but large scale commercial systems are rare (Pardo et al., 2014). Renewably derived synthetic liquid (like methanol and ammonia) and gas (like methane and hydrogen) are increasingly being seen as a feasible storage options for renewable energy (producing fuel for use in industry during times when solar and wind are abundant) (Bruce et al., 2010; Jiang et al., 2010; Ezeji, 2017) but, in the case of carbonaceous storage media, would need a renewable source of carbon to make a positive contribution to GHG reduction (von der Assen et al., 2013; Abanades et al., 2017) (see also Section 4.3.4.5). The use of electric vehicles as a form of storage has been modelled and evaluated as an opportunity, and demonstrations are emerging (Dhar et al., 2017; Green and Newman, 2017a), but challenges to upscaling remain.

4.3.1.5 **Options for Adapting Electrical Systems to 1.5°C**

Climate change has started to disrupt electricity generation and, if climate change adaptation options are not considered, it is predicted that these disruptions will be lengthier and more frequent (Jahandideh-Tehrani et al., 2014; Bartos and Chester, 2015; Kraucunas et al., 2015; van Vliet et al., 2016). Adaptation would both secure vulnerable infrastructure and ensure the necessary generation capacity (Minville et al., 2009; Eisenack and Stecker, 2012; Schaeffer et al., 2012; Cortekar and Groth, 2015; Murrant et al., 2015; Panteli and Mancarella, 2015; Goytia et al., 2016). The literature shows high agreement that climate change impacts need to be planned for in the design of any kind of infrastructure, especially in the energy sector (Nierop, 2014), including interdependencies with other sectors that require electricity to function, including water, data, telecommunications and transport (Fryer, 2017).

Recent research has developed new frameworks and models that aim to assess and identify vulnerabilities in energy infrastructure and create more proactive responses (Francis and Bekera, 2014; Ouyang and Dueñas-Osorio, 2014; Arab et al., 2015; Bekera and Francis, 2015; Knight et al., 2015; Jeong and An, 2016; Panteli et al., 2016; Perrier, 2016; Erker et al., 2017; Fu et al., 2017). Assessments of energy infrastructure adaptation, while limited, emphasise the need for redundancy (Liu et al. 2017). The implementation of controllable and islandable microgrids including the use of residential batteries, and can increase resiliency, especially after extreme weather events (Qazi and Young Jr., 2014; Liu et al., 2017). Hybrid renewables-based power systems with non-hydro capacity, such as with high-penetration wind generation, could provide the required system flexibility (Canales et al., 2015). Overall, there is high agreement that hybrid systems, taking advantage of an array of sources and time of use strategies, can help make electricity generation more
resilient (Parkinson and Djilali, 2015), given that energy security standards are in place (Almeida Prado et al., 2016).

Interactions between water and energy are complex (IEA, 2017g). Water scarcity patterns and electricity disruptions will differ across regions. There is high agreement that mitigation and adaptation options for thermal electricity generation (if that remains fitted with CCS) need to consider increasing water shortages, taking into account other factors such as ambient water resources and demand changes in irrigation water (Hayashi et al., 2018). Increasing the efficiency of power plants can reduce emissions and water needs (Eisenack and Stecker, 2012; van Vliet et al., 2016), but applying CCS would increase water consumption (Koornneef et al 2012). The technological, economic, social and institutional feasibility of efficiency improvements is high, but insufficient to limit temperature rise to 1.5°C (van Vliet et al., 2016).

In addition, a number of options for water cooling management systems have been proposed, such as hydraulic measures (Eisenack and Stecker, 2012) and alternative cooling technologies (Chandel et al., 2011; Eisenack and Stecker, 2012; Bartos and Chester, 2015; Murrant et al., 2015; Bustamante et al., 2016; van Vliet et al., 2016; Huang et al., 2017b). There is high agreement on the technological and economic feasibility of these technologies as their absence can severely impact the functioning of the power plant as well as safety and security standards.

4.3.1.6 Carbon Dioxide Capture and Storage in the Power Sector

The AR5 (IPCC, 2014b) as well as Section 2.4.2 assign significant emission reductions over the course of this century to CO₂ capture and storage (CCS) in the power sector. This section focuses on CCS in the fossil-fuelled power sector; Section 4.3.4 discusses CCS in non-power industry, and Section 4.3.7 bioenergy with CCS (BECCS). Section 2.4.2 puts the cumulative CO₂ stored from fossil-fuelled power at 410 (199–470 interquartile range) GtCO₂ over this century. Such modelling suggests that CCS in the power sector can contribute to cost-effective achievement of emission reduction requirements for limiting warming to 1.5°C. CCS may also offer employment and political advantages for fossil fuel-dependent economies (Kern et al., 2016), but may entail more limited co-benefits than other mitigation options (that, e.g., generate power) and therefore for its business case and economic feasibility relies on climate policy incentives. Since 2017, two CCS projects in the power sector capture 2.4 MtCO₂ annually, while 30 MtCO₂ is captured annually in all CCS projects (Global CCS Institute, 2017).

The technological maturity of CO₂ capture options in the power sectors has improved considerably (Abanades et al., 2015; Bui et al., 2018), but costs have not come down between 2005 and 2015 due to limited learning in commercial settings and increased energy and resources costs (Rubin et al., 2015). Storage capacity estimates vary greatly, but Section 2.4.2 as well as literature (V. Scott et al., 2015) indicate that perhaps 10,000 GtCO₂ could be stored in underground reservoirs. Regional availability of this may not be sufficient, and it requires efforts to have this storage and the corresponding infrastructure available at the necessary rates and times (de Coninck and Benson, 2014). CO₂ retention in the storage reservoir was recently assessed as 98% over 10,000 years for well-managed reservoirs, and 78% for poorly regulated ones Alcade et al 2018. A paper reviewing 42 studies on public perception of CCS (Seigo et al., 2014) found that social acceptance of CCS is predicted by trust, perceived risks and benefits. The technology itself mattered less than the social context of the project. Though insights on communication of CCS projects to the general public and inhabitants of the area around the CO₂ storage sites have been documented over the years, project stakeholders are not consistently implementing these lessons, although some projects have observed good practices (Ashworth et al., 2015).

CCS in the power sector is hardly being realised at scale, mainly because the incremental costs of capture, and the development of transport and storage infrastructures are not sufficiently compensated by market or government incentives (IEA, 2017c). In both full-scale projects in the power sector, part of the capture costs are compensated for by revenues from Enhanced Oil Recovery (EOR) (Global CCS Institute, 2017), demonstrating that EOR helps developing CCS further. EOR is a technique that uses CO₂ to mobilise more oil out of depleting oil fields, leading to additional CO₂ emissions by combusting the additionally recovered
4.3.2 Land and Ecosystem Transitions

This section assesses the feasibility of mitigation and adaptation options related to land use and ecosystems. Land transitions are grouped around agriculture and food, ecosystems and forests, and coastal systems.

4.3.2.1 Agriculture and Food

In a 1.5°C world, local yields are projected to decrease in tropical regions that are major food producing areas of the world (West Africa, South-East Asia, South-Asia, and Central and northern South America) (Schleussner et al., 2016). Some high-latitude regions may benefit from the combined effects of elevated CO₂ and temperature because their average temperatures are below optimal temperature for crops. In both cases there are consequences for food production and quality (Cross-Chapter Box 6 in Chapter 3 on Food Security), conservation agriculture, irrigation, food wastage, bioenergy and the use of novel technologies.

Food production and quality. Increased temperatures, including 1.5°C warming, would affect the production of cereals such as wheat and rice, impacting food security (Schleussner et al., 2016). There is medium agreement that elevated CO₂ concentrations can change food composition, with implications for nutritional security (Taub et al., 2008; Högy et al., 2009; DaMatta et al., 2010; Loladze, 2014; De Souza et al., 2015), with the effects being different depending on the region (Medek et al., 2017).

Meta-analyses of the effects of drought, elevated CO₂ and temperature conclude that at 2°C local warming and above, aggregate production of wheat, maize, and rice are expected to decrease in both temperate and tropical areas (Challinor et al., 2014). These production losses could be lowered if adaptation measures are taken (Challinor et al., 2014), such as developing varieties better adapted to changing climate conditions.

Adaptation options can help ensure access to sufficient, quality food. These include conservation agriculture, improved livestock management, increasing irrigation efficiency, agroforestry and management of food loss and waste. Complementary adaptation and mitigation options, for example, the use of climate services (Section 4.3.5), bioenergy (Section 4.3.1) and biotechnology (Section 4.4.4) can also serve to reduce emissions intensity and the carbon footprint of food production.

Conservation Agriculture (CA). Soil management that reduces the disruption of soil structure and biotic processes by minimising tillage. A recent meta-analysis showed that no-till practices work well in water-limited agroecosystems when implemented jointly with residue retention and crop rotation but may by themselves decrease yields in other situations (Pittelkow et al., 2014). Additional climate adaptations include adjusting planting times and crop varietal selection and improving irrigation efficiency. Adaptations such as these may increase wheat and maize yields by 7–12% under climate change (Challinor et al., 2014). CA can also help build adaptive capacity (medium evidence, medium agreement) (H. Smith et al., 2017; Pradhan et al., 2018) and have mitigation co-benefits through improved fertiliser use or efficient use of machinery and fossil fuels (Harvey et al., 2014; Cui et al., 2018; Pradhan et al., 2018). CA practices can also raise soil carbon and therefore remove CO₂ from the atmosphere (Poeplau and Don 2015; Vicente-Vicente et al. 2016; Aguilera et al. 2013). However, CA adoption can be constrained by inadequate institutional arrangements and funding mechanisms (Harvey et al., 2014; Baudron et al., 2015; Li et al., 2016; Dougill et al., 2017; Smith et al., 2017b).

Sustainable intensification of agriculture consists of agricultural systems with increased production per unit area but with management of the range of potentially adverse impacts on the environment (Pretty and Bharucha, 2014). Sustainable intensification can increase the efficiency of inputs and enhance health and food security (Ramankutty et al., 2018).

Livestock management. Livestock are responsible for more GHG emissions than all other food sources.
Emissions are caused by feed production, enteric fermentation, animal waste, land-use change and livestock transport and processing. Some estimates indicate that livestock supply chains could account for 7.1 GtCO₂, equivalent to 14.5% of global anthropogenic greenhouse gas emissions (Gerber et al., 2013). Cattle (beef, milk) are responsible for about two-thirds of that total, largely due to methane emissions resulting from rumen fermentation (Gerber et al., 2013; Opio et al., 2013).

Despite ongoing gains in livestock productivity and volumes, the increase of animal products in global diets is restricting overall agricultural efficiency gains because of inefficiencies in the conversion of agricultural primary production (e.g., crops) in the feed-animal products pathway (Alexander et al., 2017), offsetting the benefits of improvements in livestock production systems (Clark and Tilman, 2017).

There is increasing agreement that overall emissions from food systems could be reduced by targeting the demand for meat and other livestock products, particularly where consumption is higher than suggested by human health guidelines. Adjusting diets to meet nutritional targets could bring large co-benefits, through GHG mitigation and improvements in the overall efficiency of food systems (Erb et al., 2009; Tukker et al., 2011; Tilman and Clark, 2014; van Dooren et al., 2014; Ranganathan et al., 2016). Dietary shifts could contribute one-fifth of the mitigation needed to hold warming below 2°C, with one-quarter of low-cost options (Griscom et al., 2017). There, however, remains limited evidence of effective policy interventions to achieve such large-scale shifts in dietary choices, and prevailing trends are for increasing rather than decreasing demand for livestock products at the global scale (Alexandratos and Bruinsma, 2012; OECD/FAO, 2017). How the role of dietary shift could change in 1.5°C-consistent pathways is also not clear (see Chapter 2).

Adaptation of livestock systems can include a suite of strategies such as using different breeds and their wild relatives to develop a genetic pool resilient to climatic shocks and longer-term temperature shifts (Thornton and Herrero, 2014), improving fodder and feed management (Bell et al., 2014; Havet et al., 2014) and disease prevention and control (Skuce et al., 2013; Nguyen et al., 2016). Most interventions that improve the productivity of livestock systems and enhance adaptation to climate changes would also reduce the emissions intensity of food production, with significant co-benefits for rural livelihoods and security of food supply (Gerber et al., 2013; FAO & NZAGRC, 2017a, 2017b, 2017c). Whether such reductions in emission intensity result in lower or higher absolute GHG emissions depends on overall demand for livestock products, indicating the relevance of integrating supply-side with demand-side measures within food security objectives (Gerber et al., 2013; Bajželj et al., 2014). Transitions in livestock production systems (e.g., from extensive to intensive) can also result in significant emission reductions as part of broader land-based mitigation strategies (Havlík et al., 2014).

Overall, there is high agreement that farm strategies that integrate mixed crop-livestock systems can improve farm productivity and have positive sustainability outcomes (Havet et al., 2014; Thornton and Herrero, 2014; Herrero et al., 2015; Weindl et al., 2015). Shifting towards mixed crop-livestock systems is estimated to reduce agricultural adaptation costs to 0.3% of total production costs while abating deforestation by 76 million ha globally, making it a highly cost-effective adaptation option with mitigation co-benefits (Weindl et al., 2015). Evidence from various regions supports this (Thornton and Herrero, 2015), although the feasible scale varies between regions and systems, as well as being moderated by overall demand in specific food products. In Australia, some farmers have successfully shifted to crop-livestock systems where, each year, they allocate land and forage resources in response to climate and price trends (Bell et al., 2014). However, there can be some unintended negative impacts of such integration, including an increased burdens on women, higher requirements of capital, competing uses of crop residues (e.g., feed vs. mulching vs. carbon sequestration) and higher requirements of management skills, which can be a challenge across several low income countries (Thornton and Herrero, 2015; Thornton et al., 2018). Finally, the feasibility of improving livestock efficiency is dependent on socio-cultural context and acceptability: there remain significant issues around widespread adoption of crossbred animals, especially by smallholders (Thornton et al., 2018).

**Irrigation efficiency.** Irrigation efficiency is especially critical since water endowments are expected to change, with 20–60 Mha of global cropland being projected to revert from irrigated to rain fed land, while
other areas will receive higher precipitation in shorter time spans thus affecting irrigation demand (Elliott et al., 2014). While increasing irrigation system efficiency is necessary, there is mixed evidence on how to enact efficiency improvements (Fader et al., 2016; Herwehe and Scott, 2017). Physical and technical strategies include building large-scale reservoirs or dams, renovating or deepening irrigation channels, building on-farm rainwater harvesting structures, lining ponds, channels and tanks to reduce losses through percolation and evaporation, and investing in small infrastructure such as sprinkler or drip irrigation sets (Varela-Ortega et al., 2016; Sikka et al., 2018). Each strategy has differing costs and benefits relating to unique biophysical, social, and economic contexts. Other concerns relating to the increase of irrigation efficiency discuss fostering irrigation dependency, hence increasing climate sensitivity, which may be maladaptive in the long-term (Lindoso et al., 2014).

Improvements in irrigation efficiency would need to be supplemented with ancillary activities, such as shifting to crops that require less water, and improving soil and moisture conservation (Fader et al., 2016; Hong and Yabe, 2017; Sikka et al., 2018). Currently, the feasibility of improving irrigation efficiency is constrained by issues of replicability across scale and sustainability over time (Burney and Naylor, 2012), institutional barriers and inadequate market linkages (Pittock et al., 2017).

Growing evidence suggests that investing in behavioural shifts towards using irrigation technology such as micro-sprinklers or drip irrigation, is an effective and quick adaptation strategy (Varela-Ortega et al., 2016; Herwehe and Scott, 2017; Sikka et al., 2018) as opposed to large dams which have high financial, ecological and social costs (Varela-Ortega et al., 2016). While improving irrigation efficiency is technically feasible (R. Fishman et al., 2015) and has clear benefits for environmental values (Pfeiffer and Lin, 2014; R. Fishman et al., 2015), feasibility is regionally differentiated as shown by examples as diverse as Kansas (Jägermeyr et al., 2015), India (R. Fishman et al., 2015) and Africa (Pittock et al., 2017).

Agroforestry. The integration of trees and shrubs into crop and livestock systems, when properly managed, can potentially restrict soil erosion, facilitate water infiltration, improve soil physical properties and buffer against extreme events (Lasco et al., 2014; Mbow et al., 2014; Quandt et al., 2017; Sida et al., 2018). There is medium evidence and high agreement on the feasibility of agroforestry practices that enhance productivity, livelihoods and carbon storage (Lusiana et al., 2012; K Murthy, 2013; Coulibaly et al., 2017; Sida et al., 2018), including from indigenous production systems (Coq-Huelva et al., 2017), with variation by region, agroforestry type, and climatic conditions (Place et al., 2012; Coe et al., 2014; Mbow et al., 2014; Iiyama et al., 2017; Abdulai et al., 2018). Long-term studies examining the success of agroforestry, however, are rare (Coe et al., 2014; Meijer et al., 2015; Brockington et al., 2016; Zomer et al., 2016).

The extent to which agroforestry practices at farm-level could be scaled up globally while satisfying growing food demand is relatively unknown. Agroforestry adoption has been relatively low and uneven (Jacobi et al., 2017; Hernández-Morcillo et al., 2018), with constraints including the expense of establishment and lack of reliable financial support, insecure land tenure, landowner’s lack of experience with trees, complexity of management practices, fluctuating market demand and prices for different food and fibre products, the time and knowledge required for management, low intermediate benefits to offset revenue lags, and inadequate market access (Pattanayak et al., 2003; Mercer, 2004; Sendzimir et al., 2011; Valdivia et al., 2012; Coe et al., 2014; Meijer et al., 2015; Coulibaly et al., 2017; Jacobi et al., 2017).

Managing food loss and waste. The way food is produced, processed and transported strongly influences GHG emissions. Around one-third of the food produced on the planet is not consumed (FAO, 2013) affecting food security and livelihoods (See Cross-Chapter Box 6 on Food Security in Chapter 3). Food wastage is a combination of food loss—decrease in mass and nutritional value of food due to poor infrastructure, logistics, and lack of storage technologies and management – and food waste that derives from inappropriate human consumption that leads to food spoilage associated with inferior quality or overproduction. Food wastage could lead to an increase in emissions estimated to 1.9–2.5 GtCO₂-eq yr⁻¹ (Hiç et al., 2016).

Decreasing food wastage has high mitigation and adaptation potential and could play an important role in land transitions towards 1.5°C, provided that reduced food waste results in lower production-side emissions
rather than increased consumption (Foley et al., 2011). There is medium agreement that a combination of individual-institutional behaviour (Refsgaard and Magnussen, 2009; Thornton and Herrero, 2014), and improved technologies and management (Lin et al., 2013; Papargyropoulou et al., 2014) can transform food waste into products with marketable value. Institutional behaviour depends on investment and policies, which if adequately addressed could enable mitigation and adaptation co-benefits, in a relatively short time.

**Novel technologies.** New molecular biology tools have been developed that can lead to fast and precise genome modification (De Souza et al., 2016; Scheben et al., 2016) (e.g., CRISPR Cas 9 (Ran et al., 2013; Schaeffer and Nakata, 2015). Such genome editing tools may moderately assist in mitigation and adaptation of agriculture in relation to climate changes, CO₂ elevation, drought and flooding (DaMatta et al., 2010; De Souza et al., 2015, 2016). These tools could contribute to developing new plant varieties that can adapt to warming of 1.5°C and overshoot, potentially avoiding some of the costs of crop shifting (Schlenker and Roberts, 2009; De Souza et al., 2016). However, biosafety concerns and government regulatory systems can be a major barrier to the use of these tools as this increases the time and cost of turning scientific discoveries into ready applicable technologies (Andow and Zwahlen, 2006; Maghari and Ardekani, 2011).

The strategy of reducing enteric methane emissions by ruminants through the development of inhibitors or vaccines has already been attempted with some successes, although the potential for application at scale and in different situations remains uncertain. A methane inhibitor has been demonstrated to reduce methane from feedlot systems by 30% over a 12-week period (Hristov et al., 2015) with some productivity benefits but the ability to apply it in grazing systems will depend on further technological developments as well as costs and incentives. A vaccine could potentially modify the microbiota of the rumen and be applicable even in extensive grazing systems by reducing the presence of methanogenic micro-organisms (Wedlock et al., 2013) but has not yet been successfully demonstrated to reduce emissions in live animals. Selective breeding for lower-emitting ruminants is becoming rapidly feasible, offering small but cumulative emissions reductions without requiring substantial changes in farm systems (Pickering et al., 2015).

Technological innovation in culturing marine and freshwater micro and macro flora has significant potential to expand food, fuel and fibre resources, and could reduce impacts on land and conventional agriculture (Greene et al., 2017).

Technological innovation could assist in increased agricultural efficiency (e.g., via precision agriculture), decrease food wastage and genetics that enhance plant adaptation traits (Section 4.4.4). Technological and associated management improvements may be ways to increase the efficiency of contemporary agriculture to help produce enough food to cope with population increases in a 1.5°C warmer world, and help reduce the pressure on natural ecosystems and biodiversity.

**4.3.2.2 Forests and Other Ecosystems**

**Ecosystem restoration.** Biomass stocks in tropical, subtropical, temperate and boreal biomes currently hold 1085, 194, 176, 190 Gt CO₂, respectively. Conservation and restoration can enhance these natural carbon sinks (Erb et al., 2017).

Recent studies explore options for conservation, restoration and improved land management estimating up to 23 GtCO₂ (Griscom et al., 2017). Mitigation potentials are dominated by reduced rates of deforestation, reforestation and forest management, and concentrated in tropical regions (Houghton, 2013; Canadell and Schulze, 2014; Grace et al., 2014; Houghton et al., 2015; Griscom et al., 2017). Much of the literature focuses on REDD+ (Reducing Emissions from Deforestation and Degradation) as an institutional mechanism. However, restoration and management activities need not be limited to REDD+ and locally adapted implementation may keep costs low, capitalise on co-benefits and ensure consideration of competing for socio-economic goals (Jantke et al., 2016; Ellison et al., 2017; Perugini et al., 2017; Spencer et al., 2017).

Half of the estimated potential can be achieved at <100 USD/tCO₂; a third of the cost-effective potential <10 USD/tCO₂ (Griscom et al., 2017). Variation of costs in projects aiming to reduce emissions from
deforestation is high when considering opportunity and transaction costs (Dang Phan et al., 2014; Overmars et al., 2014; Ickowitz et al., 2017; Rakatama et al., 2017).

However, the focus on forests raises concerns of cross-biome leakage (medium evidence, low agreement) (Popp et al., 2014a; Strassburg et al., 2014; Jayachandran et al., 2017) and encroachment on other ecosystems (Veldman et al., 2015). Reducing rates of deforestation limits the land available for agriculture and grazing with trade-offs between diets, higher yields and food prices (Erb et al., 2016a; Kreidenweis et al., 2016). Restoration and conservation are compatible with biodiversity (Rey Benayas et al., 2009; Jantke et al., 2016) and water resources; in the tropics, reducing rates of deforestation maintains cooler surface temperatures (Perugini et al., 2017) and rainfall (Ellison et al., 2017).

Its multiple potential co-benefits have made REDD+ important for local communities, biodiversity and sustainable landscapes (Ngendakumana et al., 2017; Turnhout et al., 2017). There is low agreement on whether climate impacts will reverse mitigation benefits of restoration (Le Page et al., 2013) by increasing the likelihood of disturbance (Anderegg 2015), or reinforce them through carbon fertilisation (P. Smith et al., 2014).

Emerging regional assessments offer new perspectives for upscaling. Strengthening coordination, additional funding sources, and access and disbursement points increase the potential of REDD+ in working towards 2°C and 1.5°C targets (Well and Carrapatoso, 2017). While there are indications that land tenure (Sunderlin et al., 2014) has a positive impact, a meta-analysis by (Wehkamp et al., 2018a) shows that there is medium evidence and low agreement on which aspects of governance improvements are supportive of conservation. Local benefits, especially for indigenous communities, will only be accrued if land tenure is respected and legally protected, which is not often the case (Sunderlin et al., 2014; Brugnach et al., 2017). Although payments for reduced rates of deforestation may benefit the poor, the most vulnerable populations could have limited, uneven access (Atela et al., 2014) and face lower opportunity costs from deforestation (Ickowitz et al., 2017).

Community-based Adaptation (CbA). There is medium evidence and high agreement for the use of CbA. The specific actions to take will depend upon the location, context, and vulnerability of the specific community. CbA is defined as ‘a community-led process, based on communities’ priorities, needs, knowledge, and capacities, which aim to empower people to plan for and cope with the impacts of climate change’ (Reid et al., 2009). The integration of CbA with Ecosystems-based Adaptation (EbA) has been increasingly promoted, especially in efforts to alleviate poverty (Mannke, 2011; Reid, 2016).

Despite the potential and advantages of both CbA and EbA, including knowledge exchange, information access and increased social capital and equity; institutional and governance barriers still constitute a challenge for local adaptation efforts (Wright et al., 2014; Fernández-Giménez et al., 2015).

Wetland management. In wetland ecosystems, temperature rise has direct and irreversible impacts on species functioning and distribution, ecosystem equilibrium and services, and second order impacts on local livelihoods (see Section 3.4.3). The structure and function of wetland systems are changing due to climate change. Wetland management strategies, including adjustments in infrastructural, behavioural, and institutional practices have clear implications for adaptation (Colloff et al., 2016b; Finlayson et al., 2017; Wigand et al., 2017)

Despite international initiatives on wetland restoration and management through the Ramsar Convention on Wetlands, policies have not been effective (Finlayson, 2012; Finlayson et al., 2017). Institutional reform such as flexible, locally relevant governance, drawing on principles of adaptive co-management, and multi-stakeholder participation becomes increasingly necessary for effective wetland management (Capon et al., 2013; Finlayson et al., 2017).
4.3.2.3 Coastal Systems

Managing coastal stress. Particularly to allow for the landward relocation of coastal ecosystems under a transition to 1.5°C, planning for climate change would need to be integrated with the use of coastlines by humans (Saunders et al., 2014; Kelleway et al., 2017). Adaptation options for managing coastal stress include coastal hardening through the building of seawalls and the re-establishment of coastal ecosystems such as mangroves (André et al., 2016; Cooper et al., 2016). While the feasibility of the solutions is high, they are expensive to scale (robust evidence, medium agreement).

There is low evidence and high agreement that reducing the impact of local stresses (Halpern et al., 2015) will improve the resilience of marine ecosystems as they transition to a 1.5°C world (O’Leary et al., 2017). Approaches to reducing local stresses are considered feasible, cost-effective and highly scalable. Ecosystem resilience may be increased through alternative livelihoods (e.g., sustainable aquaculture), which are among a suite of options for building resilience in coastal ecosystems. These options enjoy high levels of feasibility yet are expensive, which stands in the way of scalability (robust evidence, medium agreement) (Hiwasaki et al., 2015; Brugnach et al., 2017).

Working with coastal communities has the potential for improving the resilience of coastal ecosystems. Combined with the advantages of using Indigenous knowledge to guide transitions, solutions can be more effective when undertaken in partnership local communities, cultures, and knowledge (See Box 4.3).

Restoration of coastal ecosystems and fisheries. Marine restoration is expensive compared to terrestrial restoration, and the survival of projects is currently low, with success depending on the ecosystem and site, rather than the size of the financial investment (Bayraktarov et al., 2016). Mangrove replanting shows evidence of success globally, with numerous examples of projects that have established forests (Kimball et al., 2015; Bayraktarov et al., 2016).

Efforts with reef-building corals have been attempted with a low level of success (Bayraktarov et al., 2016). Technologies to help re-establish coral communities are limited (Rinkevich, 2014), as are largely untested disruptive technologies (e.g., genetic manipulation, assisted evolution) (van Oppen et al., 2015). Current technologies also have trouble scaling given the substantial costs and investment required (Bayraktarov et al., 2016).

(Johannessen and Macdonald, 2016) report the ‘blue carbon’ sink to be 0.4–0.8% of global anthropogenic emissions. However, this does not adequately account for post-depositional processes and could overestimate removal potentials, subject to a risk of reversal. Seagrass beds will thus not contribute significantly to enabling 1.5°C-consistent pathways.

4.3.3 Urban and Infrastructure System Transitions

There will be approximately 70 million additional urban residents every year through to the mid part of this century (UN, 2014). The majority of these new urban citizens will reside in small and medium sized cities in low- and middle-income countries (Cross-Chapter Box 13 in Chapter 5). The combination of urbanisation and economic and infrastructure development could account for an additional 226 GtCO by 2050 (Bai et al., 2018). However, urban systems can harness the mega-trends of urbanisation, digitalisation, financialisation and growing sub-national commitment to smart cities, green cities, resilient cities, sustainable cities and adaptive cities, for the type of transformative change required by 1.5°C-consistent pathways (Revi and Rosenzweig, 2013; Parag and Sovacool, 2016; Roberts, 2016; Wachsmuth et al., 2016; Revi, 2017; Solecki et al., 2018). There is a growing number of urban climate responses driven by cost-effectiveness, development, work creation and inclusivity considerations (Floater et al., 2014; Revi et al., 2014a; Villarroel Walker et al., 2014; Kennedy et al., 2015; Rodríguez, 2015; Newman et al., 2017; UN-Habitat, 2017; Westphal et al., 2017) (Solecki et al. 2013; Ahern et al. 2014; McGranahan et al. 2016; Dodman et al. 2017a).
In addition, low-carbon cities could reduce the need to deploy Carbon Dioxide Removal (CDR) and Solar Radiation Modification (SRM) (Fink, 2013; Thomson and Newman, 2016).

Cities are also places in which the risks associated with warming of 1.5°C, such as heat stress, terrestrial and coastal flooding, new disease vectors, air pollution and water scarcity, will coalesce (see Section 3.3) (Dodman et al., 2017a; Satterthwaite and Bartlett, 2017). Unless adaptation and mitigation efforts are designed around the need to decarbonise urban societies in the developed world and provide low-carbon solutions to the needs of growing urban populations in developing countries, they will struggle to deliver the pace or scale of change required by 1.5°C-consistent pathways (Hallegatte et al., 2013; Villarroel Walker et al., 2014; Roberts, 2016; Solecki et al., 2018). The pace and scale of urban climate responses can be enhanced by attention to social equity (including gender equity), urban ecology (Brown and McGranahan, 2016; Wachsmuth et al., 2016; Ziervogel et al., 2016a) and participation in sub-national networks for climate action (Cole, 2015; Jordan et al., 2015).

The long-lived urban transport, water and energy systems that will be constructed in the next three decades to support urban populations in developing countries and to retrofit cities in developed countries will have to be different to that built in Europe and North America in the 20th century, if they are to support the required transitions (Freire et al., 2014; Cartwright, 2015; McPhearson et al., 2016; Roberts, 2016; Lwasa, 2017). Recent literature identifies energy, infrastructure, appliances, urban planning, transport and adaptation options as capable of facilitating systemic change. It is these aspects of the urban system that are discussed below and from which options in Section 4.5 are selected.

4.3.3.1 Urban Energy Systems

Urban economies tend to be more energy intensive than national economies due to higher levels of per capita income, mobility and consumption (Kennedy et al., 2015; Broto, 2017; Gota et al., 2018). However, some urban systems have begun decoupling development from the consumption of fossil fuel powered energy through energy efficiency, renewable energy and locally managed smart-grids (Dodman, 2009; Freire et al., 2014; Eyre et al., 2018; Glazebrook and Newman, 2018a).

The rapidly expanding cities of Africa and Asia, where energy poverty currently undermines adaptive capacity (Westphal et al., 2017; Satterthwaite et al., 2018), have the opportunity to benefit from recent price changes in renewable energy technologies to enable clean energy access to citizens (SDG 7) (Cartwright, 2015; Watkins, 2015; Lwasa, 2017; Kennedy et al., 2018; Teferi and Newman, 2018). This will require strengthened energy governance in these countries (Eberhard et al., 2017). Where renewable energy displaces paraffin, wood fuel or charcoal feedstocks in informal urban settlements, it provides the co-benefits of improved indoor air quality, reduced fire-risk and reduced deforestation, all of which can enhance adaptive capacity and strengthen demand for this energy (Newham and Conradie, 2013; Winkler, 2017; Kennedy et al., 2018; Teferi and Newman, 2018).

4.3.3.2 Urban Infrastructure, Buildings and Appliances

Buildings are responsible for 32% of global energy consumption (IEA, 2016c) and have a large energy saving potential with available and demonstrated technologies such as energy efficiency improvements in technical installations and in thermal insulation (Toleikyte et al., 2018) and energy sufficiency (Thomas et al., 2017). (Kuramochi et al., 2017) show that 1.5°C-consistent pathways require building emissions to be reduced by 80–90% by 2050, new construction to be fossil-free and near-zero energy by 2020, and an increased rate of energy refurbishment of existing buildings to 5% per annum in OECD (Organisation for Economic Co-operation and Development) countries (see also Section 4.2.1). Chapter 2 based on the IEA-ETP (IEA, 2017g) identifies large saving potential in heating and cooling through improved building design, efficient equipment, lighting and appliances. Several examples of net zero energy in buildings are now available (Wells et al., 2018). In existing buildings, refurbishment enables
energy saving (Semprini et al., 2017; Brambilla et al., 2018; D’Agostino and Parker, 2018; Sun et al., 2018) and cost savings (Toleikyte et al., 2018; Zangheri et al., 2018).

Reducing the embodied energy in buildings material provides further energy and GHG savings (Cabeza et al., 2013; Oliver and Morecroft, 2014; Kozejakov et al., 2018), in particular through bio-based materials (Lupišek et al., 2015) and wood construction (Ramage et al., 2017). The United Nations Environment Programme (UNEP) estimates that improving embodied energy, thermal performance, and direct energy use of buildings can reduce emissions by 1.9 GtCO₂e yr⁻¹ (UNEP, 2017b), with an additional reduction of 3 GtCO₂e yr⁻¹ through energy efficient appliances and lighting (UNEP, 2017b). Further increasing the energy efficiency of appliances and lighting, heating and cooling offers the potential for further savings (Parikh and Parikh, 2016; Garg et al., 2017).

Smart technology, drawing on the Internet of Things (IoT) and building information modelling, offer opportunities to accelerate energy efficiency in buildings and cities (Moreno-Cruz and Keith, 2013; Hoy, 2016) (see also Section 4.4.4). Some developing country cities are drawing on these technologies to adopt ‘leapfrog’ infrastructure, buildings and appliances to pursue low-carbon development (Newman et al., 2017; Teferi and Newman, 2017) (Cross-Chapter Box 13 in Chapter 5).

4.3.3.3 Urban Transport and Urban Planning

Urban form impacts demand for energy (Sims et al., 2014) and other welfare related factors: a meta-analysis of 300 papers reported energy savings of 26 USD per person per year attributable to a 10% increase in urban population density (Ahlfeldt and Pietro Stefani, 2017). Significant reductions in car use are associated with dense, pedestrianised cities and towns and medium-density transit corridors (Newman and Kenworthy, 2015; Newman et al., 2017) relative to low-density cities in which car dependency is high (Kenworthy and Schiller, 2018). Combined dense urban forms and new mass transit systems in Shanghai and Beijing have yielded less car use (Gao and Newman, 2018) (see Box 4.9). Compact cities also create the passenger density required to make public transport more financially viable (Ahlfeldt and Pietro Stefani, 2017; Rode et al., 2017) and enable combinations of cleaner fuel feed stocks and urban smart-grids, in which vehicles form part of the storage capacity (Oldenbroek et al., 2017). Similarly, the spatial organisation of urban energy influenced the trajectories of urban development in cities as diverse as Hong Kong, Bengaluru and Maputo (Broto, 2017).

The informal settlements of middle- and low-income cities where urban density is more typically associated with a range of water- and vector-borne health risks, may provide a notable exception to the adaptive advantages of urban density (Mitlin and Satterthwaite, 2013; Lilford et al., 2017) unless new approaches and technologies are harnessed to accelerate slum upgrading (Teferi and Newman, 2017)

Scenarios consistent with 1.5°C pathways, depend on an almost 40% reduction in final energy use by the transport sector by 2050 (Chapter 2, Figure 2.12). In one analysis the phasing out of fossil fuel passenger vehicle sales by 2035-2050 was identified as a benchmark for aligning with 1.5°C-consistent pathways (Kuramochi et al., 2017). Reducing emissions from transport has lagged the power sector (Sims et al., 2014; Creutzig et al., 2015a) but evidence since AR5 suggests that cities are urbanising and re-urbanising in ways that co-ordinate transport sector adaptation and mitigation (Colenbrander et al., 2017; Newman et al., 2017; Salvo et al., 2017; Gota et al., 2018). The global transport sector could reduce 4.7GtCO₂e yr⁻¹ (4.1–5.3) by 2030. This is significantly more than is predicted by Integrated Assessment Models (IAMs; UNEP, 2017b). Such a transition depends on cities that enable modal shifts, avoided journeys, provide incentives for uptake of improved fuel efficiency and changes in urban design that encourage walkable cities, non-motorised transport and shorter commuter distances (IEA, 2016a; Mittal et al., 2016; Zhang et al., 2016; Li and Loo, 2017). In at least four African cities, 43 Asian cities and 54 Latin American cities, Transit Oriented Development (TOD), has emerged as an organising principle for urban growth and spatial planning (Colenbrander et al., 2017; Lwasa, 2017; BRT Data, 2018). This trend is important to counter the rising
demand for private cars in developing country cities (OECD, 2016b). In India TOD has been combined with localized solar PV installations and new ways of financing rail expansion (Sharma, 2018).

Cities pursuing sustainable transport benefit from reduced air pollution, congestion and road fatalities and are able to harness the relationship between transport systems, urban form, urban energy intensity and social cohesion (Goodwin and Van Dender, 2013; Newman and Kenworthy, 2015; Wee, 2015)

Technology and electrification trends since AR5 make carbon efficient urban transport easier (Newman et al., 2016), but realising urban transport’s contribution to a 1.5°C-consistent pathways will require the type of governance that can overcome the financial, institutional, behavioural and legal barriers to change (Geels, 2014; Bakker et al., 2017).

Adaptation to a 1.5°C world is enabled by urban design and spatial planning policies that consider extreme weather conditions and reduce displacement by climate related disasters (UNISDR, 2009; UN-Habitat, 2011; Mitlin and Satterthwaite, 2013).

Building codes and technology standards for public lighting, including traffic lights (Beccali et al., 2015), play a critical role in reducing carbon emissions, enhancing urban climate resilience and managing climate risk (Steenhof and Sparling, 2011; Parnell, 2015; Shapiro, 2016; Evans et al., 2017). Building codes can support the convergence to zero emissions from buildings (Wells et al., 2018), and can be used retrofit the existing building stock for energy efficiency (Ruparathna et al., 2016).

The application of building codes and standards for 1.5°C-consistent pathways will require improved enforcement, which can be a challenge in developing countries where inspection resources are often limited and codes are poorly tailored to local conditions (Ford et al., 2015c; Chandel et al., 2016; Eisenberg, 2016; Shapiro, 2016; Hess and Kelman, 2017; Mavhura et al., 2017). In all countries, building codes can be undermined by industry interests, and can be maladaptive if they prevent buildings or land use from evolving to reduce climate impacts (Eisenberg, 2016; Shapiro, 2016).

The deficit in building codes and standards in middle-income and developing country cities need not be a constraint to more energy-efficient and resilient buildings (Tait and Euston-Brown, 2017). For example, the relatively high price that poor households pay for unreliable and at times dangerous household energy in African cities has driven the uptake of renewable energy and energy efficiency technologies in the absence of regulations or fiscal incentives (Eberhard et al., 2011, 2016; Cartwright, 2015; Watkins, 2015). The Kuyasa Housing Project in Khayelitsha, one of Cape Town’s poorest suburbs, created significant mitigation and adaptation benefits by installing ceilings, solar water heaters and energy efficient lightbulbs in houses independent of the formal housing or electrification programme (Winkler, 2017).

4.3.3.4 Electrification of Cities and Transport

The electrification of urban systems, including transport, has shown global progress since AR5 (IEA, 2016a; Kennedy et al., 2018; Kenworthy and Schiller, 2018). High growth rates are now appearing in electric vehicles (Figure 4.1), electric bikes and electric transit (IEA, 2018), which would need to displace fossil-fuel powered passenger vehicles by 2035–2050 to remain in line with 1.5°C-consistent pathways. China’s 2017 Road Map calls for 20% of new vehicle sales to be electric. India is aiming for exclusively electric vehicles (EVs) by 2032 (NITI Aayog and RMI, 2017). Globally, EV sales were up 42% in 2016 relative to 2015, and in the United States EV sales were up 36% over the same period (Johnson and Walker, 2016).
The extent of electric railways in and between cities has expanded since AR5 (IEA, 2016a; Mittal et al., 2016; Zhang et al., 2016; Li and Loo, 2017). In high income cities there is medium evidence for the decoupling of car use and wealth since AR5 (Newman, 2017). In cities where private vehicle ownership is expected to increase, less carbon-intensive fuel sources and reduced car journeys will be necessary as well as electrification of all modes of transport (Mittal et al., 2016; van Vuuren et al., 2017). Some recent urban data show a decoupling of urban growth and GHG emissions (Newman and Kenworthy, 2015) and that ‘peak car’ has been reached in Shanghai and Beijing (Gao and Kenworthy, 2017) and beyond (Manville et al., 2017) (also see Box 4.9).

An estimated 800 cities globally have operational bike-share schemes (E. Fishman et al., 2015) and China had 250 million e-bikes in 2017 (Newman et al., 2017). Advances in Information and Communication Technologies (ICT) offer cities the chance to reduce urban transport congestion and fuel consumption by making better use of the urban vehicle fleet through car sharing, driverless cars and coordinated public transport, especially when electrified (Wee, 2015; Glazebrook and Newman, 2018b). Advances in ‘big-data’ can assist in creating a better understanding of the connections between cities, green infrastructure, environmental services and health (Jennings et al., 2016) and improve decision-making in urban development (Lin et al., 2017).

4.3.3.5 Shipping, Freight and Aviation

International transport hubs, including airports and ports and the associated mobility of people, are major economic contributors to most large cities even while under the governance of national authorities and international legislation. Shipping, freight and aviation systems have grown rapidly and little progress has been made since AR5 on replacing fossil fuels, though some trials are continuing (Zhang, 2016; Bouman et al., 2017; EEA, 2017). Aviation emissions do not yet feature in IAMs (Bows-Larkin, 2015), but could be reduced by between a third and two-thirds through energy efficiency measures and operational changes (Dahlmann et al., 2016). On shorter inter-city trips, aviation could be replaced by high-speed electric trains drawing on renewable energy (Åkerman, 2011). Some progress has been made on the use of electricity in planes and shipping (Grewe et al., 2017) though no commercial applications have arisen. Studies indicate that biofuels are the most viable means of decarbonising intercontinental travel, given their technical characteristics, energy content and affordability (Wise et al., 2017). The lifecycle emissions of bio-based jet fuels and marine fuels can be considerable (Cox et al., 2014; IEA, 2017g) depending on their location (Elshout et al., 2014), but can be reduced by feedstock and conversion technology choices (de Jong et al., 2017).

In recent years the potential for transport to use synfuels, such as ethanol, methanol, methane, ammonia and hydrogen, created from renewable electricity and CO₂ has gained momentum but has not yet demonstrated benefits on a scale consistent with 1.5°C pathways (Ezeji, 2017; Fasihi et al., 2017). Decarbonising the fuel
used by the world’s 60,000 large vessels faces governance barriers and the need for a global policy (Bows and Smith, 2012; IRENA, 2015; Rehmatulla and Smith, 2015). Low-emission marine fuels could simultaneously address sulphur and black carbon issues in ports and around waterways and accelerate the electrification of all large ports (Bouman et al., 2017; IEA, 2017g).

4.3.3.6 Climate-Resilient Land Use

Urban land use influences energy intensity, risk exposure and adaptive capacity (Carter et al., 2015; Araos et al., 2016a; Ewing et al., 2016; Newman et al., 2016; Broto, 2017). Accordingly, urban land-use planning can contribute to climate mitigation and adaptation (Parnell, 2015; Francesch-Huidobro et al., 2017) and the growing number of urban climate adaptation plans provide instruments for planning (Carter et al., 2015; Dhar and Khirfan, 2017; Siders, 2017; Stults and Woodruff, 2017). Adaptation plans can reduce exposure to urban flood risk that, in a 1.5°C world, could double relative to 1976–2005 (Alfieri et al., 2017), reduce heat stress (Section 3.5.5.8), fire risk (Section 3.4.3.4) and sea-level rise (Section 3.4.5.1) (Schleussner et al., 2016).

Cities can reduce their risk exposure by considering investment in infrastructure and buildings that are more resilient to warming of 1.5°C or beyond. Where adaptation planning and urban planning generate the type of local participation that enhances capacity to cope with risks, they can be mutually supportive processes (Archer et al., 2014; Kettle et al., 2014; Campos et al., 2016; Chu et al., 2017; Siders, 2017; Underwood et al., 2017). Not all adaptation plans are reported as effective (Measham et al., 2011; Hetz, 2016; Woodruff and Stults, 2016; Mahlkow and Donner, 2017), especially in developing country cities (Kiunsi, 2013). Where adaptation planning further marginalises poor citizens through limited local control over establishing adaptation priorities, or the displacement of impacts onto poorer communities, justice, equity, and broad participation would need to be considered in the dimensions of successful urban risk reduction, and recognition of the political economy of adaptation (Archer, 2016; Shi et al., 2016; Ziervogel et al., 2016a, 2017; Chu et al., 2017).

4.3.3.7 Green Urban Infrastructure and Ecosystem Services

Integrating and promoting green urban infrastructure (including street trees, parks, green roofs and facades, water features) into city planning can be difficult (Leck et al., 2015) and increases urban resilience to impacts of 1.5°C warming (Table 4.2) in ways that can be more cost effective than conventional infrastructure (Culwick and Bobbins (2016) (Cartwright et al., 2013).

Table 4.2: Green urban infrastructure and benefits.

<table>
<thead>
<tr>
<th>Green infrastructure</th>
<th>Adaptation benefits</th>
<th>Mitigation benefits</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban trees planting, urban parks</td>
<td>Reduced heat island effect, psychological benefits</td>
<td>Less cement, reduced air-conditioning</td>
<td>(Demuzere et al., 2014; Mullaney et al., 2015; Soderlund and Newman, 2015; Beaudoin and Gosselin, 2016; Green et al., 2016; Lin et al., 2017)</td>
</tr>
<tr>
<td>Permeable surfaces</td>
<td>Water recharge</td>
<td>Less cement in city, some bio-sequestration, less water pumping</td>
<td>(Liu et al., 2014; Lamond et al., 2015; Skougaard Kaspersen et al., 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; Mguni et al., 2016; Xie et al., 2017)</td>
</tr>
<tr>
<td>Forest retention, and urban agricultural land</td>
<td>Flood mediation, healthy lifestyles</td>
<td>Air pollution reduction</td>
<td>(Nowak et al., 2006; Tallis et al., 2011; Elmqvist et al., 2013; Buckeridge, 2015; Culwick and Bobbins, 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; White et al., 2017)</td>
</tr>
<tr>
<td>Wetland restoration,</td>
<td>Reduced urban flooding, Low</td>
<td>Some bio-sequestration, Less</td>
<td>(Cartwright et al., 2013; Elmqvist et al., 2015; Brown and McGranahan, 2016; Camps-Calvet et al., 2016;</td>
</tr>
</tbody>
</table>
Realising climate benefits from urban green infrastructure sometimes requires a city-region perspective (Wachsmuth et al., 2016). Where the urban impact on ecological systems in and beyond the city is appreciated, the potential for transformative change exists (Soderlund and Newman, 2015; Ziervogel et al., 2016a), and a locally appropriate combination of green space, ecosystem goods and services and the built environment can increase the set of urban adaptation options (Puppim de Oliveira et al., 2013).

Milan, Italy, a city with deliberate urban greening policies, planted 10,000 hectares of new forest and green areas over the last two decades (Sanesi et al., 2017). The accelerated growth of urban trees, relative to rural trees, in several regions of the world is expected to decrease tree longevity (Pretzsch et al., 2017), requiring monitoring and additional management of urban trees if their contribution to urban ecosystem based adaptation and mitigation is to be maintained in a 1.5°C world (Buckeridge, 2015; Pretzsch et al., 2017).

4.3.3.8 Sustainable Urban Water and Environmental Services

Urban water supply and wastewater treatment is energy intensive, and currently accounts for significant GHG emissions (Nair et al., 2014). Cities can integrate sustainable water resource management and the supply of water services in ways that support mitigation, adaptation and development through waste-water recycling and storm water diversion (Xue et al., 2015; Poff et al., 2016). Governance and finance challenges complicate balancing sustainable water supply and rising urban demand, particularly in low-income cities (Bettini et al., 2015; Deng and Zhao, 2015; Hill Clarvis and Engle, 2015; Lemos, 2015; Margerum and Robinson, 2015).

Urban surface sealing with impervious materials affects the volume and velocity of run-off and flooding during intense rainfall (Skougaard Kaspersen et al., 2015), but urban design in many cities now seeks to mediate run-off, encourage groundwater recharge and enhance water quality (Liu et al., 2014; Lamond et al., 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; Mguni et al., 2016; Xie et al., 2017). Challenges remain for managing intense rainfall events that are reported to be increasing in frequency and intensity in some locations (Ziervogel et al., 2016b) and urban flooding is expected to increase at 1.5°C warming (Alfieri et al., 2017). This risk falls disproportionately on women and poor people in cities (Mitlin, 2005; Chu et al., 2016; Ziervogel et al., 2016b; Chant et al., 2017; Dodman et al., 2017a, b).

Nexus approaches that highlight urban areas as socio-ecological systems, can support policy coherence (Rasul and Sharma, 2016) and sustainable urban livelihoods (Biggs et al., 2015). The Water-Energy-Food (WEF) nexus is especially important to growing urban populations (Tacoli et al., 2013; Lwasa et al., 2014; Villarroel Walker et al., 2014).

4.3.4 Industrial Systems Transitions

Industry consumes about one third of global final energy and contributes, directly and indirectly, about one third of global GHG emissions (IPCC, 2014b). If global temperatures are to remain under 1.5°C, modelling indicates that industry cannot emit more than 2 GtCO₂ in 2050, corresponding > 70% GHG emission reduction compared to 2010 (see Figures 2.20 and 2.21). Moreover, the consequences of climate change of 1.5°C or more pose substantial challenges for industrial diversity. This section will first briefly discuss the limited literature on adaptation options for industry. Subsequently, new literature since AR5 on the feasibility of industrial mitigation options will be discussed.

Research assessing adaptation actions by industry indicates that only a small fraction of corporations have
developed adaptation measures. Studies of adaptation in the private sector remain limited (Agrawala et al., 2011; Linnenluecke et al., 2015; Averchenkova et al., 2016; Bremer and Linnenluecke, 2016; Pauw et al., 2016a) and for 1.5°C are largely absent. This knowledge gap is particularly evident for medium-sized enterprises and in low- and middle-income nations (Surminski, 2013).

Depending on the industrial sector, mitigation consistent with 1.5°C would mean, across industries, a reduction of final energy demand by one-third, an increase of the rate of recycling of materials and the development of a circular economy in industry (Lewandowski, 2016; Linder and Williander, 2017), the substitution of materials in high-carbon products with those made up of renewable materials (e.g., wood instead of steel or cement in the construction sector, natural textile fibres instead of plastics), and a range of deep emission reduction options, including use of bio-based feedstocks, low-emission heat sources, electrification of production processes, and/or capture and storage of all CO₂ emissions by 2050 (Åhman et al., 2016). Some of the choices for mitigation options and routes for GHG-intensive industry are discrete and potentially subject to path dependency: if an industry goes one way (e.g., in keeping existing processes), it will be harder to transition to process change (e.g., electrification) (Bataille et al., 2018). In the context of rising demand for construction, an increasing share of industrial production may be based in developing countries (N. Li et al., 2017), where current efficiencies may be lower than in developed countries, and technical and institutional feasibility may differ (Ma et al., 2015).

Except for energy efficiency, costs of disruptive change associated with hydrogen- or electricity-based production, bio-based feedstocks and Carbon Dioxide Capture, (Utilisation) and Storage (CC(U)S) for trade-sensitive industrial sectors (in particular the iron and steel, petrochemical and refining industries) make policy action by individual countries challenging because of competitiveness concerns (Åhman et al., 2016; Nabernegg et al., 2017).

Table 4.3 provides an overview of applicable mitigation options for key industrial sectors.

Table 4.3: Overview of different mitigation options potentially consistent with 1.5°C and applicable to main industrial sectors, including examples of application (Napp et al., 2014; Boulamanti and Moya, 2017; Wesseling et al., 2017).

<table>
<thead>
<tr>
<th>Process and energy efficiency</th>
<th>Iron/steel</th>
<th>Cement</th>
<th>Refineries and petrochemicals</th>
<th>Chemicals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coke can be made from biomass instead of coal</td>
<td>Can make a difference on of between 10% and 50%, depending on the plant. Relevant but not enough for 1.5°C</td>
<td>Partial (only energy-related emissions)</td>
<td>Biomass can replace fossil feedstocks</td>
<td></td>
</tr>
<tr>
<td>More recycling and replacement by low-emission materials, including alternative chemistries for cement</td>
<td>Limited potential</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct reduction with hydrogen. Heat generation through electricity</td>
<td>Partial (only electrified heat generation)</td>
<td>Electrified heat and hydrogen generation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Possible for process emissions and energy. Reduces emissions by 80-95%, and become negative when combined with biofuel</td>
<td>Can be applied to energy emissions and different stacks but not on emissions of products in the use phase (e.g., gasoline)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3.4.1 Energy Efficiency

Isolated efficiency implementation in energy-intensive industries is a necessary but insufficient condition for deep emission reductions (Napp et al., 2014; Aden, 2017). Various options specific to different industries are available. In general, their feasibility depends on lowering capital costs and raising awareness and expertise (Wesseling et al., 2017). General purpose technologies, such as ICT, and energy management tools can...
improve the prospects of energy efficiency in industry (see Section 4.4.4).

Cross-sector technologies and practices, which play a role in all industrial sectors including Small- and Medium-sized Enterprises (SMEs) and non-energy intensive industry, also offer potential for considerable energy efficiency improvements. They include motor systems (for example electric motors, variable speed drives, pumps, compressors and fans), responsible for about 10% of industrial energy consumption with an energy efficiency improvement potential of around 20–25%, worldwide (Napp et al., 2014); steam systems, responsible for about 30% of industrial energy consumption and energy saving potentials of about 10% (Hasanbeigi et al., 2014; Napp et al., 2014). Waste heat recovery from industry has substantial potential for energy efficiency and emission reduction (Forman et al., 2016). Low awareness and competition from other investments limit the feasibility of such options (Napp et al., 2014).

4.3.4.2 Substitution and Circularity

Recycling materials and developing a circular economy can be institutionally challenging as it requires advanced capabilities (Henry et al., 2006) and organisational changes (Cooper-Searle et al., 2018), but has advantages in terms of cost, health, governance and environment (Ali et al., 2017). An assessment of the impacts on energy use and environmental issues is not available, but substitution could play a large role in reducing emissions (Åhman et al., 2016) although its potential depends on the demand for material, and the turnover of for example in buildings (Haas et al., 2015). Material substitution and CO₂ storage options are under development, for example, the use of algae and renewable energy for carbon fibre production, which could become a net sink of CO₂ (Arnold et al., 2018).

4.3.4.3 Bio-Based Feedstocks

Bio-based feedstock processes could be partly seen as part of the circular materials economy (see Section above). In several sectors, bio-based feedstocks would leave the production process of materials relatively untouched, and a switch would not affect the product quality, making the option more attractive. However, energy requirements for processing bio-based feedstocks are often high, costs are also still higher, and the emissions over the full lifecycle, both upstream and downstream, could be significant (Wesseling et al., 2017). Bio-based feedstocks may put pressure on natural resources by increasing land demand, biodiversity impacts beyond bioenergy demand for electricity, transport and buildings (Slade et al., 2014), and, partly as a result, face barriers in public acceptance (Sleenhoff et al., 2015).

4.3.4.4 Electrification and Hydrogen

Electrification of manufacturing processes would constitute a significant technological challenge and a more disruptive innovation in industry than bio-based or CCS options, to get to very low or zero emissions, except potentially in steel-making (Philibert, 2017). The disruptive characteristics could potentially lead to stranded assets, and could reduce political feasibility and industry support (Åhman et al., 2016). Electrification of manufacturing would require further technological development in industry, as well as an ample supply of cost-effective low-emission electricity (Philibert, 2017).

Low-emission hydrogen can be produced either by natural gas with CCS, by electrolysis of water powered by zero-emission electricity, or potentially in the future by generation IV nuclear reactors. Feasibility of electrification and use of hydrogen in production processes or fuel cells is affected by technical development in terms of efficient hydrogen production and electrification of processes, by geophysical factors related to the availability of low-emission electricity (MacKay, 2013), by associated public perception and by economic feasibility, except in areas with ample solar and/or wind resources (Philibert, 2017; Wesseling et al., 2017).
4.3.5.5 CO₂ Capture, Utilisation and Storage in Industry

CO₂ capture in industry is generally considered more feasible than CCS in the power sector (Section 4.3.1) or from bioenergy sources (Section 4.3.7), although CCS in industry faces similar barriers. Almost all of the current full-scale (>1 MtCO₂ yr⁻¹) CCS projects capture CO₂ from industrial sources, including the Sleipner project in Norway, which has been injecting CO₂ from a gas facility in an offshore saline formation since 1996 (Global CCS Institute, 2017). Compared to the power sector, retrofitting CCS on existing industrial plants would leave the production process of materials relatively untouched (Åhman et al., 2016), though significant investments and modifications still have to be made. Some industries, in particular cement, emit CO₂ as inherent process emissions and can therefore not reduce emissions to zero without CC(U)S. CO₂ stacks in some industries have a high economic and technical feasibility for CO₂ capture as the CO₂ concentration in the exhaust gases is relatively high (IPCC, 2005; Leeson et al., 2017), but others require strong modifications in the production process, limiting technical and economic feasibility, though costs remain lower than other deep GHG reduction options (Rubin et al., 2015). There are indications that the energy use in CO₂ capture through amine solvents (for solvent regeneration) can decrease by around 60%, from 5 GJ tCO₂⁻¹ in 2005 to 2 GJ tCO₂⁻¹ in the best-performing pilot plants (Idem et al., 2015), increasing both technical and economic potential for this option. The heterogeneity of industrial production processes might point to the need for specific institutional arrangements to incentivise industrial CCS (Mikunda et al., 2014), and may decrease institutional feasibility.

The contribution of Carbon Dioxide Utilisation (CCU) to limiting warming to 1.5°C depends on the origin of CO₂ (fossil, biogenic or atmospheric), the source of electricity for converting the CO₂ or regenerating catalysts, and the lifetime of the product. Review studies indicate that carbon dioxide utilisation in industry has a small role to play in limiting warming to 1.5°C because of the limited potential of re-using CO₂ with currently available technologies and the re-emission of CO₂ when used as a fuel (IPCC, 2005; Mac Dowell et al., 2017). However, there are new developments, in particular in CO₂ use as a feedstock for carbon-based materials that would isolate CO₂ from the atmosphere for a long time and greater availability of low-cost, low-emission electricity. The conversion of CO₂ to fuels using zero-emission electricity has a lower technical, economic and environmental feasibility than direct CO₂ capture and storage from industry (Abanades et al., 2017), although the economic prospects have improved recently (Philibert, 2017).

4.3.5 Overarching Adaptation Options Supporting Adaptation Transitions

This section assesses overarching adaptation options, which are specific solutions from which actors can choose and make decisions to reduce climate vulnerability and build resilience. We examine their feasibility in the context of transitions of energy, land and ecosystem, urban and infrastructure, and industrial systems here, and further in Section 4.5. These options can contribute to creating an enabling environment for adaptation (see Table 4.4 and Section 4.4).

4.3.5.1 Disaster Risk Management (DRM)

DRM is a process for designing, implementing and evaluating strategies, policies and measures to improve the understanding of disaster risk, and promoting improvement in disaster preparedness, response and recovery (IPCC, 2012). There is increased demand to integrate DRM and adaptation (Howes et al., 2015; Kelman et al., 2015; Serrao-Neumann et al., 2015; Archer, 2016; Rose, 2016; van der Keur et al., 2016; Kelman, 2017; Wallace, 2017) to reduce vulnerability, but institutional, technical and financial capacity challenges in frontline agencies constitute constraints (medium evidence, high agreement) (Eakin et al., 2015; Kita, 2017; Wallace, 2017).

4.3.5.2 Risk Sharing and Spreading

Risks associated with 1.5°C warming (Section 3.4) have the potential to increase the demand for options that
share and spread financial burdens. Formal, market-based (re)insurance spreads risk and provides a financial buffer against the impact of climate hazards (Linnerooth-Bayer and Hochrainer-Stigler, 2015; Wolfrom and Yokoi-Arai, 2015; O’Hare et al., 2016; Glaas et al., 2017; Patel et al., 2017). As an alternative to traditional indemnity-based insurance, index-based micro-crop and livestock insurance programmes have been rolled out in regions with less developed insurance markets (Akter et al., 2016, 2017; Jensen and Barrett, 2017). There is medium evidence and medium agreement on the feasibility of insurance for adaptation, with financial, social, and institutional barriers to implementation and uptake, especially in low-income nations (García Romero and Molina, 2015; Joyette et al., 2015; Lashley and Warner, 2015; Jin et al., 2016). Social protection programmes include cash and in-kind transfers to protect poor and vulnerable households from the impact of economic shocks, natural disasters and other crises (World Bank, 2017b), and can build generic adaptive capacity and reduce vulnerability when combined with a comprehensive climate risk management approach (medium evidence, medium agreement) (Devereux, 2016; Lemos et al., 2016).

4.3.5.3 Education and Learning

Educational adaptation options motivate adaptation through building awareness (Butler et al., 2016; Myers et al., 2017), leveraging multiple knowledge systems (Pearce et al., 2015; Janif et al., 2016), developing participatory action research and social learning processes (Butler and Adamowski, 2015; Ensor and Harvey, 2015; Butler et al., 2016; Thi Hong Phuong et al., 2017; Ford et al., 2018), strengthening extension services, and building learning and knowledge sharing mechanisms through community-based platforms, international conferences and knowledge networks (Vinke-de Kruijf and Pahl-Wostl, 2016) (medium evidence, high agreement).

4.3.5.4 Population Health and Health System Adaptation Options

Until mid-century, climate change will exacerbate existing health challenges (Section 3.4.7). Enhancing current health services includes providing access to safe water and improved sanitation, enhancing access to essential services such as vaccination, and developing or strengthening integrated surveillance systems (WHO, 2015). Combining these with iterative management can facilitate effective adaptation (medium evidence, high agreement).

4.3.5.5 Indigenous Knowledge

There is medium evidence and high agreement that Indigenous knowledge is critical for adaptation, underpinning adaptive capacity through the diversity of Indigenous agro-ecological and forest management systems, collective social memory, repository of accumulated experience, and social networks (Hiwasaki et al., 2015; Pearce et al., 2015; Mapfumo et al., 2016; Sherman et al., 2016; Ingty, 2017) (Box 4.3). It is threatened by acculturation, dispossession of land rights and land grabbing, rapid environmental changes, colonisation, and social change, increasing vulnerability to climate change, which climate policy can exacerbate if based on limited understanding of Indigenous worldviews (Thornton and Manasfi, 2010; Ford, 2012; Nakashima et al., 2012; McNamara and Prasad, 2014). Many scholars argue that recognition of Indigenous rights, governance systems and laws is central to adaptation, mitigation and sustainable development (Magni, 2017; Thornton and Comberti, 2017; Pearce, 2018).

4.3.5.6 Human Migration

Human migration, whether planned, forced or voluntary, is increasingly gaining attention as a response, particularly where climatic risks are becoming severe (Section 3.4.10.2). There is medium evidence and low agreement as to whether migration is adaptive, in relation to cost effectiveness (Grecequet et al., 2017) and scalability (Brzoska and Fröhlich, 2016; Gemmen and Blocher, 2017; Grecequet et al., 2017) concerns. Migrating can have mixed outcomes on reducing socio-economic vulnerability (Birk and Rasmussen, 2014;
Kothari, 2014; Adger et al., 2015; Betzold, 2015; Kelman, 2015; Grecequet et al., 2017; Melde et al., 2017; World Bank, 2017a, 2018b) and its feasibility is constrained by low political and legal acceptability, and inadequate institutional capacity (Betzold, 2015; Methmann and Oels, 2015; Brzoska and Fröhlich, 2016; Gemenne and Blocher, 2017; Grecequet et al., 2017; Yamamoto et al., 2017).

4.3.5.7 Climate Services

There is medium evidence and high agreement that climate services can play a critical role in aiding adaptation decision making (Vaughan and Dessai, 2014; Wood et al., 2014; Lourenço et al., 2016; Trenberth et al., 2016; Singh et al., 2017; Vaughan et al., 2018). The higher uptake of short-term climate information such as weather advisories and daily forecasts contrast with lesser use of longer-term information such as seasonal forecasts and multi-decadal projections (Singh et al., 2017; Vaughan et al., 2018). Climate service interventions have met challenges with scaling-up due to low capacity, inadequate institutions, and difficulties in maintaining systems beyond pilot project stage (Sivakumar et al., 2014; Tall et al., 2014; Gebru et al., 2015; Singh et al., 2016b), and technical, institutional, design, financial and capacity barriers to the application of climate information for better decision-making remain (WMO, 2015; Briley et al., 2015; L. Jones et al., 2016; Lourenço et al., 2016; Snow et al., 2016; Harjanne, 2017; Singh et al., 2017; C.J. White et al., 2017).

Table 4.4: Assessment of overarching adaptation options in relation to enabling conditions. For more details, see Supplementary Material 4.B.

<table>
<thead>
<tr>
<th>Option</th>
<th>Enabling Conditions</th>
<th>Examples</th>
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<tbody>
<tr>
<td>Disaster risk management (DRM)</td>
<td>Governance and institutional capacity: supports post-disaster recovery and reconstruction (Kelman et al., 2015; Kull et al., 2016).</td>
<td>Early warning systems (Anacona et al., 2015), and monitoring of dangerous lakes and surrounding slopes (including using remote sensing) offer DRM opportunities (Emmer et al., 2016; Milner et al., 2017).</td>
</tr>
<tr>
<td>Risk sharing and spreading: insurance</td>
<td>Institutional capacity and finance: buffers climate risk (Wolf from and Yokoi-Arai, 2015; O’Hare et al., 2016; Glaas et al., 2017; Jenkins et al., 2017; Patel et al., 2017).</td>
<td>In 2007, the Caribbean Catastrophe Risk Insurance Facility was formed to pool risk from tropical cyclones, earthquakes, and excess rainfalls (Murphy et al., 2012; CCRIF, 2017).</td>
</tr>
<tr>
<td>Risk sharing and spreading: social protection programmes</td>
<td>Institutional capacity and finance: builds generic adaptive capacity and reduces social vulnerability (Weldegebriel and Prowse, 2013; Eakin et al., 2014; Lemos et al., 2016; Schwan and Yu, 2017).</td>
<td>In sub-Saharan Africa, cash transfer programmes targeting poor communities have proven successful in smoothing household welfare and food security during droughts, strengthening community ties, and reducing debt levels (del Ninno et al., 2016; Asfaw et al., 2017; Asfaw and Davis, 2018).</td>
</tr>
<tr>
<td>Education and learning</td>
<td>Behavioural change and institutional capacity: social learning strengthens adaptation and affects longer-term change (Clemens et al., 2015; Ensor and Harvey, 2015; Henly-Shepard et al., 2015).</td>
<td>Participatory scenario planning is a process by which multiple stakeholders work together to envision future scenarios under a range of climatic conditions (Oteros-Rozas et al., 2015; Butler et al., 2016; Flynn et al., 2018).</td>
</tr>
<tr>
<td>Population health and health system</td>
<td>Institutional capacity: 1.5°C warming will primarily exacerbate existing health challenges (K.R. Smith et al., 2014), which can be targeted by enhancing health services.</td>
<td>Heat wave early warning and response systems coordinate the implementation of multiple measures in response to predicted extreme temperatures (e.g. public announcements, opening public cooling shelters, distributing information on heat stress symptoms) (Knowlton et al., 2014; Takahashi et al., 2015; Nitschke et al., 2016, 2017).</td>
</tr>
<tr>
<td>Indigenous knowledge</td>
<td>Institutional capacity and behavioural change: knowledge of environmental conditions helps communities detect and monitor change (Johnson et al., 2015; Mistry and Berardi, 2016; Williams et al., 2017).</td>
<td>Options such as integration of Indigenous knowledge into resource management systems and school curricula, are identified as potential adaptations (Cunsolo Willox et al., 2013; McNamara and Prasad, 2014; MacDonald et al., 2015; Pearce et al., 2015; Chambers et al., 2017; Inamara and Thomas, 2017).</td>
</tr>
</tbody>
</table>
### Cross-Chapter Box 9: Risks, Adaptation Interventions, and Implications for Sustainable Development and Equity Across Four Social-Ecological Systems: Arctic, Caribbean, Amazon, and Urban

**Authors:** Debora Ley (Guatemala/Mexico), Malcolm E Araos (Canada), Amir Bazaz (India), Marcos Buckeridge (Brazil), Ines Camilloni (Argentina), James Ford (UK/Canada), Bronwyn Hayward (New Zealand), Shagun Mehrotra (USA/India), Antony Payne (UK), Patricia Pinho (Brazil), Aromar Revi (India), Kevon Rhiney (Jamaica), Chandni Singh (India), William Solecki (USA), Avelino Suarez (Cuba), Michael Taylor (Jamaica), Adelle Thomas (Bahamas).

This box presents four case studies from different social-ecological systems as examples of risks of 1.5°C warming and higher (Chapter 3); adaptation options that respond to these risks (Chapter 4); and their implications for poverty, livelihoods and sustainability (Chapter 5). It is not yet possible to generalise adaptation effectiveness across regions due to a lack of empirical studies and monitoring and evaluation of current efforts.

**Arctic**

The Arctic is undergoing the most rapid climate change globally (Larsen et al., 2014), warming by 1.9°C over the last 30 years (Walsh, 2014; Grosse et al., 2016). For 2°C warming relative to pre-industrial levels, chances of an ice-free Arctic during summer are substantially higher than at 1.5°C (see Sections 3.3.5 and 3.3.8), with permafrost melt, increased instances of storm surge, and extreme weather events anticipated along with later ice freeze up, earlier break up, and a longer ice free open water season (Bring et al., 2016; DeBeer et al., 2016; Jiang et al., 2016; Chadburn et al., 2017; Melvin et al., 2017). Negative impacts on health, infrastructure, and economic sectors (AMAP, 2017a, b, 2018) are projected, although the extension of the summer ocean shipping season has potential economic opportunities (Ford et al., 2015b; Dawson et al., 2016; K.Y. et al., 2018).

Communities, many with Indigenous roots, have adapted to environmental change, developing or shifting harvesting activities and patterns of travel and transitioning economic systems (Forbes et al., 2009; Wenzel, 2009; Ford et al., 2015a; Pearce et al., 2015), although emotional and psychological effects have been documented (Cunsolo Willox et al., 2012; Cunsolo and Ellis, 2018). Besides climate change (Keskitalo et al., 2011; Loring et al., 2016), economic and social conditions can constrain the capacity to adapt unless resources and cooperation are available from public and private sector actors (AMAP, 2017a, 2018)(see Box 5.3Section ). In Alaska, the economic impacts of climate change on public infrastructure are significant, estimated at 5.5 billion USD to 4.2 billion USD from 2015 to 2099, with adaptation efforts halving these estimates (Melvin et al., 2017). Marginalisation, colonisation, and land dispossession provide broader underlying challenges facing many communities across the circumpolar north in adapting to change (Ford et al., 2015a; Sejersen, 2015) (see Section 4.3.5).

Adaptation opportunities include alterations to building codes and infrastructure design, disaster risk management, and surveillance (Ford et al., 2014a; AMAP, 2017a, b; Labbé et al., 2017). Most adaptation initiatives are currently occurring at local levels in response to both observed and projected environmental

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<table>
<thead>
<tr>
<th>Human migration</th>
<th>Governance: revising and adopting migration issues in national disaster risk management policies, National Adaptation Plans and NDCs (Kuruppu and Willie, 2015; Yamamoto et al., 2017).</th>
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</thead>
<tbody>
<tr>
<td>Climate services</td>
<td>Technological innovation: rapid technical development (due to increased financial inputs and growing demand) is enabling quality of climate information provided (WMO, 2015; Rogers and Tsirkunov, 2010; Clements et al., 2013; Perrels et al., 2013; Gasc et al., 2014; Roudier et al., 2016).</td>
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Climate services are seeing wide application in sectors such as agriculture, health, disaster management, insurance (Lourenço et al., 2016; Vaughan et al., 2018) with implications for adaptation decision-making (Singh et al., 2017).
changes as well as social and economic stresses (Ford et al., 2015a). In a recent study of Canada, most adaptations were found to be in the planning stages (Labbé et al., 2017). Studies have suggested that a number of the adaptation actions are not sustainable, lack evaluation frameworks, and hold potential for maladaptation (Loboda, 2014; Ford et al., 2015a; Larsson et al., 2016). Utilising Indigenous and local knowledge and stakeholder engagement can aid the development of adaptation policies and broader sustainable development, along with more proactive and regionally coherent adaptation plans and actions, and regional cooperation (e.g. through the Arctic Council) (Larsson et al., 2016; AMAP, 2017a; Melvin et al., 2017; Forbis Jr and Hayhoe, 2018) (see Section 4.3.5).

**Caribbean SIDS and Territories**

Extreme weather, linked to tropical storms and hurricanes, represent one of the largest risks facing Caribbean island nations (Section 3.4.5.3). Non-economic damages include detrimental health impacts, forced displacement and destruction of cultural heritages. Projections of increased frequency of the most intense storms at 1.5°C and higher warming levels (Wehner et al., 2018; Section 3.3.6; Box 3.5) are a significant cause for concern, making adaptation a matter of survival (Mycoo, 2017).

Despite a shared vulnerability arising from commonalities in location, circumstance and size (Bishop and Payne, 2012; Nurse et al., 2014), adaptation approaches are nuanced by differences in climate governance, affecting vulnerability and adaptive capacity (see Section 4.4.1). Three cases exemplify differences in disaster risk management.

**Cuba:** Together with a robust physical infrastructure and human resource base (Kirk, 2017), Cuba has implemented an effective civil defence system for emergency preparedness and disaster response, centred around community mobilisation and preparedness (Kirk, 2017). Legislation to manage disasters, an efficient and robust early warning system, emergency stockpiles, adequate shelter system and continuous training and education of the population help create a ‘culture of risk’ (Isayama and Ono, 2015; Lizarralde et al., 2015) which reduces vulnerability to extreme events (Pichler and Striessnig, 2013). Cuba’s infrastructure is still susceptible to devastation, as seen in the aftermath of the 2017 hurricane season.

**United Kingdom Outer Territories (UKOT):** All UKOT have developed National Disaster Preparedness Plans (PAHO/WHO, 2016) and are part of the Caribbean Disaster Risk Management Program which aims to improve disaster risk management within the health sector. Different vulnerability levels across the UKOT (Lam et al., 2015) indicate the benefits of greater regional cooperation and capacity-building, not only within UKOT, but throughout the Caribbean (Forster et al., 2011). While sovereign states in the region can directly access climate funds and international support, Dependent Territories are reliant on their controlling states (Bishop and Payne, 2012). There tends to be low-scale management for environmental issues in UKOT, which increases UKOT’s vulnerability. Institutional limitations, lack of human and financial resources, and limited long-term planning are identified as barriers to adaptation (Forster et al., 2011).

**Jamaica:** Disaster management is coordinated through a hierarchy of national, parish and community disaster committees under the leadership of the Office of Disaster Preparedness and Emergency Management (ODPEM). ODPEM coordinates disaster preparedness and risk reduction efforts among key state and non-state agencies (Grove, 2013). A National Disaster Committee provides technical and policy oversight to the ODPEM and is comprised of representatives from multiple stakeholders (Osei, 2007). Most initiatives are primarily funded through a mix of multi-lateral and bi-lateral loan and grant funding focusing on strengthening technical and institutional capacities of state and research-based institutions and supporting integration of climate change considerations into national and sectoral development plans (Robinson, 2017).

To improve climate change governance in the region, Pittman et al 2015 suggest incorporating holistic and integrated management systems, improving flexibility in collaborative processes, implementing monitoring programs, and increasing the capacity of local authorities. Implementation of the 2030 Sustainable Development Agenda and the Sustainable Development Goals (SDGs) can contribute to addressing the risks related with extreme events (Box 5.3).
The Amazon
Terrestrial forests, such as the Amazon, are sensitive to changes in the climate, particularly drought (Laurance and Williamson, 2001) which might intensify through the 21st century (Marengo and Espinoza, 2016) (Section 3.5.5.6).

The poorest communities in the region face substantial risks with climate change, and barriers and limits to adaptive capacity (Maru et al., 2014; Pinho et al., 2014, 2015; Brondízio et al., 2016). The Amazon is considered a hotspot with interconnections between increasing temperature, decreased precipitation and hydrological flow (Betts et al., 2018) (Sections 3.3.2.2, 3.3.3.2 and 3.3.5), low levels of socioeconomic development (Pinho et al., 2014), and high levels of climate vulnerability (Darela et al., 2016). Limiting temperature warming to 1.5°C could increase food and water security in the region compared to 2°C (Betts et al., 2018), reduce the impact on poor people and sustainable development, and make adaptation easier (O’Neill et al., 2017) particularly in the Amazon (Bathiany et al., 2018) (Section 5.2.2).

Climate policy in many Amazonian nations has focused on forests as carbon sinks (Soares-Filho et al., 2010). In 2009, the Brazilian National Policy on Climate Change acknowledged adaptation as a concern and the government sought to mainstream adaptation into public administration. Brazil’s National Adaptation Plan sets guidelines for sectoral adaptation measures, primarily by developing capacity building, plans, assessments and tools to support adaptive decision making. Adaptation is increasingly being presented as having mitigation co-benefits in the Brazilian Amazon (Gregorio et al., 2016), especially within ecosystem-based adaptation (Locatelli et al., 2011). In Peru’s Framework Law for Climate Change, every governmental sector will consider climatic conditions as potential risks and/or opportunities to promote economic development and to plan adaptation.

Drought and flood policies have had limited effectiveness in reducing vulnerability (Marengo et al., 2013). In the absence of effective adaptation, achieving the SDGs will be challenging, mainly in poverty, health, water and sanitation, inequality and gender equality (Section 5.2.3).

Urban systems
Around 360 million people reside in urban coastal areas where precipitation variability is exposing inadequacies of urban infrastructure and governance, with the poor especially vulnerable (Reckien et al., 2017)(Cross-Chapter Box 13 in Chapter 5). Urban systems have seen growing adaptation action (Revi et al., 2014b; Araos et al., 2016b; Amundsen et al., 2018). Developing cities spend more on health and agriculture-related adaptation options while developed cities spend more on energy and water (Georgesen et al., 2016). Current adaptation activities are lagging in emerging economies which are major centres of population growth facing complex interrelated pressures on investment in health, housing and education (Georgesen et al., 2016; Reckien et al., 2017).

New York: Adaptation plans are undertaken across government levels, sectors and departments (NYC Parks, 2010; Vision 2020 Project Team, 2011; The City of New York, 2013), and have been advanced by an expert science panel that is obligated by local city law to provide regular updates on policy relevant climate science (NPCC, 2015). Federal initiatives include 2013’s Rebuild By Design competition to promote resilience through infrastructural projects (HUD, 2013). In 2013 the Mayor’s office, in response to Hurricane Sandy, published the city’s adaptation strategy (The City of New York, 2013). In 2015, the OneNYC Plan for a Strong and Just City (OneNYC Team, 2015) laid out a strategy for urban planning through a justice and equity lens. In 2017, new climate resiliency guidelines proposed that new construction must include sea level rise projections into planning and development (The City of New York, 2017). Although this attention to climate-resilient development may help reduce income inequality, its full effect could be constrained, if a policy focus on resilience obscures analysis of income redistribution for the poor (Fainstein, 2018).

Kampala: Kampala Capital City Authority (KCCCA) has the statutory responsibility for managing the city. The Kampala Climate Change Action Strategy (KCCAS) is responding to climatic impacts of elevated temperature and more intense, erratic rain. KCCAS has considered multi-scale and temporal aspects of response (Chelleri et al., 2015; Douglas, 2017; Fraser et al., 2017), strengthened community adaptation (Lwasa, 2010; Dobson, 2017), responded to differential adaptive capacities (Waters and Adger, 2017) and
Believes in participatory processes and bridging of citywide linkages (KCCA, 2016). Analysis of the implications of uniquely adapted local solutions (e.g., motorcycle taxis) suggests sustainability can be enhanced when planning recognises the need to adapt to uniquely local solutions (Evans et al., 2018).

Rottterdam: The Rotterdam Climate Initiative (RCI) was launched to reduce Greenhouse Gas (GHG) emissions and climate-proof Rotterdam (RCI, 2017). Rotterdam has an integrated adaptation strategy, built on flood management, accessibility, adaptive building, urban water systems and urban climate, defined through Rotterdam Climate Proof and Rotterdam Climate Change Adaptation Strategy (RCI, 2008, 2013). Governance mechanisms that enabled integration of flood risk management plans with other policies, citizen participation, institutional eco-innovation, and focussing on green infrastructure (Albers et al., 2015; Dircke and Molenaar, 2015; de Boer et al., 2016a; Huang-Lachmann and Lovett, 2016) have contributed to effective adaptation (Ward et al., 2013). Entrenched institutional characteristics constrain the response framework (Francesch-Huidobro et al., 2017) but emerging evidence suggests that new governance arrangements and structures could potentially overcome these barriers in Rotterdam (Hölscher et al., 2018).

[END CROSS-CHAPTER BOX 9 HERE]

4.3.6 Short Lived Climate Forcers

The main Short-Lived Climate Forcer (SLCF) emissions that cause warming are methane (CH4), other precursors of tropospheric ozone (i.e., carbon monoxide (CO), Non-Methane Volatile Organic Compounds (NMVOC)), black carbon (BC) and hydrofluorocarbons (HFCs) (Myhre et al., 2013). SLCFs also include emissions that lead to cooling, such as sulphur dioxide (SO2) and organic carbon (OC). Nitrogen oxides (NOx) can have both warming and cooling effects, by affecting ozone (O3) and CH4, depending on timescale and location (Myhre et al., 2013).

Cross-Chapter Box 2 in Chapter 1 provides a discussion of role of SLCFs in comparison to long-lived GHGs. Chapter 2 shows that 1.5°C-consistent pathways require stringent reductions in CO2 and CH4, and that non-CO2 climate forcers reduce carbon budgets by ~2200 GtCO2 per degree of warming attributed to them (see Chapter 2 Annex).

Reducing non-CO2 emissions is part of most mitigation pathways (IPCC, 2014c). All current GHG emissions and other forcing agents affect the rate and magnitude of climate change over the next few decades, while long-term warming is mainly driven by CO2 emissions. CO2 emissions result in a virtually permanent warming, while temperature change from SLCFs disappears within decades after emissions of SLCFs are ceased. Any scenario that fails to reduce CO2 emissions to net zero would not limit global warming, even if SLCFs are reduced, due to accumulating CO2-induced warming that overwhelms SLCFs’ mitigation benefits in a couple of decades (Shindell et al., 2012; Schmale et al., 2014) and see Section 2.3.3.1).

Mitigation options for warming SLCFs often overlap with other mitigation options, especially since many warming SLCFs are co-emitted with CO2. SLCFs are generally mitigated in 1.5°C- or 2°C-consistent pathways as an integral part of an overall mitigation strategy (Chapter 2). For example, section 2.3 indicates that most very low-emissions pathways include a transition away from the use of coal and natural gas in the energy sector and oil in transportation, which coincides with emission reduction strategies related to methane from the fossil fuel sector and BC from the transportation sector. Much SLCF emission reduction aims at BC-rich sectors and considers the impacts of several co-emitted SLCFs (Bond et al., 2013; Sand et al., 2015; Stohl et al., 2015). However, it is uncertain whether such strategies would lead to additional long-term climate benefits compared to BC emissions reductions achieved through CO2 mitigation and associated co-control on BC-rich sectors in 1.5°C and 2°C pathways (Robelj et al., 2014).

Some studies have evaluated the focus on SLCFs in mitigation strategies and point towards trade-offs between short-term SLCF benefits and lock-in of long-term CO2 warming (Smith and Mizrahi, 2013; Pierrehumbert, 2014). Reducing fossil fuel combustion will reduce aerosols levels, and thereby cause warming from removal of cooling effects (Myhre et al., 2013; Xu and Ramanathan, 2017; Samset et al.,
2018). Recent studies have also found lower temperature effects of BC than what can be expected from the direct radiative forcing alone, thus questioning the effectiveness of targeted BC mitigation for climate change mitigation (Myhre et al., 2013; Baker et al., 2015; Stjern et al., 2017; Samset et al., 2018).

Table 4.5 provides an overview of three warming SLCFs and their emission sources, with examples of options for emission reductions and associated co-benefits.

Table 4.5: Overview of main characteristics of three warming Short-Lived Climate Forcers (SLCFs) (core information based on (Pierrehumbert, 2014) and (Schmale et al., 2014); rest of the details as referenced).

<table>
<thead>
<tr>
<th>SLCF compound</th>
<th>Atmospheric lifetime</th>
<th>Annual global emission</th>
<th>Main anthropogenic emission sources</th>
<th>Examples of options to reduce emissions consistent with 1.5°C</th>
<th>Examples of co-benefits based on (Haines et al., 2017) unless specified otherwise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>On the order of 10 years</td>
<td>0.3 GtCH₄ (2010) (Pierrehumbert, 2014)</td>
<td>Fossil fuel extraction and transportation Land-use change Cultivation Waste and wastewater</td>
<td>Managing manure from livestock Intermittent irrigation of rice Capture and usage of methane Change in diet</td>
<td>Reduction of tropospheric ozone Health benefits of dietary changes Increased crop yields Improved access to drinking water</td>
</tr>
<tr>
<td>HFCs</td>
<td>Months to decades, depending on the gas</td>
<td>0.35 GtCO₂-eq (2010) (Velders et al., 2015)</td>
<td>Air conditioning Refrigeration Construction material</td>
<td>Alternatives to HFCs in air-conditioning and refrigeration applications</td>
<td>Greater energy efficiency (Mota-Babiloni et al., 2017)</td>
</tr>
<tr>
<td>Black carbon</td>
<td>Days</td>
<td>~7 Mt (2010) (Klimont et al., 2017)</td>
<td>Incomplete combustion of fossil fuels or biomass in vehicles (esp. diesel), cook stoves or kerosene lamps Field and biomass burning</td>
<td>Fewer and cleaner vehicles Reducing agricultural biomass burning Cleaner cook stoves, gas-based or electric cooking Replacing brick and coke ovens Solar lamps</td>
<td>Health benefits of better air quality Increased education opportunities Reduced coal consumption for modern brick kilns Reduced deforestation</td>
</tr>
</tbody>
</table>

A wide range of options to reduce SLCF emissions was extensively discussed in AR5 (IPCC, 2014b). Fossil fuel and waste sector methane mitigation options have high cost-effectiveness, producing a net profit over a few years, considering market costs only. Moreover, reducing roughly one-third to one-half of all human-caused emissions has societal benefits greater than mitigation costs when considering environmental impacts only (UNEP, 2011; Höglund-Isaksson, 2012; IEA, 2017b; Shindell et al., 2017a). Since AR5, new options for methane, such as those related to shale gas, have been included in mitigation portfolios (e.g., Shindell et al. 2017b).

Reducing BC emissions and co-emissions has sustainable development co-benefits, especially around human health (Stohl et al., 2015; Haines et al., 2017; Aakre et al., 2018), avoiding premature deaths and increasing crop yields (Scovronick et al., 2015; Peng et al., 2016). Additional benefits include lower likelihood of non-linear climate changes and feedbacks (Shindell et al., 2017a) and temporarily slowing down the rate of sea level rise (Hu et al., 2013). Interventions to reduce BC offer tangible local air quality benefits, increasing the
likelihood of local public support (Eliasson, 2014; Venkataraman et al., 2016) (see Section 5.4.1.2). Limited interagency co-ordination, poor science-policy interactions (Zusman et al., 2015), and weak policy and absence of inspections and enforcement (Kholod and Evans, 2016) are among barriers that reduce the institutional feasibility of options to reduce vehicle-induced BC emissions. A case study for India shows that switching from biomass cook stoves to cleaner gas stoves (based on liquefied petroleum gas or natural gas) or to electric cooking stoves is technically and economically feasible in most areas, but faces barriers in user preferences, costs and the organisation of supply chains (Jeuland et al., 2015). Similar feasibility considerations emerge in switching to lighting from kerosene wick lamps to solar lanterns, from current low-efficiency brick kilns and coke ovens to cleaner production technologies; and from field burning of crop residues to agricultural practices using deep-sowing and mulching technologies (Williams et al., 2011; Wong, 2012).

The radiative forcing from HFCs are currently small but have been growing rapidly (Myhre et al., 2013). The Kigali amendment (from 2016) to the Montreal Protocol set out a global accord for phasing out these compounds (Höglund-Isaksson et al., 2017). HFC mitigation options include alternatives with reduced warming effects, ideally combined with improved energy efficiency so as to simultaneously reduce CO\(_2\) and co-emissions (Shah et al., 2015). Costs for most of HFC’s mitigation potential are estimated to be below USD\(_{2010}\) 60 tCO\(_2\)-eq\(^{-1}\), and the remainder below roughly double that number (Höglund-Isaksson et al., 2017).

Reductions in SLCFs can provide large benefits towards sustainable development, beneficial for social, institutional and economic feasibility. Strategies that reduce SLCFs can provide benefits that include improved air quality (for example (Anenberg et al., 2012)) and crop yields (for example (Shindell et al., 2012)), energy access, gender equality and poverty eradication (for example (Shindell et al., 2012; Haines et al., 2017)). Institutional feasibility can be negatively affected by an information deficit, with the absence of international frameworks for integrating SLCFs into emissions accounting and reporting mechanisms being a barrier for policy-making to address SLCF emissions (Venkataraman et al., 2016). The incentives for reducing SLCFs are particularly strong for small groups of countries, and such a collaboration could increase feasibility and effectiveness of SLCF mitigation options (Aakre et al., 2018).

### 4.3.7 Carbon Dioxide Removal (CDR)

CDR methods refer to a set of techniques for removing CO\(_2\) from the atmosphere. In the context of 1.5°C-consistent pathways (Chapter 2), they serve to offset residual emissions that take longer to abate or to compensate for emissions occurring after running out of the 1.5°C carbon budget. See Cross-Chapter Box 7 in Chapter 3 for a synthesis of land-based CDR options. Cross-cutting issues and uncertainties are summarised in Table 4.6.

#### 4.3.7.1 Bioenergy with carbon capture and storage (BECCS)

BECCS has been assessed in previous IPCC reports (IPCC, 2005; P. Smith et al., 2014; Minx et al., 2017) and has been incorporated into integrated assessment models (Clarke et al., 2014). In the meantime, 1.5°C pathways without BECCS have emerged (Bauer et al., 2018; Grübler, 2018; Mousavi and Blesl, 2018; van Vuuren et al., 2018). Still, models indicate that 3.7–8 GtCO\(_2\) yr\(^{-1}\) (interquartile range) and 14 GtCO\(_2\) yr\(^{-1}\) (median) would be removed by BECCS by 2050 and 2100, respectively, with some models starting BECCS in 2030 already (Section 2.3.4). BECCS is constrained by sustainable bioenergy potentials (Sections 4.3.1.2, 5.4.3 and Cross-Chapter Box 6 in Chapter 3), and availability of safe storage for CO\(_2\) (Section 4.3.1.6). Literature estimates for BECCS mitigation potentials in 2050 range from 1-85 GtCO\(_2\)\(^{\dagger}\). Fuss et al. (2018) narrow this range to 0.5–5 GtCO\(_2\) yr\(^{-1}\) (medium agreement, high evidence) (Figure 4.3), thus falling below

\(^{\dagger}\) FOOTNOTE: As more bottom-up literature exists on bioenergy potentials, this exercise explored the bioenergy literature and converted those estimates to BECCS potential with 1EJ of bioenergy yielding 0.02–0.05 GtCO\(_2\) emission reduction. For the bottom-up literature references for the potentials range, please refer to Supplementary Material C Table 1.

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the upper end of 1.5°C pathways. This is, among other things, related to sustainability concerns (Boysen et al., 2017; Heck et al., 2018; Henry et al., 2018).

Assessing BECCS deployment in 2°C pathways (of about 12 GtCO\textsubscript{2}-eq yr\textsuperscript{-1}, here considered as a lower deployment limit for 1.5°C, Smith et al. (2016b) estimate a land-use intensity of 0.3–0.5 ha tCO\textsubscript{2}-eq\textsuperscript{-1} yr\textsuperscript{-1} using forest residues, 0.16 ha CO\textsubscript{2}-eq\textsuperscript{-1} yr\textsuperscript{-1} for agricultural residues, and 0.03–0.1 ha tCO\textsubscript{2}-eq\textsuperscript{-1} yr\textsuperscript{-1} for purpose-grown energy crops. The average amount of BECCS in these pathways requires 25–46% of arable and permanent crop area in 2100. Land area estimates differ in scale and are not necessarily a good indicator of competition with, e.g., food production, because requiring a smaller land area for the same potential could indicate that high-productivity agricultural land is used. In general, the literature shows low agreement on the availability of land (Fritz et al., 2011); see (Erb et al., 2016b) for recent advances. Productivity, food production and competition with other ecosystem services and land use by local communities are important factors for the design of regulation. These potentials and trade-offs are not homogenously distributed across regions. However, (Robledo-Abad et al., 2017) find that regions with higher potentials are understudied, given their potential contribution. Researchers have expressed the need to complement global assessments with regional, geographically explicit bottom-up studies of biomass potentials and socio-economic impacts (e.g., de Wit and Faaij 2010; Kraxner et al., 2014; Baik et al., 2018).

Energy production, land and water footprints show wide ranges in bottom-up assessments due to differences in technology, feedstock and other parameters (−1–150 EJ yr\textsuperscript{-1} of energy, 109–990 Mha, 6–79 MtN, 218–4758 km\textsuperscript{3} yr\textsuperscript{-1} of water per GtCO\textsubscript{2} yr\textsuperscript{-1} (Smith and Torn, 2013; Smith et al., 2016b; Fajardy and Mac Dowell, 2017) and are not comparable to IAM pathways which consider system effects (Bauer et al., 2018). Global impacts on nutrients and albedo are difficult to quantify (Smith et al., 2016b). BECCS competes with other land-based CDR and mitigation measures for resources (Chapter 2).

There is uncertainty about the feasibility of timely upscaling. CCS (see Section 4.3.1) is largely absent from the nationally determined contributions (Spencer et al., 2015) and lowly ranked in investment priorities (Fridahl, 2017). Although there are dozens of small-scale BECCS demonstrations (Kemper, 2015) and a full scale project capturing 1 MtCO\textsubscript{2} exists (Finley, 2014), this is well below the numbers associated with 1.5°C or 2°C-compatible pathways (IEA, 2016a; Peters et al., 2017). Although the majority of BECCS cost estimates are below 200 USD tCO\textsubscript{2}-1 (Figure 4.3), estimates vary widely. Economic incentives for ramping up large CCS or BECCS infrastructure are weak (Bhave et al., 2017). The 2050 average investment costs for such a BECCS infrastructure for bio-electricity and biofuels are estimated at 138 and 123 billion USD yr\textsuperscript{-1}, respectively (Smith et al., 2016b).

BECCS deployment is further constrained by bioenergy’s carbon accounting, land, water and nutrient requirements (Section 4.3.1), its compatibility with other policy goals and limited public acceptance of both bioenergy and CCS (Section 4.3.1). Current pathways are believed to have inadequate assumptions on the development of societal support and governance structures (Vaughan and Gough, 2016). However, removing BECCS and CCS from the portfolio of available options significantly raises mitigation costs (Kriegler et al., 2013) (Bauer et al., 2018).
**Figure 4.2:** Evidence on Carbon Dioxide Removal (CDR) abatement costs, 2050 deployment potentials, and key side effects. Panel A presents estimates based on a systematic review of the bottom up literature (Fuss et al., 2018), corresponding to dashed blue boxes in Panel B. Dashed lines represent saturation limits for the corresponding technology. Panel B shows the percentage of papers at a given cost or potential estimate. Reference year for all potential estimates is 2050, while all cost estimates preceding 2050 have been...
Afforestation implies planting trees on land not forested for a long time (e.g., over the last 50 years in the context of the Kyoto Protocol), while reforestation implies re-establishment of forest formations after a temporary condition with less than 10% canopy cover due to human-induced or natural perturbations. Houghton et al. (2015) estimate about 500 Mha could be available for the re-establishment of forests on lands previously forested, but not currently used productively. This could sequester at least 3.7 Gt CO₂ yr⁻¹ for decades. The full literature range gives 2050 potentials of 1–7 Gt CO₂ yr⁻¹ (low evidence, medium agreement), narrowed down to 0.5–3.6 Gt CO₂ yr⁻¹ based on a number of constraints (Fuss et al., 2018). Abatement costs are estimated to be low compared to other CDR options, 5–50 USD t CO₂-eq⁻¹ (robust evidence, high agreement). Yet, realising such large potentials comes at higher land and water footprints than BECCS, although there would be a positive impact on nutrients, and the energy requirement would be negligible (Smith et al., 2016b; Cross-Chapter Box 7 in Chapter 3). The 2030 estimate by Griscom et al. (2017) is up to 17.9 Gt CO₂ yr⁻¹ for reforestation with significant co-benefits (Cross-Chapter Box 7 in Chapter 3).

Biogenic storage is not as permanent as emission reductions of geological storage. In addition, forest sinks saturate, a process which typically occurs in decades to centuries compared to the thousands of years of residence time of CO₂ stored geologically (Smith et al., 2016a) and is subject to disturbances that can be exacerbated by climate change (e.g., drought, forest fires and pests) (Seidl et al., 2017). Handling this requires careful forest management. There is much practical experience with AR, facilitating upscaling but with two caveats: AR potentials are heterogeneously distributed (Bala et al., 2007), partly because the planting of less reflective forests results in higher net-absorbed radiation and localised surface warming in higher latitudes (Bright et al., 2015; Jones et al., 2015), and forest governance structures and monitoring capacities can be bottlenecks and are usually not considered in models (Wang et al., 2016; Wehkamp et al., 2018b). There is medium agreement on the positive impacts of AR on ecosystems and biodiversity due to different forms of afforestation discussed in the literature: afforestation of grassland ecosystems or diversified agricultural landscapes with monocultures or invasive alien species can have significant negative impacts on biodiversity, water resources, etc. (P. Smith et al., 2014), while forest ecosystem restoration (forestry and agroforestry) with native species have positive social and environmental impacts (Cunningham et al., 2015; Locatelli et al., 2015; Paul et al., 2016); See Section 4.3.2).

Synergies with other policy goals are possible (see also Section 4.5.4); for example land spared by diet shifts could be afforested (Röös et al., 2017) or used for energy crops (Grübler, 2018). Such land-sparing strategies could also benefit other land-based CDR options.

Soil Carbon Sequestration and Biochar

At local scales there is robust evidence that Soil Carbon Sequestration (SCS, e.g., agroforestry, De Stefano and Jacobson, 2018), restoration of degraded land (Griscom et al., 2017), or conservation agriculture management practices (Aguilera et al., 2013; Poeplau and Don, 2015; Vicente-Vicente et al., 2016) have co-benefits in agriculture and that many measures are cost-effective even without supportive climate policy.
Evidence at global scale for potentials and especially costs is much lower. The literature spans cost ranges of −40–100 USD tCO$_2$–1 (negative costs relating to the multiple co-benefits of SCS, such as increased productivity and resilience of soils (P. Smith et al., 2014) and 2050 potentials are estimated between 1–11 GtCO$_2$ yr$^{-1}$, narrowed down to 2–5 GtCO$_2$ yr$^{-1}$ considering that studies above 5 GtCO$_2$ yr$^{-1}$ often do not apply constraints, while estimates lower than 2 GtCO$_2$ yr$^{-1}$ mostly focus on single practices (Fuss et al., 2018).

SCS has negligible water and energy requirements (Smith, 2016), affects nutrients and food security favourably (high agreement, robust evidence) and can be applied without changing current land use thus making it socially more acceptable than CDR options with a high land footprint. However, soil sinks saturate after 10–100 years, depending on the SCS option, soil type and climate zone (Smith, 2016).

Biochar is formed by recalcitrant (i.e., very stable) organic carbon obtained from pyrolysis which applied to soil can increase soil carbon sequestration leading to improved soil fertility properties. Looking at the full literature range, the global potential in 2050 lies between 1–35 Gt CO$_2$ yr$^{-1}$ (low agreement, low evidence), but considering limitations in biomass availability and uncertainties due to a lack of large-scale trials of biochar application to agricultural soils under field conditions, Fuss et al. (2018) lower the 2050 range to 0.3–2 GtCO$_2$ yr$^{-1}$. This potential is below previous estimates (e.g., Woolf et al., 2010), which additionally consider the displacement of fossil fuels through biochar. Permanence depends on soil type and biochar production temperatures, varying between a few decades and several centuries (Fang et al., 2014). Costs are 30–120 USD tCO$_2$–1 (medium agreement, medium evidence) (McCarl et al., 2009; McGlashan et al., 2012; McLaren, 2012; Smith, 2016).

Water requirements are low and at full theoretical deployment, up to 65 EJ yr$^{-1}$ of energy could be generated as a side product (Smith, 2016). Positive side effects include a favourable effect on nutrients and reduced N$_2$O emissions (Cayuela et al., 2014; Kammann et al., 2017). However, 40–260 Mha are needed to grow the biomass for biochar for implementation at 0.3 GtCO$_2$-eq yr$^{-1}$ (Smith, 2016), even though it is also possible to use residues (e.g., Windeatt et al., 2014). Biochar is further constrained by the maximum safe holding capacity of soils (Lenton, 2010) and the labile nature of carbon sequestered in plants and soil at higher temperatures (Wang et al., 2013).

4.3.7.4 Enhanced Weathering (EW) and Ocean Alkalisation

Weathering is the natural process of rock decomposition via chemical and physical processes in which CO$_2$ is spontaneously consumed and converted to solid or dissolved alkaline bicarbonates and/or carbonates (IPCC 2005). The process is controlled by temperature, reactive surface area, interactions with biota and, in particular, water solution composition. CDR can be achieved by accelerating mineral weathering through the distribution of ground-up rock material over land (Hartmann and Kempe, 2008; Wilson et al., 2009; Köhler et al., 2010; Renforth, 2012; ten Berge et al., 2012; Manning and Renforth, 2013; Taylor et al., 2016), shorelines (Hangx and Spiers, 2009; Montserrat et al., 2017) or the open ocean (House et al., 2007; Harvey, 2008; Köhler et al., 2013; Hauck et al., 2016). Ocean alkalisation adds alkalinity to marine areas to locally increase the CO$_2$ buffering capacity of the ocean (González and Ilyina, 2016; Renforth and Henderson, 2017).

In the case of land application of ground minerals, the estimated CDR potential range is 0.72–95 GtCO$_2$ yr$^{-1}$ (Hartmann and Kempe, 2008; Köhler et al., 2010; Hartmann et al., 2013; Taylor et al., 2016; Strefler et al., 2018) (low evidence, low agreement). Marine application of ground minerals is limited by feasible rates of mineral extraction, grinding and delivery, with estimates of 1–6 GtCO$_2$ yr$^{-1}$ (Köhler et al., 2013; Hauck et al., 2016; Renforth and Henderson, 2017) (low evidence, low agreement). Agreement is low due to a variety of assumptions and unknown parameter ranges in the applied modelling procedures that would need to be verified by field experiments (Fuss et al., 2018). As with other CDR options, scaling and maturity are

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FOOTNOTE: Other pyrolysis products that can achieve net CO$_2$ removals are bio-oil (pumped into geological storages) and permanent-pyrogas (capture and storage of CO$_2$ from gas combustion) (Werner et al., 2018)
challenges, with deployment at scale potentially requiring decades (NRC, 2015a), considerable costs in transport and disposal (Hangx and Spiers, 2009; Strefler et al., 2018) and mining (NRC, 2015a; Strefler et al., 2018)\(^6\).

Site-specific cost estimates vary depending on the chosen technology for rock grinding – an energy-intensive process (Köhler et al., 2013; Hauck et al., 2016) – material transport and rock source (Renforth, 2012; Hartmann et al., 2013), ranging from 15–40 USD tCO\(_2\)^{−1} to 3,460 USD tCO\(_2\)^{−1} (Schuiling and Krijgsman, 2006; Köhler et al., 2010; Taylor et al., 2016, limited evidence, low agreement; Figure 4.2). The evidence base for costs of ocean alkalinisation and marine enhanced weathering is sparser than the land applications. The ocean alkalinisation potential is assessed to be 0.1–10 GtCO\(_2\) yr\(^{-1}\) with costs of 14–>500 USD tCO\(_2\)^{−1} (Renforth and Henderson, 2017).

The main side effects of terrestrial EW are an increase in water pH (Taylor et al., 2016), the release of heavy metals like Ni and Cr, and plant nutrients like K, Ca, Mg, P and Si (Hartmann et al., 2013), and changes in hydrological soil properties. Respirable particle sizes, though resulting in higher potentials, can have impacts on health (Schuiling and Krijgsman, 2006; Taylor et al., 2016); utilisation of wave-assisted decomposition through deployment on coasts could avert the need for fine grinding (Hangx and Spiers, 2009; Schuiling and de Boer, 2010). Side effects of marine EW and ocean alkalinisation are the potential release of heavy metals like Ni and Cr (Montserrat et al., 2017). Increasing ocean alkalinity helps counter ocean acidification (Albright et al., 2016; Feng et al., 2016). Ocean alkalinisation could affect ocean biogeochemical functioning (González and Ilyina, 2016). A further caveat of relates to saturation state and the potential to trigger spontaneous carbonate precipitation.\(^7\) While the geochemical potential to remove and store CO\(_2\) is quite large, limited evidence on the preceding topics makes it difficult to assess the true capacity, net benefits and desirability of EW and ocean alkalinity addition in the context of CDR.

4.3.7.5 Direct Air Carbon Dioxide Capture and Storage (DACCs)

Capturing CO\(_2\) from ambient air through chemical processes with subsequent storage of the CO\(_2\) in geological formations is independent of source and timing of emissions, and can avoid competition for land. Yet, this is also the main challenge: while the theoretical potential for DACCs is mainly limited by the availability of safe and accessible geological storage, the CO\(_2\) concentration in ambient air is 100–300 times lower than at gas- or coal-fired power plants (Sanz-Pérez et al., 2016) thus requiring more energy than flue gas CO\(_2\) capture (Pritchard et al., 2015). This appears to be the main challenge to DACCs (Sanz-Pérez et al., 2016; Barkakaty et al., 2017).

Studies explore alternative techniques to reduce the energy penalty of DACCs (van der Giesen et al., 2017). Energy consumption could be up to 12.9 GJ tCO\(_2\)-eq\(^{-1}\); translating into an average of 156 EJ yr\(^{-1}\) by 2100 (current annual global primary energy supply is 600 EJ); water requirements are estimated to average 0.8–24.8 km\(^3\) GtCO\(_2\)-eq\(^{-1}\) yr\(^{-1}\) (Smith et al., 2016, based on Socolow et al., 2011).

However, the literature shows low agreement and is fragmented (Broehm et al., 2015). This fragmentation is reflected in a large range of cost estimates: from 20–1,000 USD tCO\(_2\)^{−1} (Keith et al., 2006; Pielke, 2009; House et al., 2011; Ranjan and Herzog, 2011; Simon et al., 2011; Goeppert et al., 2012; Holmes and Keith, 2012; Zeman, 2014; Sanz-Pérez et al., 2016; Sinha et al., 2017). The interquartile range (see Figure 4.2) is 40–449 USD tCO\(_2\)^{−1}; there is lower agreement and a smaller evidence base at the lower end of the cost range.

Research and efforts by small-scale commercialisation projects focus on utilisation of captured CO\(_2\) (Wilcox

\(^6\)FOOTNOTE: It has also been suggested that ocean alkalinity can be increased through accelerated weathering of limestone (Rau and Caldeira, 1999; Rau, 2011; Chou et al., 2015) or electrochemical processes (House et al., 2007; Rau, 2008; Rau et al., 2013b; Lu et al., 2015). However, these techniques have not been proven at large scale either (Renforth and Henderson, 2017).

\(^7\)FOOTNOTE: This analysis relies on the assessment in Fuss et al. (2018b), which provides more detail on saturation and permanence.
et al., 2018). Given that only a few IAM scenarios incorporate DACCS (e.g., Chen and Tavoni 2013; Streefkerk et al. 2018a) its possible role in cost-optimised 1.5°C scenarios is not yet fully explored. Given the technology’s early stage of development (McLaren, 2012; NRC, 2015a; Nemeth et al., 2018) and few demonstrations (Holmes et al., 2013; Rau et al., 2013; Agee et al., 2016), deploying the technology at scale is still a considerable challenge though both optimistic (Lackner et al., 2012) and pessimistic outlooks exist (Pritchard et al., 2015).

4.3.7.6 Ocean Fertilisation

Nutrients can be added to the ocean resulting in increased biologic production, leading to carbon fixation in the sunlit ocean and subsequent sequestration in the deep ocean or sea floor sediments. The added nutrients can be either micronutrients (such as iron) or macronutrients (such as nitrogen and/or phosphorous) (Harrison 2017). There is limited evidence and low agreement on the readiness of this technology to contribute to rapid decarbonisation (Williamson et al. 2012). Only small-scale field experiments and theoretical modelling have been conducted (e.g., McLaren (2012)). The full range of CDR potential estimates is 15.2 ktCO₂ yr⁻¹ (Bakker et al. 2001) for a spatially constrained field experiment to 4.4 GtCO₂ yr⁻¹ (Sarmiento and Orr 1991) following a modelling approach, but Fuss et al. (2018b) consider the potential to be extremely limited given the evidence and existing barriers. Due to scavenging of iron, the iron addition only leads to inefficient use of the nitrogen in exporting carbon (Aumont and Bopp 2006; Zahariev et al. 2008; Zeebe 2005).

Cost estimates range from 2 USD tCO₂⁻¹ (for iron fertilization) (Boyd and Denman 2008) to 457 USD tCO₂⁻¹ (Harrison 2013). Jones (2014) proposed values greater than 20 USD tCO₂⁻¹ for nitrogen fertilisation. Fertilisation is expected to impact food webs by stimulating its base organisms (Matear 2004), and extensive algal blooms may cause anoxia (Matear 2004; Russell et al. 2012; Sarmiento and Orr 1991) and deep water oxygen decline (Matear 2004), with negative impacts on biodiversity. Nutrient inputs can shift ecosystem production from an iron-limited system to a P-, N-, or Si-limited system depending on the location (Bertram 2010; Matear 2004) and non-CO₂ GHGs may increase (Bertram 2010; Sarmiento and Orr 1991; Matear 2004). The greatest theoretical potential for this practice is the Southern Ocean, posing challenges for monitoring and governance (Robinson et al. 2014). The London Protocol of the International Maritime Organization has asserted authority for regulation of ocean fertilisation (Strong et al. 2009), which is widely viewed as a, de facto moratorium* on commercial ocean fertilisation activities.

There is low agreement in the technical literature on the permanence of CO₂ in the ocean, with estimated residence times of 1,600 years to millennia, especially if injected or buried in or below the sea floor (Williams and Druffel, 1987; Jones, 2014). Storage at the surface would mean that the carbon would be rapidly released after cessation (Aumont and Bopp 2006; Zeebe 2005).

Table 4.6: Cross-cutting issues and uncertainties across Carbon Dioxide Removal (CDR) options aspects and uncertainties

<table>
<thead>
<tr>
<th>Area of uncertainty</th>
<th>Cross-cutting issues and uncertainties</th>
</tr>
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| Technology upscaling | • CDR options are at different stages of technological readiness (McLaren, 2012) and differ with respect to scalability.  
• Nemeth et al. (2018) find >50% of the CDR innovation literature concerned with the earliest stages of the innovation process (R&D) identifying a dissonance between the large CO₂ removals needed in 1.5°C pathways and the long-time periods involved in scaling up novel technologies.  
• Lack of post-R&D literature, including incentives for early deployment, niche markets, scale-up, demand, and public acceptance. |
| Emerging and niche technologies | • For BECCS, there are niche opportunities with high efficiencies and fewer trade-offs (e.g., sugar and paper processing facilities (Möllersten et al., 2003), district heating (Kärki et al., 2013; Ericsson and Werner, 2016), industrial and municipal waste (Sanna et al., 2012). Turner et al. (2018) constrain potential using |

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*Ref.: This term is not defined in the text and might need clarification.
sustainability considerations and overlap with storage basins to avoid the CO\textsubscript{2} transportation challenge, providing a possible, though limited entry point for BECCS.

- The impacts on land use, water, nutrients and albedo of BECCS could be alleviated using marine sources of biomass that could include aqua-cultured micro and macro flora (Hughes et al., 2012; Lenton, 2014)
- Regarding captured CO\textsubscript{2} as a resource is discussed as an entry point for CDR. However, this does not necessarily lead to carbon removals, particularly if the CO\textsubscript{2} is sourced from fossil fuels and/or if the products do not store the CO\textsubscript{2} for climate-relevant horizons (von der Assen et al. 2013) (see also Section 4.3.4.5).
- Methane\textsuperscript{8} is a much more potent GHG than CO\textsubscript{2} (Montzka et al., 2011), associated with difficult-to-abate emissions in industry and agriculture, outgassing from lakes, wetlands, and oceans (Lockley, 2012; Stolaroff et al., 2012). Enhancing processes that naturally remove methane, either by chemical or biological decomposition (Sundqvist et al., 2012), has been proposed to remove CH\textsubscript{4}. There is low confidence that existing technologies for methane removal are economically or energetically suitable for large-scale air capture (Boucher and Folberth, 2010). Methane removal potentials are limited due to its low atmospheric concentration and its low chemical reactivity at ambient conditions.

### Ethical aspects
- Preston (2013) identifies distributive and procedural justice, permissibility, moral hazard (Shue, 2018), and hubris as ethical aspects that could apply to large-scale CDR deployment.
- There is a lack of reflection on the climate futures produced by recent modelling and implying very different ethical costs/risks and benefits (Minx et al., 2018).

### Governance
- Existing governance mechanisms are scarce and either targeted at particular CDR options (e.g., ocean-based) or aspects (e.g., concerning indirect land-use change (iLUC) associated with bioenergy upscaling) and often the mechanisms are at national or regional scale (e.g., EU). Regulation accounting for iLUC by formulating sustainability criteria (e.g., the EU Renewable Energy Directive) has been assessed as insufficient in avoiding leakage (e.g., Frank et al., 2013)
- An international governance mechanism is only in place for R&D of Ocean Fertilisation within the Convention on Biological Diversity (IMO, 1972, 1996, CBD, 2008, 2010).

### Policy
- The CDR potentials that can be realised are constrained by the lack of policy portfolios incentivising large-scale CDR (Peters and Geden, 2017).
- Near-term opportunities could be supported through modifying existing policy mechanisms (Lomax et al., 2015).
- Scott and Geden (2018) sketch three possible routes for limited progress, (1) at EU-level, (2) at EU Member State level, and (3) at private sector level, noting the implied paradigm shift this would entail.
- EU may struggle to adopt policies for CDR deployment on the scale or time-frame envisioned by IAMs (Geden et al., 2018).
- Social impacts of large-scale CDR deployment (Buck, 2016) require policies taking these into account.

### Carbon cycle
- On long time scales, natural sinks could reverse (C.D. Jones et al., 2016)
- No robust assessments yet of the effectiveness of CDR in reverting climate change (Tokarska and Zickfeld, 2015; Wu et al., 2015; Keller et al., 2018), see also Section 2.2.2 and 2.6.2.

\textsuperscript{8} FOOTNOTE: Current work (e.g.de Richter et al. 2017) examines other technologies considering non-CO\textsubscript{2} GHGs like N\textsubscript{2}O.
4.3.8 Solar Radiation Modification (SRM)

This report refrains from using the term ‘geoengineering’ and separates SRM from CDR and other mitigation options (see Section 1.4.1 and Glossary).

Table 4.6 gives an overview of SRM methods and characteristics. For a more comprehensive discussion of currently proposed SRM methods, and their implications for geophysical quantities and sustainable development, see Cross-Chapter Box 10 in this Chapter. This section assesses the feasibility, from an institutional, technological, economic and social-cultural viewpoint, focusing on Stratospheric Aerosol Injection (SAI) unless otherwise indicated, as most available literature is about SAI.

Some of the literature on SRM appears in the forms of commentaries, policy briefs, viewpoints and opinions (e.g., (Horton et al., 2016; Keith et al., 2017; Parson, 2017). This assessment covers original research rather than viewpoints, even if the latter appear in peer-reviewed journals.

Table 4.7: Overview of the main characteristics of the most-studied SRM methods

<table>
<thead>
<tr>
<th>Description of SRM method</th>
<th>Stratospheric aerosol injection (SAI)</th>
<th>Marine cloud brightening (MCB)</th>
<th>Cirrus cloud thinning (CCT)</th>
<th>Ground-based albedo modification (GBAM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiative forcing efficiencies</td>
<td>Injection of a gas in the stratosphere, which then converts to aerosols. Injection of other particles also considered.</td>
<td>Spraying sea salt or other particles into marine clouds, making them more reflective.</td>
<td>Seeding to promote nucleation, reducing optical thickness and cloud lifetime, to allow more outgoing longwave radiation to escape into space.</td>
<td>Whitening roofs, changes in land use management (e.g., no-till farming), change of albedo at a larger scale (covering glaciers or deserts with reflective sheeting and changes in ocean albedo).</td>
</tr>
<tr>
<td>Amount needed for 1°C overshoot</td>
<td>1–4 TgS W$^{-1}$ m$^{-2}$ yr$^{-1}$</td>
<td>100–295 Tg dry sea salt W$^{-1}$ m$^{-2}$ yr$^{-1}$</td>
<td>Not known</td>
<td>Small on global scale, up to 1–3°C on regional scale</td>
</tr>
<tr>
<td>SRM specific impacts on climate variables</td>
<td>Changes in precipitation patterns and circulation regimes; in case of SO$_2$ injection disruption to stratospheric chemistry (for instance NOx depletion and changes in methane lifetime); increase in stratospheric water vapour and tropospheric-stratospheric ice formation affecting cloud microphysics.</td>
<td>Regional rainfall responses; reduction in hurricane intensity</td>
<td>Low-level cloud changes; tropospheric drying; intensification of the hydrological cycle</td>
<td>Impacts on precipitation in monsoon areas; could target hot extremes</td>
</tr>
<tr>
<td>SRM specific impacts on human/natural systems</td>
<td>In case of SO$_2$ injection - stratospheric ozone loss (which could also have a positive effect</td>
<td>Reduction in the number of mild crop failures</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Do Not Cite, Quote or Distribute
SRM could reduce some of the global risks of climate change related to temperature rise (Izrael et al., 2014; MacMartin et al., 2014), rate of sea level rise (Moore et al., 2010), sea-ice loss (Berdahl et al., 2014) and frequency of extreme storms in the North Atlantic and heatwaves in Europe (Jones et al., 2018). SRM also holds risks of changing precipitation and ozone concentrations and potentially reductions in biodiversity (Pitari et al., 2014; Visioni et al., 2017a; Trisos et al., 2018). Literature only supports SRM as a supplement to deep mitigation, for example in overshoot scenarios (Smith and Rasch, 2013; MacMartin et al., 2018).

4.3.8.1 Governance and Institutional Feasibility

There is robust evidence but medium agreement for unilateral action potentially becoming a serious SRM governance issue (Weitzman, 2015; Rabitz, 2016), as some argue that enhanced collaboration might emerge around SRM (Horton, 2011). An equitable institutional or governance arrangement around SRM would have to reflect views of different countries (Heyen et al., 2015; Robock, 2016) and be multilateral because of the risk of termination, and risks that implementation or unilateral action by one country or organisation will produce negative precipitation or extreme weather effects across borders (Lempert and Prosnitz, 2011; Dilling and Hauser, 2013; NRC, 2015b). Some have suggested that the governance of research and field experimentation can help clarify uncertainties surrounding deployment of SRM (Long and Shepherd, 2014; Parker, 2014; NRC, 2015c; Caldeira and Bala, 2017; Lawrence and Crutzen, 2017), and that SRM is compatible with democratic processes (Horton et al., 2018) or not (Szyszynski et al., 2013; Owen, 2014).

Several possible institutional arrangements have been considered for SRM governance: under the UNFCCC (in particular under the Subsidiary Body on Scientific and Technological Advice (SBSTA)) or the United Nations Convention on Biological Diversity (UNCBD) (Honegger et al., 2013; Nicholson et al., 2018), or through a consortium of states (Bodansky, 2013; Sandler, 2017). Voice in SRM diplomacy, prevention of unilateral action by others and benefits from research collaboration might be reasons for states to join an international governance framework for SRM (Lloyd and Oppenheimer, 2014).

Alongside SBSTA, the WMO, UNESCO and UN Environment could play a role in governance of SRM (Nicholson et al., 2018). Each of these organisations has relevance with respect to the regulatory framework (Bodle et al., 2012; Williamson and Bodle, 2016). The UNCBD gives guidance that ‘that no climate-related geo-engineering activities that may affect biodiversity take place’ (UNCBD, 2010).
4.3.8.2 Economic and Technological Feasibility

The literature on engineering cost of SRM is limited and may be unreliable in the absence of testing or deployment. There is high agreement that cost of SAI (not taking into account indirect and social costs, research and development costs and monitoring expenses) may be in the range of 1–10 billion USD yr\(^{-1}\) for injection of 1–5 MtS to achieve cooling of 1–2 W m\(^{-2}\) (Robock et al., 2009; McClellan et al., 2012; Ryaboshapko and Revokatova, 2015; Moriyama et al., 2016), suggesting that cost-effectiveness may be high if side-effects are low or neglected (McClellan et al., 2012). The overall economic feasibility of SRM also depends on externalities and social costs (Moreno-Cruz and Keith, 2013; Mackerron, 2014), climate sensitivity (Kosugi, 2013), option value (Arino et al., 2016), presence of climate tipping points (Eric Bickel, 2013) and damage costs as a function of the level of SRM (Bahn et al., 2015; Heutel et al., 2018). Modelling of game-theoretic, strategic interactions of states under heterogeneous climatic impacts shows low agreement on the outcome and viability of a cost-benefit analysis for SRM (Ricke et al., 2015; Weitzman, 2015).

For SAI, there is high agreement that aircrafts after some modifications could inject millions of tons of SO\(_2\) in the lower stratosphere (~20 km; (Davidson et al., 2012; McClellan et al., 2012; Irvine et al., 2016).

4.3.8.3 Social Acceptability and Ethics

Ethical questions around SRM include those of international responsibilities for implementation, financing, compensation for negative effects, the procedural justice questions of who is involved in decisions, privatisation and patenting, welfare, informed consent by affected publics, intergenerational ethics (because SRM requires sustained action in order to avoid termination hazards), and the so-called ‘moral hazard’ (Burns, 2011; Whyte, 2012; Gardiner, 2013; Lin, 2013; Buck et al., 2014; Klepper and Rickels, 2014; Morrow, 2014; Wong, 2014; Reynolds, 2015; Lockley and Coffman, 2016; McLaren, 2016; Suarez and van Aalst, 2017; Reynolds et al., 2018). The literature shows low agreement on whether SRM research and deployment may lead policy-makers to reduce mitigation efforts and thus imply a moral hazard (Linnér and Wibeck, 2015), but even a subtle difference in the articulation of information about SRM can influence subsequent judgements of favourability (Corner and Pidgeon, 2014). The argument that SRM research increases the likelihood of deployment (the ‘slippery slope’ argument), is also made (Parker, 2014; Quaas et al., 2017; Bellamy and Healey, 2018).

Unequal representation and deliberate exclusion are plausible in decision-making on SRM, given diverging regional interests and the anticipated low resource requirements to deploy SRM (Ricke et al., 2013). Whyte (2012) argues that the concerns, sovereignties, and experiences of Indigenous peoples may particularly be at risk.

The general public can be characterised as ignorant and worried about SRM (Carr et al., 2013; Parkhill et al., 2013; Wibeck et al., 2017). An emerging literature discusses public perception of SRM, showing a lack of knowledge and unstable opinions (Scheer and Renn, 2014). The perception of controllability affects legitimacy and public acceptability of SRM experiments (Bellamy et al., 2017). In Germany, laboratory work on SRM is generally approved of, field research much less so, and immediate deployment is largely rejected (Merk et al., 2015; Braun et al., 2017). Various factors could explain variations in the degree of rejection of SRM between Canada, China, Germany, Switzerland, the United Kingdom, and the United States (Visschers et al., 2017).
Cross-Chapter Box 10: Solar Radiation Modification in the Context of 1.5°C Mitigation Pathways

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Solar Radiation Modification (SRM) refers to a range of radiation modification measures not related to Greenhouse Gas (GHG) mitigation, which seek to limit global warming (see Section 1.4.1). Most methods involve reducing the solar incoming radiation reaching the surface, but others also act on the longwave radiation budget reducing optical thickness and cloud lifetime (see Table 4.6). In the context of this report, SRM is assessed in terms of its potential to limiting warming below 1.5°C in temporary overshoot scenarios as a way to reduce elevated temperatures and associated impacts (Irvine et al., 2016; Keith and Irvine, 2016; Chen and Xin, 2017; Sugiyama et al., 2017a; Visioni et al., 2017a; MacMartin et al., 2018). The inherent variability of the climate system would make it difficult to detect the efficacy or side-effects of SRM intervention when deployed in such a temporary scenario (Jackson et al., 2015).

A. Potential SRM timing and magnitude

Published SRM approaches are summarised in Table 4.6. The timing and magnitude of potential SRM deployment depends on the temperature overshoot associated with mitigation pathways. All overshooting pathways make use of carbon dioxide removal. Therefore, if considered, SRM would only be deployed as a supplement measure to large-scale carbon dioxide removal (Section 2.3).

Cross-Chapter Box 10, Figure 1 below illustrates an example of how a hypothetical SRM deployment based on Stratospheric Aerosols Injection (SAI) could be used to limit warming below 1.5°C using an ‘adaptive SRM’ approach (e.g., Kravitz et al. 2011; Tilmes et al., 2016), where global mean temperature exceeds 1.5°C compared to pre-industrial level by mid-century and returns below before 2100 with a 66% likelihood (see Chapter 2). In all such limited adaptive deployment scenarios, deployment of SRM only commences under conditions in which CO₂ emissions have already fallen substantially below their peak level and are continuing to fall. In order to hold warming to 1.5°C, a hypothetical SRM deployment could span from one to several decades with the earliest possible threshold exceedance occurring before mid-century. Over this duration, SRM has to compensate for warming that exceeds 1.5°C (displayed with hatching on panel a) with a decrease in radiative forcing (panel b) which could be achieved with a rate of SAI varying between 0–5.9 MtSO₂ yr⁻¹ (panel c) (Robock et al., 2008; Heckendorn et al., 2009).
Cross-Chapter Box CB10, Figure 1: Evolution of hypothetical SRM deployment (based on SAI) in the context of 1.5°C-consistent pathways. (a) Range of median temperature outcomes as simulated by MAGICC (see in Section 2.2) given the range of CO₂ emissions (b) and other climate forcers for mitigation pathways exceeding 1.5°C at mid-century and returning below by 2100 with a 66% likelihood. Geophysical characteristics are represented by the magnitude of radiative forcing (c) and the amount of stratospheric SO₂ injection (d) that are required to keep the global median temperature below 1.5°C during the temperature overshoot (given by the blue hatching on panel a). SRM surface radiative forcing has been diagnosed using a mean cooling efficiency of 0.3°C (W⁻¹ m²) of Plazzotta et al. (2018). Magnitude and timing of SO₂ injection have been derived from published estimates of Heckendorn et al. (2009) and Robock et al. (2008).

SAI is the most researched SRM method with high agreement that it could limit warming to below 1.5°C (Tilmes et al., 2016; Jones et al., 2018). The response of global temperature to SO₂ injection, however, is uncertain and varies depending on the model parametrisation and emission scenarios (Jones et al., 2011; Kravitz et al., 2011; Izrael et al., 2014; Crook et al., 2015; Niemeier and Timmreck, 2015; Tilmes et al., 2016; Kashimura et al., 2017). Uncertainty also arises due to the nature and the optical properties of injected aerosols.

Other approaches are less well researched but the literature suggests that Ground-Based Albedo Modification (GBAM), Marine Cloud Brightening (MCB) or Cirrus Cloud Thinning (CCT) are not assessed to be able to substantially reduce overall global temperature (Irvine et al., 2011; Seneviratne et al., 2018). However, these SRM approaches are known to create spatially heterogeneous forcing and potentially more spatially heterogeneous climate effects, which may be used to mitigate regional climate impacts. This may be of most relevance in the case of GBAM when applied to crop and urban areas (Seneviratne et al. 2018). Most of the literature on regional mitigation has focused on GBAM in relationship with land-use land cover changes scenarios. Both models and observations suggest that there is a high agreement that GBAM would result in
cooling over the region of changed albedo, and in particular reduce hot extremes (Irvine et al., 2011; Akbari et al., 2012; Jacobson and Ten Hoeve, 2012; Davin et al., 2014; Crook et al., 2015, 2016; Alkama and Cescatti, 2016; Seneviratne et al., 2018). In comparison, there is a limited evidence on the ability of MCB or CCT to mitigate regional climate impacts of 1.5°C warming because the magnitude of the climate response to MCB or CCT remains uncertain and the processes are not fully understood (Lohmann and Gasparini, 2017).

B. General consequence and impacts of solar radiation modification
It has been proposed that deploying SRM as a supplement to mitigation may reduce increases in global temperature-related extremes and rainfall intensity, and lessen the loss of coral reefs from increasing sea-surface temperatures (Keith and Irvine, 2016), but it would not address or even worsen (Tjiputra et al., 2016) negative effects from continued ocean acidification.

Another concern with SRM is the risk of a ‘termination shock’ or ‘termination effect’ when suddenly stopping SRM, which might cause rapid temperature rise and associated impacts (Jones et al., 2013; Izrael et al., 2014; McCusker et al., 2014; Robock, 2016), most noticeably biodiversity loss (Trisos et al., 2018). The severity of the termination effect has recently been debated (Parker and Irvine, 2018) and depends on the degree of SRM cooling. This report only considers limited SRM in the context of mitigation pathways to 1.5°C. Other risks of SRM deployment could be associated with the lack of testing of the proposed deployment schemes (e.g., (Schäfer et al., 2013)). Ethical aspects and issues related to the governance and economics are discussed in Section 4.3.8.

C. Consequences and impacts of SRM on the carbon budget
Because of its effects on surface temperature, precipitation and surface shortwave radiation, SRM would also alter the carbon budget pathways to 1.5°C or 2°C (Eliseev, 2012; Keller et al., 2014; Keith et al., 2017; Lauvset et al., 2017).

Despite the large uncertainties in the simulated climate response to SRM, current model simulations suggest that SRM would lead to altered carbon budgets compatible with 1.5°C or 2°C. The 6 CMIP5 models investigated simulated an increase of natural carbon uptake by land biosphere and, to a smaller extent, by the oceans (high agreement). The multi-model mean of this response suggests an increase of the RCP4.5 carbon budget of about 150 GtCO₂ after 50 years of SO₂ injection with a rate of 4 TgS yr⁻¹, which represents about 4 years of CO₂ emissions at the current rate (36 GtCO₂ yr⁻¹). However, there is uncertainty around quantitative determination of the effects that SRM or its cessation has on the carbon budget due to a lack of understanding of the radiative processes driving the global carbon cycle response to SRM (Ramachandran et al., 2000; Mercado et al., 2009; Eliseev, 2012; Xia et al., 2016), uncertainties about how the carbon cycle will respond to termination effects of SRM, and uncertainties in climate-carbon cycle feedbacks (Friedlingstein et al., 2014).

D. Sustainable development and SRM
There are few studies investigating potential implications of SRM for sustainable development. These are based on a limited number of scenarios and hypothetical considerations, mainly referring to benefits from lower temperatures (Irvine et al., 2011; Nicholson, 2013; Anshelm and Hansson, 2014; Harding and Moreno-Cruz, 2016). Other studies suggest negative impacts from SRM implementation concerning issues related to regional disparities (Heyen et al., 2015), equity (Buck, 2012), fisheries, ecosystems, agriculture, and termination effects (Robock, 2012; Morrow, 2014; Wong, 2014). If SRM is initiated by the richer nations, there might be issues with local agency, and possibly worsening conditions for those suffering most under climate change (Buck et al., 2014). In addition, ethical issues related to testing SRM have been raised (e.g., (Lenferna et al., 2017)). Overall, there is high agreement that SRM would affect many development issues but limited evidence on the degree of influence, and how it manifests itself across regions and different levels of society.

E. Overall feasibility of SRM
If mitigation efforts do not keep global mean temperature below 1.5°C, SRM can potentially reduce the climate impacts of a temporary temperature overshoot, in particular extreme temperatures, rate of sea level
rise and intensity of tropical cyclones, alongside intense mitigation and adaptation efforts. While theoretical developments show that SRM is technically feasible (see Section 4.3.8.2), global field experiments have not been conducted and most of the knowledge about SRM is based on imperfect model simulations and some natural analogues. There are also considerable challenges to the implementation of SRM associated with disagreements over the governance, ethics, public perception, and distributional development impacts (Boyd, 2016; Preston, 2016; Asayama et al., 2017; Sugiyama et al., 2017b; Svoboda, 2017; McKinnon, 2018; Talberg et al., 2018) (see Section 4.3.8). Overall, the combined uncertainties surrounding the various SRM approaches, including technological maturity, physical understanding, potential impacts, and challenges of governance, constrain the ability to implement SRM in the near future.

[END CROSS-CHAPTER BOX 10 HERE]

### 4.4 Implementing Far-Reaching and Rapid Change

The feasibility of 1.5°C-compatible pathways is contingent upon enabling conditions for systemic change (see Cross Chapter Box 3 in Chapter 1). Section 4.3 identifies the major systems, and options within those systems, that offer the potential for change to align with 1.5°C pathways.

AR5 identifies enabling conditions as influencing the feasibility of climate responses (Kolstad et al., 2014). This section draws on 1.5°C-specific and related literature on rapid and scale-up change, to identify the enabling conditions that influence the feasibility of adaptation and mitigation options assessed in Section 4.5. Examples from diverse regions and sectors are provided to illustrate how these conditions could enable or constrain the implementation of incremental, rapid, disruptive and transformative mitigation and adaptation consistent with 1.5°C pathways.

Coherence between the enabling conditions holds potential to enhance feasibility of 1.5°C-consistent pathways and adapting to the consequences. This includes better alignment across governance scales (OECD/IEA/NEA/ITF, 2015; Geels et al., 2017), enabling multi-level governance (Cheshmehzangi, 2016; Revi, 2017; Tait and Euston-Brown, 2017) and nested institutions (Abbott, 2012). It also includes inter-disciplinary actions, combined adaptation and mitigation action (Göpfert et al., 2018) and science-policy partnerships (Vogel et al., 2007; Hering et al., 2014; Roberts, 2016; Figueres et al., 2017; Leal Filho et al., 2018). These partnerships are difficult to establish and sustain, but can generate trust (Cole, 2015; Jordan et al., 2015) and inclusivity that ultimately can provide durability and the realisation of co-benefits for sustained rapid change (Blanchet, 2015; Ziervogel et al., 2016a).

#### 4.4.1 Enhancing Multi-Level Governance

Addressing climate change and implementing responses to 1.5°C-consistent pathways will need to engage with various levels and types of governance (Betsill and Bulkeley, 2006; Kern and Alber, 2009; Christoforidis et al., 2013; Romero-Lankao et al., 2018). AR5 highlighted the significance of governance as a means of strengthening adaptation and mitigation and advancing sustainable development (Fleurbaey et al., 2014). Governance is defined in the broadest sense as the ‘processes of interaction and decision making among actors involved in a common problem’ (Kooiman 2003, Hufty 2011) (Fleurbaey et al., 2014). This definition goes beyond notions of formal government or political authority and integrates other actors, networks, informal institutions and communities.

#### 4.4.1.1 Institutions and their Capacity to Invoke Far-Reaching and Rapid Change

Institutions, the rules and norms that guide human interactions (Section 4.4.2), enable or impede the structures, mechanisms and measures that guide mitigation and adaptation. Institutions, understood as the ‘rules of the game’ (North, 1990), exert direct and indirect influence over the viability of 1.5°C-consistent pathways (Munck et al., 2014; Willis, 2017). Governance would be needed to support wide-scale and
effective adoption of mitigation and adaptation options. Institutions and governance structures are strengthened when the principle of the ‘commons’ is explored as a way of sharing management and responsibilities (Ostrom et al., 1999; Chaffin et al., 2014; Young, 2016). Institutions would need to be strengthened to interact amongst themselves, and to share responsibilities for the development and implementation of rules, regulations and policies (Ostrom et al., 1999; Wejs et al., 2014; Craig et al., 2017), with the goal of ensuring that these embrace equity, justice, poverty alleviation and sustainable development, enabling a 1.5°C world (Reckien et al., 2017; Wood et al., 2017).

Several authors have identified different modes of cross-stakeholder interaction in climate policy, including the role played by large multinational corporations, small enterprises, civil society and non-state actors. Ciplet et al. (2015) argue that civil society is to a great extent the only reliable motor for driving institutions to change at the pace required. Kern and Alber (2009) recognise different forms of collaboration relevant to successful climate policies beyond the local level. Horizontal collaboration (e.g., transnational city networks) and vertical collaboration within nation-states can play an enabling role (Ringel, 2017). Vertical and horizontal collaboration requires synergistic relationships between stakeholders (Ingold and Fischer, 2014; Hsu et al., 2017). The importance of community participation is emphasised in literature, and in particular the need to take into account equity and gender considerations (Chapter 5) (Graham et al., 2015; Bryan et al., 2017; Wangui and Smucker, 2017). Participation often faces implementation challenges and may not always result in better policy outcomes. Stakeholders, for example, may not view climate change as a priority and may not share the same preferences, potentially creating a policy deadlock (Preston et al., 2013, 2015; Ford et al., 2016).

4.4.1.2 International Governance

International treaties help strengthen policy implementation, providing a medium and long-term vision (Obergassel et al., 2016). International climate governance is organised via many mechanisms, including international organisations, treaties and conventions, for example, UNFCCC, the Paris Agreement and the Montreal Protocol. Other multilateral and bilateral agreements, such as trade agreements, also have a bearing on climate change.

There are significant differences between global mitigation and adaptation governance frames. Mitigation tends to be global by its nature and it is based on the principle of the climate system as a global commons (Ostrom et al., 1999). Adaptation has traditionally been viewed as a local process, involving local authorities, communities, and stakeholders (Khan, 2013; Preston et al., 2015), although is now recognised to be a multi-scaled, multi-actor process that transcends from local and sub-national, to national and international scales (Mimura et al., 2014; UNEP, 2017a). National governments provide a central pivot for coordination, planning, determining policy (Section 4.4.5) priorities and distributing resources. National governments are accountable to the international community through international agreements. Yet, many of the impacts of climate change are transboundary, so that bilateral and multilateral cooperation are needed (Nalau et al., 2015; Donner et al., 2016; Magnan and Ribera, 2016; Tilleard and Ford, 2016; Lesnikowski et al., 2017). The Kigali Amendment to the Montreal Protocol demonstrates that a global environmental agreement facilitating common but differentiated responsibilities is possible (Sharadin, 2018). This was operationalised by developed countries acting first, with developing countries following and benefiting from leap-frogging the trial-and-error stages of innovative technology development.

Work on international climate governance has focused on the nature of ‘climate regimes’ and coordinating the action of nation-states (Aykut, 2016) organised around a diverse set of intruments: i) binding limits allocated by principles of historical responsibility and equity, ii) carbon prices, emissions quotas, iii) pledges and review of policies and measures or iv) a combination of these options (Stavins, 1988; Grubb, 1990; Pizer, 2002; Newell and Pizer, 2003).

Literature on the Kyoto Protocol provides two important insights for 1.5°C transition: the challenge of agreeing on rules to allocate emissions quotas (Shukla, 2005; Caney, 2012; Winkler et al., 2013; Gupta, 2014; Méjean et al., 2015) and a climate-centric vision (Shukla, 2005; Winkler et al., 2011), separated from
development issues which drove resistance from many developing nations (Roberts and Parks, 2006). For the former, a burden sharing approach led to an adversarial process among nations to decide who shall be allocated ‘how much’ of the remainder of the emissions budget (Caney, 2014; Ohndorf et al., 2015; Roser et al., 2015; Giménez-Gómez et al., 2016). Industry group lobbying, further contributed to reducing space for manoeuvre of some major emitting nations (Newell and Paterson, 1998; Levy and Egan, 2003; Dunlap and McCright, 2011; Michaelowa, 2013; Geels, 2014).

Given the political unwillingness to continue with the Kyoto Protocol approach a new approach was introduced in the Copenhagen Accord, the Cancun Agreements, and finally in the Paris Agreement. The transition to 1.5°C requires carbon neutrality and thus going beyond the traditional framing of climate as a ‘tragedy of the commons’ to be addressed via cost-optimal allocation rules, which demonstrated a low probability of enabling a transition to 1.5°C consistent pathways (Patt, 2017). The Paris Agreement, built on a ‘pledge and review’-system is thought to be more effective in securing trust (Dagnet et al., 2016), enables effective monitoring and timely reporting on national actions (including adaptation), allowing for international scrutiny and persistent efforts of civil society and non-state actors to encourage action in both national and international contexts (Allan and Hadden, 2017; Bäckstrand and Kuypers, 2017; Höhne et al., 2017; Lesnikowski et al., 2017; Maor et al., 2017; UNEP, 2017a), with some limitations (Nieto et al., 2018).

The paradigm shift enabled at Cancun succeeded by focusing on the objective of ‘equitable access to sustainable development’ (Hourcade et al., 2015). The use of ‘pledge and review’ now underpins the Paris Agreement. This consolidates multiple attempts to define a governance approach that relies on National Determined Contributions (NDCs) and on means for a ‘facilitative model’ (Bodansky and Diringer, 2014) to reinforce them. This enables a regular, iterative, review of NDCs allowing countries to set their own ambitions after a global stocktake and more flexible, experimental forms of climate governance, which may provide room for a higher ambition, and be consistent with the needs of governing for a rapid transition to close the emission gap (Clémençon, 2016; Falkner, 2016) (Cross-Chapter Box 11 in this Chapter). Beyond a general consensus on the necessity of Measurement, Reporting and Verification (MRV) mechanisms as a key element of a climate regime (Ford et al., 2015b; van Asselt et al., 2015), some authors emphasise different governance approaches to implement the Paris Agreement. Through market mechanisms under Article 6 of the Paris Agreement and the new proposed sustainable development mechanism, it allows the space to harness the lowest cost mitigation options worldwide. This may incentivise policymakers to enhance mitigation ambition by speeding up climate action as part of ‘climate regime complex’ (Keohane and Victor, 2011) of loosely interrelated global governance institutions. In the Paris Agreement, the Common But Differentiated Responsibilities and Respective Capabilities (CBDR-RC) principle could be expanded and revisited under a ‘sharing the pie’ paradigm (Ji and Sha, 2015) as a tool to open innovation processes towards alternative development pathways (Chapter 5).

COP16 in Cancun was also the first time in the UNFCCC that adaptation was recognised to have similar priority as mitigation. The Paris Agreement recognises the importance of adaptation action and cooperation to enhance such action. (Chung Tian Fook, 2017; Lesnikowski et al., 2017) suggest that the Paris Agreement is explicit about multilevel adaptation governance, outlines stronger transparency mechanisms, links adaptation to development and climate justice, and is hence, suggestive of greater inclusiveness of non-state voices and the broader contexts of social change.

1.5°C-consistent pathways require further exploration of conditions of trust and reciprocity amongst nation states (Schelling, 1991; Ostrom and Walker, 2005). Some authors (Colman et al., 2011; Courtois et al., 2015) suggest a departure from the vision of actors acting individually in the pursuit of self-interest to that of iterated games with actors interacting over time showing that reciprocity, with occasional forgiveness and initial good faith, can lead to win-win outcomes and to cooperation as a stable strategy (Axelrod and Hamilton, 1981).

Regional cooperation plays an important role in the context of global governance. Literature on climate regimes has only started exploring innovative governance arrangements including: coalitions of transnational actors including state, market and non-state actors (Bulkeley et al., 2012; Hovi et al., 2016; Hagen et al., 2017; Hermwille et al., 2017; Roelfsema et al., 2018) and groupings of countries, as a complement to the
UNFCCC (Abbott and Snidal, 2009; Biermann, 2010; Zelli, 2011; Nordhaus, 2015). Climate action requires multi-level governance from the local and community level to national, regional and international levels. Box 4.1 shows the role of sub-national authorities, e.g. regions and provinces in facilitating urban climate action, while Box 4.2 shows that climate governance can be organised across hydrological and not only political units as well.

4.4.1.3 Sub-National Governance

Local governments can play a key role (Melica et al., 2018; Romero-Lankao et al., 2018) in influencing mitigation and adaptation strategies. It is important to understand how rural and urban areas, small islands, informal settlements and communities might intervene to reduce climate impacts (Bulkeley et al., 2011), either by implementing climate objectives defined at higher government levels, taking initiative autonomously or collectively (Aall et al., 2007; Reckien et al., 2014; Araos et al., 2016a; Heidrich et al., 2016). Local governance faces the challenge of reconciling local concerns with global objectives. Local governments could coordinate and develop effective local responses, and could pursue procedural justice in ensuring community engagement and more effective policies around energy and vulnerability reduction (Moss et al., 2013; Fudge et al., 2016). They can enable more participative decision-making (Barrett, 2015; Hesse, 2016). Fudge et al. (2016) argue that local authorities are well-positioned to involve the wider community in: designing and implementing climate policies, engaging with sustainable energy generation, e.g., by supporting energy communities (Slee, 2015), and the delivery of demand-side measures and adaptation implementation.

By 2050, it is estimated three billion people will be living in slums and informal settlements: neighbourhoods without formal governance, on un-zoned land developments and in places that are exposed to climate-related hazards (Bai et al., 2018). Emerging research is examining how citizens can contribute informally to governance with rapid urbanisation and weaker government regulation (Sarmiento and Tilly, 2018). It remains to be seen how the possibilities and consequences of alternative urban governance models for large, complex problems and addressing inequality and urban adaptation will be managed (Amin and Cirolia, 2018; Bai et al., 2018; Sarmiento and Tilly, 2018).

Expanding networks of cities sharing experiences on coping with climate change and drawing economic and development benefits from climate change responses represent a recent institutional innovation. This could be complemented by efforts of national governments through national urban policies to enhance local climate action (Broekhoff et al., 2018). Over the years, non-state actors have set up several transnational climate governance initiatives to accelerate the climate response, for example ICLEI (1990), C–40 (2005), the Global Island Partnership (2006) and the Covenant of Mayors (2008) (Gordon and Johnson, 2017; Hsu et al., 2017; Ringel, 2017; Kona et al., 2018; Melica et al., 2018) and to exert influence on national governments and the UNFCCC (Bulkeley, 2005). However, (Michaelowa and Michaelowa, 2017) find low effectiveness of over 100 of such mitigation initiatives.

4.4.1.4 Interactions and Processes for Multi-Level Governance

Literature has proposed multi-level governance in climate change as an enabler for systemic transformation and effective governance, as the concept is thought to allow for combining decisions across levels, sectors and institutional types at the same level (Romero-Lankao et al., 2018) with multi-level reinforcement and the mobilisation of economic interests at different levels of governance (Jancicke and Quitzow, 2017). These governance mechanisms are based on accountability and transparency rules and participation and coordination across and within these levels.

A study of 29 European countries showed that the rapid adoption and diffusion of adaptation policymaking is largely driven by internal factors, at the national and sub-national levels (Massey et al., 2014). An assessment of national level adaptation in 117 countries (Berrang-Ford et al., 2014), find good governance to be the one of the strongest predictors of national adaptation policy. An analysis of climate response by 200
large and medium-sized cities across eleven European countries find that factors such as membership of climate networks, population size, Gross Domestric Product (GDP) per capita and adaptive capacity act as drivers of mitigation and adaptation plans (Reckien et al., 2015).

Adaptation policy has seen growth in some areas (Massey et al., 2014; Lesnikowski et al., 2016), although efforts to track adaptation progress are constrained by an absence of data sources on adaptation (Berrang-Ford et al. 2011; Ford and Berrang-Ford 2016; Magnan and Ribera 2016; Magnan 2016). Many developing countries have made progress in formulating national policies, plans and strategies on responding to climate change. The NDCs have been identified as one such institutional mechanism (Magnan et al., 2015; Kato and Ellis, 2016; Peters et al., 2017) (Cross-Chapter Box 11 in this Chapter).

To overcome barriers to policy implementation, local conflicts of interest or vested interests, strong leadership and agency is needed by political leaders. As shown by the Covenant of Mayors initiative (Box 4.1), political leaders with a vision for the future of the local community can succeed in reducing GHG emissions, when they are supported by civil society (Rivas et al., 2015; Croci et al., 2017; Kona et al., 2018). Any political vision would need to be translated into an action plan, of which elements could be describing policies and measures needed to achieve transition, the human and financial resources needed, milestones, and appropriate measurement and verification processes (Azvedo and Leal, 2017). Discussing the plan with stakeholders and civil society, including citizens and right of participation for minorities, and having them provide input and endorse it, is found to increase the likelihood of success (Rivas et al., 2015; Wamsler, 2017). However, as described by Nightingale (2017) and Green (2016), struggles over natural resources and adaptation governance both at the national and community levels would need to be addressed too, ‘in politically unstable contexts, where power and politics shape adaptation outcomes’.

[START BOX 4.1 HERE]

**Box 4.1: Multi-Level Governance in the EU Covenant of Mayors: Example of the Provincia di Foggia**

Since 2005, cities have emerged as a locus of institutional and governance climate innovation (Melica et al., 2018) and are driving responses to climate change (Roberts, 2016). Many cities have adopted more ambitious Greenhouse Gas (GHG) emission reduction targets than countries (Kona et al., 2018), with an overall commitment of GHG emission reduction targets by 2020 of 27%, almost 7 percentage points higher than the minimum target for 2020 (Kona et al., 2018). The Covenant of Mayors (CoM) is an initiative in which municipalities voluntarily commit to CO2 emission reduction. The participation of small municipalities has been facilitated by the development and testing of a new multi-level governance model involving Covenant Territorial Coordinators (CTCs), i.e., provinces and regions, which commit to providing strategic guidance, financial and technical support to municipalities in their territories. Results from the 315 monitoring inventories submitted shows an achievement of 23% reduction in emissions (compared to an average year 2005) of more than half of the cities under a CTC schema (Kona et al., 2018).

The Province of Foggia, acting as a CTC, gave support to 36 municipalities to participate in the CoM and to prepare Sustainable Energy Action Plans (SEAPs). The Province developed a common approach to prepare SEAPs, provided data to compile municipal emission inventories (Bertoldi et al., 2018) and guided the signatory to identify an appropriate combination of measures to curb GHG emissions programme. The local Chamber of Commerce had a key role also in the implementation of these projects by the municipalities (Lombardi et al., 2016). The joint action by the province and the municipalities in collaboration with the local business community could be seen as an example of multi-level governance (Lombardi et al., 2016).

Researchers have investigated local forms of collaboration within local government, with the active involvement of citizens and stakeholders, and acknowledge that public acceptance is key to the successful implementation of policies (Larsen and Gunnarsson-Östling, 2009; Musall and Kuik, 2011; Pollak et al., 2011; Christoforidis et al., 2013; Pasimeni et al., 2014; Lee and Painter, 2015). Achieving ambitious targets would need leadership, enhanced multi-level governance, vision and widespread participation in transformative change (Castán Broto and Bulkeley, 2013; Rosenzweig et al., 2015; Castán Broto, 2017;
Fazey et al., 2017; Wamsler, 2017; Romero-Lankao et al., 2018). The Section 5.6.4 case studies of climate-resilient development pathways, at state and community scales, show that participation, social learning and iterative decision-making are governance features of strategies that deliver mitigation, adaptation, and sustainable development in a fair and equitable manner. Other insights include that incremental voluntary changes are amplified through community networking, poly-centric governance (Dorsch and Flachsland, 2017) and partnerships and long-term change to governance systems at multiple levels (Stevenson and Dryzek, 2014; Lövbrand et al., 2017; Pichler et al., 2017; Termeer et al., 2017).

[END BOX 4.1 HERE]

Multilevel governance includes adaptation across local, regional, and national scales (Adger et al., 2005). The whole-of-government approach to understanding and influencing climate change policy design and implementation puts analytical emphasis on how different levels of government and different types of actors (e.g., public and private) can constrain or support local adaptive capacity (Corfee-Morlot et al., 2011), including the role of the civil society. National governments, for example, have been associated with enhancing adaptive capacity through building awareness of climate impacts, encouraging economic growth, providing incentives, establishing legislative frameworks conducive to adaptation, and communicating climate change information (Berrang-Ford et al., 2014; Massey et al., 2014; Austin et al., 2015; Henstra, 2016; Massey and Huitema, 2016). Local governments, on the other hand, are responsible for delivering basic services and utilities to the urban population, and protecting their integrity from the impacts of extreme weather (Austin et al., 2015; Cloutier et al., 2015; Nalau et al., 2015; Araos et al., 2016b). National policies and transnational governance could be seen as complementary, rather than competitors, and strong national policies favour sub- and non-state actors to engage transnationally (Andonova et al., 2017). Local initiatives are complementary with higher level policies and can be integrated in the multi-level governance system (Fuhr et al., 2018).

A multilevel approach considers that adaptation planning is affected by scale mismatches between the local manifestation of climate impacts and the diverse scales at which the problem is driven (Shi et al., 2016). Multilevel approaches may be relevant in low-income countries where limited financial resources and human capabilities within local governments often lead to greater dependency on national governments and other (donor) organisations, to strengthen adaptation responses (Donner et al., 2016; Adenle et al., 2017). National governments or international organisations may motivate urban adaptation externally through broad policy directives or projects by international donors. Municipal governments on the other hand work within the city to spur progress on adaptation. Individual political leadership in municipal government, for example, has been cited as a factor driving adaptation policy of early adapters in Quito, Ecuador, and Durban, South Africa (Anguelovski et al., 2014), and for adaptation more generally (Smith et al., 2009). Adaptation pathways can help identify maladaptive actions (Juhola et al., 2016; Magnan et al., 2016; Gajjar et al., 2018) and encourage social learning approaches across multiple levels of stakeholders in sectors such as marine biodiversity and water supply (Bosomworth et al., 2015; Butler et al., 2015; van der Brugge and Roosjen, 2015).

Box 4.2 exemplifies how multilevel governance has been used for watershed management in different basins, given the impacts on water sources (Section 3.4.2).

[START BOX 4.2 HERE]

**Box 4.2: Watershed Management in a 1.5°C World**

Water management is necessary if the global community would adapt to 1.5°C-consistent pathways. Cohesive planning that includes numerous stakeholders will be required to improve access, utilisation and efficiency of water use and ensure hydrologic viability.

**Response to drought and El Niño Southern Oscillation (ENSO) in Southern Guatemala**

Hydro-meteorological events, including the ENSO, have impacted Central America (Steinhoff et al., 2014; Chang et al., 2015; Maggioni et al., 2016) and are projected to increase in frequency during a 1.5°C
The 2014–2016 ENSO damaged agriculture, seriously impacting rural communities.

In 2016, the Climate Change Institute, in conjunction with local governments, the private sector, communities and human rights organisations, established dialogue tables for different watersheds to discuss water usage amongst stakeholders and plans to mitigate the effects of drought, ameliorate social tension, and map water use of watersheds at risk. The goal was to encourage better water resource management and to enhance ecological flow through improved communication, transparency, and coordination amongst users. These goals were achieved in 2017 when each previously affected river reached the Pacific Ocean with at least its minimum ecological flow (Guerra, 2017).

**Drought management through the Limpopo Watercourse Commission**

The governments sharing the Limpopo river basin (Botswana, Mozambique, South Africa and Zimbabwe) formed the Limpopo Watercourse Commission in 2003 (Nyagwambo et al., 2008; Mitchell, 2013). It has an advisory body comprised of working groups that assess water use and sustainability, decides national level distribution of water access, and supports disaster and emergency planning. The Limpopo basin delta is highly vulnerable (Tessler et al., 2015), and is associated with a lack of infrastructure and investment capacity, requiring increased economic development together with plans for vulnerability reduction (Tessler et al., 2015) and water rights (Swatuk, 2015). The high vulnerability is influenced by gender inequality, limited stakeholder participation and institutions to address unequal water access (Mehta et al., 2014). The implementation of Integrated Water Resources Management (IWRM) would need to consider pre-existing social, economic, historical and cultural contexts (Merrey, 2009; Mehta et al., 2014). The Commission therefore could play a role in improving participation and in providing an adaptable and equitable strategy for cross-border water sharing (Ekblom et al., 2017).

**Flood management in the Danube**

The Danube River Protection Convention is the official instrument for cooperation on transboundary water governance between the countries that share the Danube Basin. The International Commission for the Protection of the Danube River (ICPDR) provides a strong science-policy link through expert working groups dealing with issues including governance, monitoring and assessment and flood protection (Schmeier, 2014). The Trans-National Monitoring Network (TNMN) was developed to undertake comprehensive monitoring of water quality (Schmeier, 2014). Monitoring of water quality constitutes almost 50% of ICPDR's scientific publications, which also works on governance, basin planning, monitoring, and IWRM, indicating the importance. The ICPDR is an example of IWRM ‘coordinating groundwater, surface water abstractions, flood management, energy production, navigation, and water quality’ (Hering et al., 2014).

**Cross-Chapter Box 11: Consistency Between Nationally Determined Contributions and 1.5°C Scenarios**

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**Mitigation**

1. Introduction

There is high agreement that Nationally Determined Contributions (NDCs) are important for the global response to climate change and represent an innovative bottom-up instrument in climate change governance (Section 4.4.1), with contributions from all signatory countries (den Elzen et al., 2016; Rogelj et al., 2016; Vandyck et al., 2016; Luderer et al., 2018; Vrontisi et al., 2018). The global emission projection resulting...
from full implementation of the NDCs represent an improvement compared to business as usual (Rogelj et al., 2016) and current policies scenarios to 2030 (den Elzen et al., 2016; Vrontisi et al., 2018). Most G20 economies would require new policies and actions to achieve their NDC targets (den Elzen et al., 2016; Vandyck et al., 2016; Kuramochi et al., 2017; UNEP, 2017b).

2. The effect of NDCs on global Greenhouse Gas (GHG) emissions

Several studies estimate global emission levels that would be achieved under the NDCs (e.g., den Elzen et al., 2016; Luderer et al., 2016; Rogelj et al., 2016, 2017; Vandyck et al., 2016; Rose et al., 2017; Vrontisi et al., 2018). Rogelj et al. (2016) and (UNEP, 2017b) concluded that the full implementation of the unconditional and conditional NDCs are expected to result in global GHG emissions of about 55 (52–58) and 53 (50–54) GtCO₂-eq yr⁻¹, respectively (Cross-Chapter Box 11, Figure 1 below).

Cross-Chapter Box 11, Figure 1: GHG emissions are all expressed in units of CO₂-equivalence computed with 100-year Global Warming Potentials (GWPs) reported in IPCC SAR, while the emissions of the 1.5°C and 2°C scenarios in Table 2.4 are reported using the 100-year GWPs reported in IPCC AR4, and are hence about 3% higher. Using IPCC AR4 instead of SAR GWP values is estimated to result in a 2-3% increase in estimated 1.5°C and 2°C emissions levels in 2030. Source: based on Rogelj et al. (2016) and UNEP (2017b).

3. The effect of NDCs on temperature increase and carbon budget

Estimates of global average temperature increase are 2.9–3.4°C above preindustrial levels with a greater than 66% probability by 2100 (Rogelj et al., 2016; UNEP, 2017b), under a full implementation of unconditional NDCs and a continuation of climate action similar to that of the NDCs. Full implementation of the conditional NDCs would lower the estimates by about 0.2°C by 2100. As an indication of the carbon budget implications of NDC scenarios, Rogelj et al. (2016) estimated cumulative emissions in the range of 690 to 850 GtCO₂ for the period 2011–2030 if the NDCs are successfully implemented. The carbon budget for post-2010 till 2100 emissions compatible with staying below 1.5°C with a 50–66% probability was estimated at 550–600 GtCO₂ (Clarke et al., 2014; Rogelj et al., 2016), which will be well exceeded by 2030 at full implementation of the NDCs. This estimate has been updated (Section 2.2 and Section 2.3.1).
4. The 2030 emissions gap with 1.5°C and urgency of action
As the 1.5°C pathways require reaching carbon neutrality by mid-century, the NDCs alone are not sufficient, as they have a time horizon until 2030. (Rogelj et al., 2016; Hof et al., 2017) have used results or compared NDC pathways with emissions pathways produced by Integrated Assessment Models (IAMs) assessing the contribution of NDCs to achieve the 1.5°C targets. There is high agreement that current NDC emission levels are not in line with pathways that limit warming to 1.5°C by the end of the century (Rogelj et al., 2016, 2017; Hof et al., 2017; UNEP, 2017b; Vrontisi et al., 2018). The median 1.5°C emissions gap (>66% chance) for the full implementation of both the conditional and unconditional NDCs for 2030 is 26 (19–29) to 28 (22–33) GtCO₂-eq (Cross-Chapter Box 11, Figure 1 above).

Studies indicate important trade-offs of delaying global emissions reductions (Sections 2.3.5 and 2.5.1). AR5 identified flexibility in 2030 emission levels when pursuing a 2°C objective (Clarke et al., 2014) indicating that strongest trade-offs for 2°C pathways could be avoided if emissions are limited to below 50 GtCO₂-eq yr⁻¹ in 2030 (here computed with the GWP–100 metric of the IPCC SAR). New scenario studies show that full implementation of the NDCs by 2030 would imply much deeper and faster emission reductions beyond 2030 in order to meet 2°C, and also higher costs and efforts of negative emissions (Fujimori et al., 2016; Sanderson et al., 2016; Rose et al., 2017; van Soest et al., 2017; Luderer et al., 2018). However, no flexibility has been found for 1.5°C pathways (Luderer et al., 2016; Rogelj et al., 2017) indicating that post–2030 emissions reductions required to remain within a 1.5°C compatible carbon budget during the 21st century (Section 2.2) are not within the feasible operating space of IAMs. This indicates that failing to reach a 1.5°C pathway are significantly increased (Riahi et al., 2015), if near-term ambition is not strengthened beyond the level implied by current NDCs.

Accelerated and stronger short-term action and enhanced longer-term national ambition going beyond the NDCs would be needed for 1.5°C-consistent pathways. Implementing deeper emissions reduction than current NDCs would imply action towards levels identified in Section 2.3.3, either as part of or over-delivering on NDCs.

5. The impact of uncertainties on NDC emission levels
The measures proposed in NDCs are not legally binding (Nemet et al., 2017), further impacting estimates of anticipated 2030 emission levels. The aggregation of targets results in high uncertainty (Rogelj et al., 2017), which could be reduced with clearer guidelines for compiling future NDCs focused more on energy accounting (Rogelj et al., 2017) and increased transparency and comparability (Pauw et al., 2018).

Many factors would influence NDCs global aggregated effects, including: (1) variations in socioeconomic conditions, (Gross Domestic Product, GDP, and population growth), (2) uncertainties in historical emission inventories, (3) conditionality of certain NDCs, (4) definition of NDC targets as ranges instead of single values, (5) the way in which renewable energy targets are expressed, and (6) the way in which traditional biomass use is accounted for. Additionally, there are land-use mitigation uncertainties (Forssell et al., 2016; Grassi et al., 2017). Land-use options play a key role in many country NDCs, however, many analyses on NDCs do not use country estimates on land-use emissions, but use model estimates, mainly because of the large difference in estimating the "anthropogenic" forest sink between countries and models (Grassi et al., 2017).

7. Comparing countries’ NDC ambition (equity, cost optimal allocation and other indicators)
Various assessment frameworks have been proposed to analyse, benchmark and compare NDCs, and indicate possible strengthening, based on equity and other indicators (Aldy et al., 2016; den Elzen et al., 2016; Höhne et al., 2017; Jiang et al., 2017; Holz et al., 2018). There is large variation in conformity/fulfillment with equity principles across NDCs and countries. Studies use assessment frameworks based on six effort sharing categories in the AR5 (Clarke et al., 2014) with the principles of ‘responsibility’, ‘capability’ and ‘equity’ (Höhne et al., 2017; Pan et al., 2017; Robiou du Pont et al., 2017). There is an important methodological gap in the assessment of the NDCs’ fairness and equity implications, partly due to lack of information on countries’ own assessment (Winkler et al., 2017). Implementation of Article 2.2 of the Paris Agreement could reflect equity and the principle of common but differentiated
responsibilities and respective capabilities, due to different national circumstances and different interpretations of equity principles (Lahn, 2017; Lahn and Sundqvist, 2017).

Adaptation

The Paris Agreement recognises adaptation by establishing a global goal for adaptation (Kato and Ellis, 2016; Rajamani, 2016; Kinley, 2017; Lesnikowski et al., 2017; UNEP, 2017a). This is assessed qualitatively, as achieve a temperature goal, would determine the level of ambition of addressing adaptation to consequent risks and impacts (Rajamani, 2016). Countries can include domestic adaptation goals in their NDCs, which together with National Adaptation Plans (NAPs) give countries flexibility to design and adjust their adaptation trajectories as their needs evolve and as progress is evaluated over time. A challenge for assessing progress on adaptation globally is the aggregation of many national adaptation actions and approaches. Knowledge gaps still remain about how to design measurement frameworks that generate and integrate national adaptation data without placing undue burdens on countries (UNEP, 2017a).

The Paris Agreement stipulates that adaptation communications shall be submitted as a component of or in conjunction with other communications, such as an NDC, a NAP, or a National Communication. Of the 197 Parties to the UNFCCC, 140 NDCs have an adaptation component, almost exclusively from developing countries. NDC adaptation components could be an opportunity for enhancing adaptation planning and implementation by highlighting priorities and goals (Kato and Ellis, 2016). At the national level they provide momentum for the development of NAPs and raise the profile of adaptation (Pauw et al., 2016b, 2018). The Paris Agreement’s transparency framework includes adaptation, through which ‘adaptation communication’ and accelerated adaptation actions are submitted and reviewed every five years (Hermwille, 2016; Kato and Ellis, 2016). This framework, unlike others used in the past, is applicable to all countries taking into account differing capacities amongst Parties (Rajamani, 2016).

Adaptation measures presented in qualitative terms include sectors, risks and vulnerabilities that are seen as priorities by the Parties. Sectoral coverage of adaptation actions identified in NDCs is uneven, with adaptation primarily reported to focus on the water sector (71% of NDCs with adaptation component), agriculture (63%), and health (54%), and biodiversity/ecosystems (50%) (Pauw et al., 2016b, 2018).

[END CROSS-CAPITOL BOX 11 HERE]

4.4.2 Enhancing Institutional Capacities

The implementation of sound responses and strategies to enable a transition to 1.5°C world would require strengthening governance and scaling up institutional capacities, particularly in developing countries (Adenle et al., 2017; Rosenbloom, 2017). Building on the characterisation of governance in Section 4.4.1, this section examines the necessary institutional capacity to implement actions to limit warming to 1.5°C and adapt to the consequences. This takes into account a plurality of regional and local responses, as institutional capacity is highly context-dependent (North, 1990; Lustick et al., 2011).

Institutions would need to interact with one another and align across scales to ensure that rules and regulations are followed (Chaffin and Gunderson, 2016; Young, 2016). The institutional architecture required for a 1.5°C world would include the growing proportion of the world’s population that live in peri-urban and informal settlements and engage in informal economic activity (Simone and Pieterse, 2017). This population, amongst the most exposed to perturbed climates in the world (Hallegatte et al., 2017), is also beyond the direct reach of some policy instruments (Jaglin, 2014; Thieme, 2017). Strategies that accommodate the informal rules of the game adopted by these populations have large chances of success (McGranahan et al., 2016; Kaika, 2017).

The goal for strengthening implementation is to ensure that these rules and regulations embrace equity, equality and poverty alleviation along 1.5°C-consistent pathways (mitigation) and enables the building of
adaptive capacity that together, will enable sustainable development and poverty reduction.

Rising to the challenge of a transition to a 1.5°C world would require enhancing institutional climate change capacities along multiple dimensions presented below.

4.4.2.1 Capacity for Policy Design and Implementation

The enhancement of institutional capacity for integrated policy design and implementation has long been among the top items on the UN agenda of addressing global environmental problems and sustainable development (UNEP, 2005) (see Section 5.5).

Political stability, an effective regulatory and enforcement framework (e.g., institutions to impose sanctions, collect taxes and to verify building codes), access to a knowledge base and the availability of resources, would be needed at various governance levels, to address a wide range of stakeholders, and their concerns. The strengthening of the global response would need to support these with different interventions, in the context of sustainable development (Pasquini et al., 2015) (Section 5.5.1).

Given the scale of change needed to achieve 1.5°C, strengthening the response capacity of relevant institutions are best addressed in ways that take advantage of existing decision-making processes in local and regional governments and within cities and communities (Romero-Lankao et al., 2013), and draw upon diverse knowledge sources including Indigenous and local knowledge (Nakashima et al., 2012; Smith and Sharp, 2012; Mistry and Berardi, 2016; Tschakert et al., 2017). Examples of successful local institutional processes and the integration of local knowledge in climate-related decisions making are provided in Box 4.3 and Box 4.4.

Implementing 1.5°C-relevant strategies would require well-functioning legal frameworks to be in place, in conjunction with clearly defined mandates, rights and responsibilities to enable the institutional capacity to deliver (Romero-Lankao et al., 2013). As an example, current rates of urbanisation occurring in cities with a lack of institutional capacity for effective land-use planning, zoning and infrastructure development, result in unplanned, informal urban settlements which are vulnerable to climate impacts. It is common for 30–50% of urban populations in low-income nations to live in informal settlements with no regulatory infrastructure (Revi et al., 2014b). For example, in Huambo (Angola), a classified ‘urban’ area extends 20km west of the city and is predominantly made up of ‘unplanned’ urban settlements (Smith and Jenkins, 2015).

Internationally, the Paris Agreement process has aimed at enhancing the capacity of decision-making institutions in developing countries to support effective implementation. These efforts are particularly reflected in Article 11 of the Paris Agreement on capacity building (the creation of the Paris Committee on Capacity Building), Article 13 (the creation of the Capacity Building Initiative on Transparency), as well as Article 15 on compliance (UNFCCC, 2015).

[START BOX 4.3 HERE]

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<th>Box 4.3: Indigenous Knowledge and Community Adaptation</th>
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Indigenous knowledge refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings (UNESCO, 2017). This knowledge can underpin the development of adaptation and mitigation strategies (Ford et al., 2014b; Green and Minchin, 2014; Pearce et al., 2015; Savo et al., 2016).

Climate change is an important concern for the Maya, who depend on climate knowledge for their livelihood. In Guatemala, the collaboration between the Mayan K’iché population of the Nahualate river basin and the Climate Change Institute has resulted in a catalogue of Indigenous knowledge, used to identify indicators for watershed meteorological forecasts (Yax L. and Álvarez, 2016). These indicators are relevant but would need continuous assessment if their continued reliability is to be confirmed (Nyong et al., 2007;
Alexander et al., 2011; Mistry and Berardi, 2016). For more than ten years, Guatemala has maintained an 'Indigenous Table for Climate Change', to enable the consideration of indigenous knowledge in disaster management and adaptation development.

In Tanzania, increased variability of rainfall is challenging Indigenous and local communities (Mahoo et al., 2015; Sewando et al., 2016). The majority of agro-pastoralists use Indigenous knowledge to forecast seasonal rainfall, relying on observations of plant phenology, bird, animal, and insect behaviour, the sun and moon, and wind (Chang'a et al., 2010; Elia et al., 2014; Shaffer, 2014). Increased climate variability has raised concerns about the reliability of these indicators (Shaffer, 2014), therefore, initiatives have focused on the co-production of knowledge, through involving local communities in monitoring and discussing the implications of indigenous knowledge and meteorological forecasts (Shaffer, 2014), and creating local forecasts by utilising the two sources of knowledge (Mahoo et al., 2013). This has resulted in increased documentation of Indigenous knowledge, understanding of relevant climate information amongst stakeholders, and adaptive capacity at the community-level (Mahoo et al., 2013, 2015; Shaffer, 2014).

The Pacific Islands and Small Island Developing States (SIDS) are vulnerable to the effects of climate change, but the cultural resilience of Pacific Island inhabitants is also recognized (Nunn et al., 2017). In Fiji and Vanuatu, strategies used to prepare for cyclones include building reserve emergency supplies, and utilising farming techniques to ensure adequate crop yield to combat potential losses from a cyclone or drought (McNamara and Prasad, 2014; Granderson, 2017; Pearce et al., 2017). Social cohesion and kinship are important in responding and preparing for climate-related hazards, including the role of resource sharing, communal labour, and remittances (McMillen et al., 2014; Gawith et al., 2016; Granderson, 2017). There is a concern that Indigenous knowledge will weaken, a process driven by westernisation and disruptions in established bioclimatic indicators and traditional planning calendars (Granderson, 2017). In some urban settlements, it has been noted that cultural practices (e.g., prioritising the quantity of food over the quality of food) can lower food security through dispersing limited resources and by encouraging the consumption of cheap but nutrient-poor foods (McCubbin et al., 2017) (See Cross-Chapter Box 6 on Food Security in Chapter 3). Indigenous practices also encounter limitations, particularly in-relation to sea level rise (Nunn et al., 2017).

[END BOX 4.3 HERE]

[START BOX 4.4 HERE]

Box 4.4: Manizales, Colombia: Supportive National Government and Localised Planning and Integration as an Enabling Condition for Managing Climate and Development Risks

Institutional reform in the city of Manizales, Colombia helps identify three important features of an enabling environment: integrating climate change adaptation, mitigation and disaster risk management at the city-scale; the importance of decentralised planning and policy formulation within a supportive national policy environment; and the role of a multi-sectoral framework in mainstreaming climate action in development activities.

Manizales is exposed to risks caused by rapid development and expansion in a mountainous terrain exposed to seismic activity and periodic wet and dry spells. Local assessments expect climate change to amplify the risk of disasters (Carreño et al., 2017). The city is widely recognised for its longstanding urban environmental policy (Biomanizales) and local environmental action plan (Bioplan), and has been integrating environmental planning in its development agenda for nearly two decades (Velásquez Barrero, 1998; Hardoy and Velásquez Barrero, 2014). When the city’s environmental agenda was updated in 2014 to reflect climate change risks, assessments were conducted in a participatory manner at the street and neighbourhood level (Hardoy and Velásquez Barrero, 2016).

The creation of a new Environmental Secretariat assisted in coordination and integration of environmental policies, disaster risk management, development and climate change (Leck and Roberts, 2015). Planning in Manizales remains mindful of steep gradients, through its longstanding Slope Guardian...
discuss the benefits of financial instruments in adaptation, including the provision of post-emission reductio...public financial institutions are limited by bo...in the ordinary course of business, while concessional financing would require taxpayer support for subsidisation. Special efforts and innovative approaches would be needed to address these challenges, for example the creation of special institutions that underwrite the value of emission reductions using auctioned price floors (Bodnar et al., 2018) to deal with price volatility.

Financial institutions are equally important for adaptation. Linnerooth-Bayer and Hochrainer-Stigler (2015) discuss the benefits of financial instruments in adaptation, including the provision of post-disaster finances.
for recovery and pre-disaster security necessary for climate adaptation and poverty reduction. Pre-disaster financial instruments and options include insurance, such as index-based weather insurance schemes, catastrophe bonds, and laws to encourage insurance purchasing. The development and enhancement of microfinance institutions to ensure social resilience and smooth transitions in the adaptation to climate change impacts could be an important local institutional innovation (Hammill et al., 2008).

4.4.2.4 Co-Operative Institutions and Social Safety Nets

Effective co-operative institutions and social safety nets may help address energy access, adaptation, as well as distributional impacts during the transition to 1.5°C-consistent pathways and enabling sustainable development. Not all countries have the institutional capabilities to design and manage these. Social capital for adaptation in the form of bonding, bridging, and linking social institutions has proved to be effective in dealing with climate crises at the local, regional, and national levels (Aldrich et al., 2016).

The shift towards sustainable energy systems in transitioning economies could impact the livelihoods of large populations, in traditional and legacy employment sectors. The transition of selected EU Member States to biofuels, for example, caused anxiety among farmers, who lacked confidence in the biofuel crop market. Enabling contracts between farmers and energy companies, involving local governments, helped create an atmosphere of confidence during the transition (McCormick and Kåberger, 2007).

How do broader socio-economic processes influence urban vulnerabilities and thereby underpin climate change adaptation? This is a systemic challenge originating from a lack of collective societal ownership of the responsibility for climate risk management. Numerous explanations, help explain this from competing time-horizons due to self-interest of stakeholders to a more ‘rational’ conception of risk assessment, measured across a risk-tolerance spectrum (Moffatt, 2014).

Self-governing and self-organised institutional settings where equipment and resource systems are commonly owned and managed can potentially generate a much higher diversity of administration solutions, than other institutional arrangements where energy technology and resource systems are either owned and administered individually in market settings or via a central authority (e.g., the state). They can also increase the adaptability of technological systems, while reducing their burden on the environment (Labanca, 2017). Educational, learning and awareness-building institutions can help strengthen the societal response to climate change (Butler et al., 2016; Thi Hong Phuong et al., 2017).

4.4.3 Enabling Lifestyle and Behavioural Change

Humans are at the centre of global climate change: their actions cause anthropogenic climate change, and social change is key to effectively respond to climate change (Vlek and Steg, 2007; Dietz et al., 2013; ISSC and UNESCO, 2013; Hackmann et al., 2014). Chapter 2 shows that 1.5°C-consistent pathways assume substantial changes in behaviour. This section assesses the potential of behaviour change, as the Integrated Assessment Models (IAMs) applied in Chapter 2 do not comprehensively assess this potential.

Table 4.8 shows examples of mitigation and adaption actions relevant for 1.5°C-consistent pathways. Reductions in population growth can reduce overall carbon demand and mitigate climate change (Bridgeman, 2017), particularly when population growth is accompanied with increases in affluence and carbon-intensive consumption (Rosa and Dietz, 2012; Clayton et al., 2017). Mitigation actions with a substantial carbon emission reduction potential (see Figure 4.3) that individuals may readily adopt would have the most climate impact (Dietz et al., 2009).
Table 4.8: Examples of mitigation and adaptation behaviours relevant for 1.5°C (Dietz et al., 2009; Jabeen, 2014; Taylor et al., 2014; Araos et al., 2016b; Steg, 2016; Stern et al., 2016b; Creutzig et al., 2018)

<table>
<thead>
<tr>
<th>Climate action</th>
<th>Type of action</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitigation</td>
<td>Implementing resource efficiency in building</td>
<td>Insulation, Low-carbon building materials</td>
</tr>
<tr>
<td></td>
<td>Adopting low-emission innovations</td>
<td>Electric vehicles, Heat pumps, district heating and cooling</td>
</tr>
<tr>
<td></td>
<td>Adopting energy efficient appliances</td>
<td>Energy-efficient heating or cooling, Energy-efficient appliances</td>
</tr>
<tr>
<td></td>
<td>Energy-saving behaviour</td>
<td>Walking or cycling rather than drive short distances, Using mass transit rather than flying, Lower temperature for space heating, Line drying of laundry, Reducing food waste</td>
</tr>
<tr>
<td></td>
<td>Buying products and materials with low GHG emissions during production and transport</td>
<td>Reducing meat and dairy consumption, Buying local, seasonal food, Replacing aluminium products by low-GHG alternatives</td>
</tr>
<tr>
<td></td>
<td>Organisational behaviour</td>
<td>Designing low-emission products and procedures, Replacing business travel by videoconferencing</td>
</tr>
<tr>
<td>Adaptation</td>
<td>Growing different crops and raising different animal varieties</td>
<td>Using crops with higher tolerance for higher temperatures or CO₂ elevation</td>
</tr>
<tr>
<td></td>
<td>Flood protective behaviour</td>
<td>Elevating barriers between rooms, Building elevated storage spaces, Building drainage channels outside the home</td>
</tr>
<tr>
<td></td>
<td>Heat protective behaviour</td>
<td>Staying hydrated, Moving to cooler places, Installing green roofs</td>
</tr>
<tr>
<td></td>
<td>Efficient water use during water shortage crisis</td>
<td>Rationing water, Constructing wells or rainwater tanks</td>
</tr>
<tr>
<td>Mitigation &amp; adaptation</td>
<td>Adoption of renewable energy sources</td>
<td>Solar PV, Solar water heaters</td>
</tr>
<tr>
<td></td>
<td>Citizenship behaviour</td>
<td>Engage through civic channels to encourage or support planning for low-carbon climate-resilient development</td>
</tr>
</tbody>
</table>
Various policy approaches and strategies can encourage and enable climate actions by individuals and organisations. Policy approaches would be more effective when they address key contextual and psycho-social factors influencing climate actions, which differ across contexts and individuals (Steg and Vlek, 2009; Stern, 2011). This suggests that diverse policy approaches would be needed in 1.5°C-consistent pathways in different contexts and regions. Combinations of policies that target multiple barriers and enabling factors simultaneously can be more effective (Nissinen et al., 2015).

In the US and Europe, GHG emissions are lower when legislators have strong environmental records (Jensen and Spoon, 2011; Dietz et al., 2015). Political elites affect public concern about climate change: pro-climate action statements increased concern, while anti-climate action statements and anti-environment voting reduced public concern about climate change (Brulle et al., 2012). In the European Union, individuals worry more about climate change and engage more in climate actions in countries where political party elites are united rather than divided in their support for environmental issues (Sohlberg, 2017).

This section discusses how to enable and encourage behaviour and lifestyle changes that strengthen implementation of 1.5°C-consistent pathways by assessing psycho-social factors related to climate action, as well as the effects and acceptability of policy approaches targeting climate actions that are consistent with 1.5°C. Box 4.5 and Box 4.6 illustrate how these have worked in practice.

4.4.3.1 Factors Related to Climate Actions

Mitigation and adaptation behaviour is affected by many factors that shape which options are feasible and considered by individuals. Besides contextual factors (see other sub-sections in Section 4.4), these include abilities and different types of motivation to engage in behaviour.

4.4.3.1.1 Ability to engage in climate action

Individuals more often engage in adaptation (Gebrehiwot and van der Veen, 2015; Koerth et al., 2017) and mitigation behaviour (Pisano and Lubell, 2017) when they are or feel more capable to do so. Hence, it is important to enhance ability to act on climate change, which depends on income and knowledge, among other things. A higher income is related to higher CO₂ emissions; higher income groups can afford more carbon-intensive lifestyles (Lamb et al., 2014; Dietz et al., 2015; Wang et al., 2015). Yet, low-income groups may lack resources to invest in energy efficient technology and refurbishments (Andrews-Speed and Ma, 2016) and adaptation options (Wamsler, 2007; Fleming et al., 2015b; Takahashi et al., 2016). Adaptive capacity further depends on gender roles (Jabeen, 2014; Bunce and Ford, 2015), technical capacities and knowledge (Feola et al., 2015; Eakin et al., 2016; Singh et al., 2016b).

Knowledge of the causes and consequences of climate change and on ways to reduce GHG emissions is not always accurate (Bord et al., 2000; Whitmarsh et al., 2011; Tobler et al., 2012), which can inhibit climate actions, even when people would be motivated to act. For example, people overestimate savings from low-energy activities, and underestimate savings from high-energy activities (Attari et al., 2010). They know little about ‘embodied’ energy (i.e., energy needed to produce products; Tobler et al., 2011), including meat (de Boer et al., 2016b). Some people mistake weather for climate (Reynolds et al., 2010), or conflate climate risks with other hazards, which can inhibit adequate adaptation (Taylor et al., 2014).

More knowledge on adaptation is related to higher engagement in adaptation actions in some circumstances (Bates et al., 2009; van Kasteren, 2014; Hagen et al., 2016). How adaptation is framed in the media can influence the types of options viewed as important in different contexts (Boykoff et al., 2013; Moser, 2014; Ford and King, 2015).

Knowledge is important, but is often not sufficient to motivate action (Trenberth et al., 2016). Climate change knowledge and perceptions are not strongly related to mitigation actions (Hornsey et al., 2016). Direct experience of events related to climate change influences climate concerns and actions (Blennow et al., 2012; Taylor et al., 2014), more so than second-hand information (Spence et al., 2011; Myers et al.,...
2012; Demski et al., 2017); high impact events with low frequency are remembered more than low impact regular events (Meze-Hausken, 2004; Singh et al., 2016b; Sullivan-Wiley and Short Gianotti, 2017). Personal experience with climate hazards strengthens motivation to protect oneself (Jabeen, 2014) and enhances adaptation actions (Bryan et al., 2009; Berrang-Ford et al., 2011; Demski et al., 2017), although this does not always translate into proactive adaptation (Taylor et al., 2014). Collectively constructed notions of risk and expectations of future climate variability shape risk perception and adaptation behaviour (Singh et al., 2016b). People with particular political views and those who emphasise individual autonomy may reject climate science knowledge and believe that there is widespread scientific disagreement about climate change (Kahan, 2010; O’Neill et al., 2013), inhibiting support for climate policy (Ding et al., 2011; McCright et al., 2013). This may explain why extreme weather experiences enhances preparedness to reduce energy use among left- but not right-leaning voters (Ogunbode et al., 2017).

4.4.3.1.2 Motivation to engage in climate action
Climate actions are more strongly related to motivational factors, reflecting individuals’ reasons for actions, such as values, ideology and worldviews than to knowledge (Hornsey et al., 2016). People consider various types of costs and benefits of actions (Gölz and Hahnel, 2016), and focus on consequences that have implications for the values they find most important (Dietz et al., 2013; Hahnel et al., 2015; Steg, 2016). This implies that different individuals consider different consequences when making choices. People who strongly value protecting the environment and other people generally more strongly consider climate impact and act more on climate change than those who strongly endorse hedonic and egoistic values (Taylor et al., 2014; Steg, 2016). People are more prone to adopt sustainable innovations when they are more open to new ideas (Jansson, 2011; Wolske et al., 2017). Further, a free-market ideology is associated with weaker climate change beliefs (McCright and Dunlap, 2011; Hornsey et al., 2016), and a capital-oriented culture tends to promote activity associated with GHG emissions (Kasser et al., 2007).

Some Indigenous populations believe it is arrogant to predict the future, and some cultures have belief systems that interpret natural phenomena as sentient, where thoughts and words are believed to influence the future, with people reluctant to talk about negative future possibilities (Natcher et al., 2007; Flynn et al., 2018). Integrating these considerations into the design of adaptation and mitigation policy is important (Cochran et al., 2013; Chapin et al., 2016; Brugnach et al., 2017; Flynn et al., 2018).

People are more prone to act on climate change when individual benefits of actions exceed costs (Steg and Vlek, 2009; Kardooni et al., 2016; Wolske et al., 2017). For this reason, people generally prefer adoption of energy-efficient appliances above energy consumption reductions; the latter is perceived as more costly (Poortinga et al., 2003; Steg et al., 2006), although transaction costs can inhibit the uptake of mitigation technology (Mundaca, 2007). Decentralised renewable energy systems are evaluated most favourably when they guarantee independence, autonomy, control and supply security (Ecker, 2017).

Besides, social costs and benefits affect climate action (Farrow et al., 2017). People engage more in climate actions when they think others expect them to do so and when others act as well (Nolan et al., 2008; Le Dang et al., 2014; Truelove et al., 2015; Rai et al., 2016), and when they experience social support (Singh et al., 2016a; Burnham and Ma, 2017; Wolske et al., 2017). Discussing effective actions with peers also encourages climate action (Esham and Garforth, 2013), particularly when individuals strongly identify with their peers (Biddau et al., 2012; Fielding and Hornsey, 2016). Further, individuals may engage in mitigation actions when they think doing so would enhance their reputation (Milinski et al., 2006; Noppers et al., 2014; Kastner and Stern, 2015). Such social costs and benefits can be addressed in climate policy (see Section 4.4.3.2).

Feelings affect climate action (Brosch et al., 2014). Negative feelings related to climate change can encourage adaptation action (Kerstholt et al., 2017; Zhang et al., 2017), while positive feelings associated with climate risks may inhibit protective behaviour (Lefevre et al., 2015). Individuals are more prone to engage in mitigation actions when they worry about climate change (Verplanken and Roy, 2013), and when they expect to derive positive feelings from such actions (Pelletier et al., 1998; Taufik et al., 2016).
Furthermore, collective consequences affect climate actions (Balcombe et al., 2013; Dócì and Vasileiadou, 2015; Kastner and Stern, 2015). People are motivated to see themselves as morally right, which encourages mitigation actions (Steg et al., 2015), particularly when long-term goals are salient (Zaval et al., 2015) and behavioural costs are not too high (Diekmann and Preisendorfer, 2003). Individuals are more prone to engage in climate actions when they believe climate change is occurring, when they are aware of threats caused by climate change and by their inaction, and when they think they can engage in actions that will reduce these threats (Esham and Garforth, 2013; Arunrat et al., 2017; Chatrchywan et al., 2017). The more individuals are concerned about climate change and aware of the negative climate impact of their behaviour, the more they feel responsible for and think their actions can help reduce such negative impacts, which can strengthen their moral norms to act accordingly (Steg and de Groot, 2010; Jakovcevic and Steg, 2013; Chen, 2015; Ray et al., 2017; Wolske et al., 2017; Woods et al., 2017). Individuals may engage in mitigation actions when they see themselves as supportive of the environment (i.e. strong environmental self-identity) (Fielding et al., 2008; van der Werff et al., 2013b; Kashima et al., 2014; Barbarossa et al., 2017); a strong environmental identity strengthens intrinsic motivation to engage in mitigation actions both at home (van der Werff et al., 2013a) and at work (Ruepert et al., 2016). Environmental self-identity is strengthened when people realise they engaged in mitigation actions, which can in turn promote further mitigation actions (van der Werff et al., 2014b).

Individuals are less prone to engage in adaptation behaviour themselves when they rely on external measures such as government interventions (Grothmann and Reusswig, 2006; Wamsler and Brink, 2014a; Armah et al., 2015; Burnham and Ma, 2017) or perceive themselves as protected by god (Gandure et al., 2013; Dang et al., 2014; Cannon, 2015).

4.4.3.1.3 Habits, heuristics and biases

Decisions are often not based on weighing costs and benefits, but on habit or automaticity, both of individuals (Aarts and Dijkstra, 2000; Kloeckner et al., 2003) and within organisations (Dooley, 2017) and institutions (Munck et al., 2014). When habits are strong, individuals are less perceptive of information (Verplanken et al., 1997; Aarts et al., 1998), and may not consider alternatives as long as outcomes are good enough (Marechal, 2010). Habits are mostly only reconsidered when the situation changed significantly (Fuji and Kitamura, 2003; Marechal, 2010; Verplanken and Roy, 2016). Hence, strategies that create the opportunity for reflection and encourage active decisions can break habits (Steg et al., 2017).

Individuals can follow heuristics, or ‘rules of thumb’, in making inferences rather than thinking through all implications of actions, which demands less cognitive resources, knowledge and time (Preston et al., 2013; Frederiks et al., 2015; Gillingham and Palmer, 2017). For example, people tend to think that larger and visible appliances use more energy, which is not always accurate (Cowen and Gatersleben, 2017). They underestimate energy used for water heating and overestimate energy used for lighting (Stern, 2014). When facing choice overload, people may choose the easiest or first available option, which can inhibit energy saving behaviour (Stern and Gardner, 1981; Frederiks et al., 2015). As a result, individuals and firms often strive for satisficing (‘good enough’) outcomes with regard to energy decisions (Wilson and Dowlatabadi, 2007; Klotz, 2011), which can inhibit investments in energy efficiency (Decanio, 1993; Frederiks et al., 2015).

Besides, biases play a role. In Mozambique, farmers displayed omission biases (unwillingness to take adaptation actions with potentially negative consequences to avoid personal responsibility for losses), while policymakers displayed action biases (wanting to demonstrate positive action despite potential negative consequences; Patt and Schröter, 2008). People tend to place greater value on relative losses than gains (Kahneman, 2003). Perceived gains and losses depend on the reference point or status-quo (Kahneman, 2003). Loss aversion and the status-quo bias prevent consumers from switching electricity suppliers (Ek and Söderholm, 2008), to time-of-use electricity tariffs (Nicolson et al., 2017), and to accept new energy systems (Leijten et al., 2014).

Owned inefficient appliances and fossil fuel-based electricity can act as endowments, increasing their value compared to alternatives (Pichert and Katsikopoulos, 2008; Dinner et al., 2011). Uncertainty and loss
aversion lead consumers to undervalue future energy savings (Greene, 2011) and savings from energy efficient technologies (Kolstad et al., 2014). Uncertainties about the performance of products and illiquidity of investments can drive consumers to postpone (profitable) energy efficient investments (Sutherland, 1991; van Soest and Bulte, 2001). People with a higher tendency to delay decisions may engage less in energy saving actions (Lillemo, 2014). Training energy auditors in loss-aversion increased their clients’ investments in energy efficiency improvements (Gonzales et al., 1988). Engagement in energy saving and renewable energy programmes can be enhanced if participation is set as a default option (Pichert and Katsikopoulos, 2008; Ölander and Thøgersen, 2014; Ebeling and Lotz, 2015).

4.4.3.2 Strategies and Policies to Promote Actions on Climate Change

Policy can enable and strengthen motivation to act on climate change via top-down or bottom-up approaches, through informational campaigns, regulatory measures, financial (dis)incentives, and infrastructural and technological changes (Adger et al., 2003; Steg and Vlek, 2009; Henstra, 2016).

Adaptation efforts tend to focus on infrastructural and technological solutions (Ford and King, 2015) with lower emphasis on socio-cognitive and finance aspects of adaptation. For example, flooding policies in cities focus on infrastructure projects and regulation such as building codes, and hardly target individual or household behaviour (Araos et al., 2016b; Georgeson et al., 2016).

Current mitigation policies emphasise infrastructural and technology development, regulation, financial incentives and information provision (Mundaca and Markandya, 2016) that can create conditions enabling climate action, but target only some of the many factors influencing climate actions (see Section 4.4.5.1). They fall short of their true potential if their social and psychological implications are overlooked (Stern et al., 2016a). For example, promising energy-saving or low carbon technology may not be adopted or not be used as intended (Pritoni et al., 2015) when people lack resources and trustworthy information (Stern, 2011; Balcombe et al., 2013).

Financial incentives or feedback on financial savings can encourage climate action (Santos, 2008; Bolderdijk et al., 2011; Maki et al., 2016) (see Box 4.5), but are not always effective (Delmas et al., 2013), and can be less effective than social rewards (Handgraaf et al., 2013) or emphasising benefits for people and the environment (Bolderdijk et al., 2013b; Asensio and Delmas, 2015; Schwartz et al., 2015). The latter can happen when financial incentives reduce a focus on environmental considerations and weaken intrinsic motivation to engage in climate action (Evans et al., 2012; Agrawal et al., 2015; Schwartz et al., 2015). Besides, pursuing small financial gains is perceived to be less worth the effort than pursuing equivalent CO₂ emission reductions (Bolderdijk et al., 2013b; Dogan et al., 2014). Also, people may not respond to financial incentives (e.g., to improve energy efficiency) because they do not trust the organisation sponsoring incentive programmes (Mundaca, 2007) or when it takes too much effort to receive the incentive (Stern et al., 2016a).

[START BOX 4.5 HERE]

**Box 4.5: How Pricing Policy has Reduced Car Use in Singapore, Stockholm and London**

In Singapore, Stockholm and London, car ownership, car use, and Greenhouse Gas (GHG) emissions have reduced because of pricing and regulatory policies and policies facilitating behaviour change. Notably, acceptability of these policies has increased as people experienced their positive effects.

Singapore implemented electronic road pricing in the central business district and at major expressways, a vehicle quota and registration fee system, and investments in mass transit. In the vehicle quota system introduced in 1990, registration of new vehicles is conditional upon a successful bid (via auctioning) (Chu, 2015), costing about 50,000 USD in 2014 (LTA, 2015). The registration tax incentivises purchases of low-emission vehicles via a feebate system. As a result, per capita transport emissions (approximately 1.25 tCO₂/yr⁻¹) and car ownership (107 vehicles per 1000 capita) (LTA, 2017) are substantially lower than in...
cities with comparable income levels. Modal share of public transport was 63% during peak hours in 2013 (LTA, 2013).

The Stockholm congestion charge implemented in 2007 (after a trial in 2006) reduced kilometres driven in the inner city by 16%, and outside the city by 5%; traffic volumes reduced by 20% and remained constant across time despite economic and population growth (Eliasson, 2014). CO₂ emissions from traffic reduced by 2–3% in Stockholm county. Vehicles entering or leaving the city centre were charged during weekdays (except for holidays). Charges were 1–2€ (maximum 6€ per day), being higher during peak hours; taxis, emergency vehicles and busses were exempted. Before introducing the charge, public transport and parking places near mass transit stations were extended. The aim and effects of the charge were extensively communicated to the public. Acceptability of the congestion charge was initially low, but gained support of about two-thirds of the population and all political parties after the scheme was implemented (Eliasson, 2014), which may be related to earmarking the revenues to constructing a motorway tunnel. After the trial, people believed that the charge had more positive effects on environmental, congestion and parking problems while costs increased less than they anticipated beforehand (Schuitema et al., 2010a). The initially hostile media eventually declared the scheme to be a success.

In 2003, a congestion charge was implemented in the Greater London area, with an enforcement and compliance scheme and an information campaign on the functioning of the scheme. Vehicles entering, leaving, driving or parking on a public road in the zone at weekdays at daytime pay a congestion charge of 8€ (until 2005 5€), with some exemptions. Revenues were invested in London’s bus network (80%), cycling facilities, and road safety measures (Leape, 2006). The number of cars entering the zone decreased by 18% in 2003 and 2004. In the charging zone, vehicle kilometres driven decreased by 15% in the first year and a further 6% a year later, while CO₂ emissions from road traffic reduced by 20% (Santos, 2008).

[END BOX 4.5 HERE]

While providing information on the causes and consequences of climate change or on effective climate actions, generally increases knowledge, it often does not encourage engagement in climate actions by individuals (Abrahamse et al., 2005; Ünal et al., 2017) or organisations (Anderson and Newell, 2004). Similarly, media coverage on the UN Climate Summit slightly increased knowledge about the conference but did not enhance motivation to engage personally in climate protection (Brüggemann et al., 2017). Fear-inducing representations of climate change may inhibit action when they make people feel helpless and overwhelmed (O’Neill and Nicholson-Cole, 2009). Energy-related recommendations and feedback (e.g., via performance contracts, energy audits, smart metering) are more effective to promote energy conservation, load shifting in electricity use and sustainable travel choices when framed in terms of losses rather than gains (Gonzales et al., 1988; Wolak, 2011; Bradley et al., 2016; Bager and Mundaca, 2017).

Credible and targeted information at the point of decision can promote climate action (Stern et al., 2016a). For example, communicating the impacts of climate change is more effective when provided right before adaptation decisions are taken (e.g., before the agricultural season) and when bundled with information on potential actions to ameliorate impacts, rather than just providing information on climate projections with little meaning to end users (e.g., weather forecasts, seasonal forecasts, decadal climate trends) (Dorward et al., 2015; Singh et al., 2017). Similarly, heat action plans that provide early alerts and advisories combined with emergency public health measures can reduce heat-related morbidity and mortality (Benmarhnia et al., 2016).

Information provision is more effective when tailored to the personal situation of individuals, demonstrating clear impacts, and resonating with individuals’ core values (Daamen et al., 2001; Abrahamse et al., 2007; Bolderdijk et al., 2013a; Dorward et al., 2015; Singh et al., 2017). Tailored information prevents information overload, and people are more motivated to consider and act upon information that aligns with their core values and beliefs (Campbell and Kay, 2014; Horsey et al., 2016). Also, tailored information can remove barriers to receive and interpret information faced by vulnerable groups, such as the elderly during heat waves (Vandentorren et al., 2006; Keim, 2008). Further, prompts can be effective when they serve as reminders to perform a planned action (Osbandston and Schott, 2012).
Feedback provision is generally effective in promoting mitigation behaviour within households (Abrahamse et al., 2005; Delmas et al., 2013; Karlin et al., 2015) and at work (Young et al., 2015), particularly when provided in real-time or immediately after the action (Abrahamse et al., 2005), which makes the implications of one’s behaviour more salient (Tiefenbeck et al., 2016). Simple information is more effective than detailed and technical data (Wilson and Dowlatabadi, 2007; Ek and Söderholm, 2010; Frederiks et al., 2015). Energy labels (Banerjee and Solomon, 2003; Stadelmann, 2017), visualisation techniques (Pahl et al., 2016), and ambient persuasive technology (Midden and Ham, 2012) can encourage mitigation actions by providing information and feedback in a format that immediately makes sense and hardly requires users’ conscious attention.

Social influence approaches that emphasise what other people do or think can encourage climate action (Clayton et al., 2015), particularly when they involve face-to-face interaction (Abrahamse and Steg, 2013). For example, community approaches, where change is initiated from the bottom-up, can promote adaptation (see Box 4.6) and mitigation actions (Middlemiss, 2011; Seyfang and Haxeltine, 2012; Abrahamse and Steg, 2013), especially when community ties are strong (Weenig and Midden, 1991). Furthermore, providing social models of desired actions can encourage mitigation action (Osbaldeston and Schott, 2012; Abrahamse and Steg, 2013). Social influence approaches that do not involve social interaction, such as social norm, social comparison and group feedback, are less effective, but can be easily administered on a large scale at low costs (Allcott, 2011; Abrahamse and Steg, 2013).

[START BOX 4.6 HERE]

**Box 4.6: Bottom-up Initiatives: Adaptation Responses Initiated by Individuals and Communities**

To effectively adapt to climate change, bottom-up initiatives by individuals and communities are essential, in addition to efforts of governments, organisations, and institutions (Wamsler and Brink, 2014a). This box presents examples of bottom-up adaptation responses and behavioural change.

Fiji increasingly faces a lack of freshwater due to decreasing rainfall and rising temperatures (Deo, 2011; IPCC, 2014a). While some villages have access to boreholes, these are not sufficient to supply the population with freshwater. Villagers are adapting by rationing water, changing diets, and setting up inter-village sharing networks (Pearce et al., 2017). Some villagers take up wage employment to buy food instead of growing it themselves (Pearce et al., 2017). In Kiribati, residents adapt to drought by purchasing rainwater tanks and constructing additional wells (Kuruppu and Liverman, 2011). An important factor that motivated residents of Kiribati to adapt to drought was the perception that they could effectively adapt to the negative consequences of climate change (Kuruppu and Liverman, 2011).

In the Philippines, seismic activity has caused some islands to flood during high tide. While the municipal government offered affected island communities the possibility to relocate to the mainland, residents preferred to stay and implement measures themselves in their local community to reduce flood damage (Laurice Jamero et al., 2017). Migration is perceived as undesirable because island communities have strong place-based identities (Mortreux and Barnett, 2009). Instead, these island communities have adapted to flooding by constructing stilted houses and raising floors, furniture, and roads to prevent water damage (Laurice Jamero et al., 2017). While inundation was in this case caused by seismic activity, this example indicates how island-based communities may respond to rising sea levels caused by climate change.

Adaptation initiatives by individuals may temporarily reduce the impacts of climate change and enable residents to cope with changing environmental circumstances. However, they may not be sufficient to sustain communities’ way of life in the long term. For instance, in Fiji and Kiribati, freshwater and food are projected to become even scarcer in the future, rendering individual adaptations ineffective. Moreover, individuals can sometimes engage in behaviour that may be maladaptive over larger spatio-temporal scales. For example, in the Philippines, many islanders adapt to flooding by elevating their floors using coral stone (Laurice Jamero et al., 2017). Over time, this can harm the survivability of their community, as coral reefs are critical for reducing flood vulnerability (Ferrario et al., 2014). In Maharashtra, India, on-farm ponds are
promoted as rainwater harvesting structures to adapt to dry spells during the monsoon season. However, some individuals fill these ponds with groundwater, leading to depletion of water tables and potentially maladaptive outcomes in the long run (Kale, 2015).

Integration of individuals’ adaptation initiatives with top-down adaptation policy is critical (Butler et al., 2015), as failing to do so may lead individual actors to mistrust authority and can discourage them from undertaking adequate adaptive actions (Wamsler and Brink, 2014a).

Goal setting can promote mitigation action, when goals are not set too low or too high (Loock et al., 2013). Commitment strategies where people make a pledge to engage in climate actions can encourage mitigation behaviour (Abrahamse and Steg, 2013; Lokhorst et al., 2013), particularly when individuals also indicate how and when they will perform the relevant action and anticipate how to cope with possible barriers (i.e., implementation intentions) (Bamberg, 2000, 2002). Such strategies take advantage of individuals’ desire to be consistent (Steg, 2016). Similarly, hypocrisy strategies that make people aware of inconsistencies between their attitudes and behaviour can encourage mitigation actions (Osbaldiston and Schott, 2012).

Actions that reduce climate risks can be rewarded and facilitated, while actions that increase climate risks can be punished and inhibited, and behaviour change can be voluntary (e.g., information provision) or imposed (e.g., by law); voluntary changes that involve rewards are more acceptable than imposed changes that restrict choices (Eriksson et al., 2006, 2008; Steg et al., 2006; Dietz et al., 2007). Policies punishing maladaptive behaviour can increase vulnerability when they reinforce socio-economic inequalities that typically produce the maladaptive behaviour in the first place (W.N. Adger et al., 2003). Change can be initiated by governments at various levels, but also by individuals, communities, profit-making organisations, trade organisations, and other non-governmental actors (Lindenberg and Steg, 2013; Robertson and Barling, 2015; Stern et al., 2016b).

Strategies can target intrinsic versus extrinsic motivation. It may be particularly important to enhance intrinsic motivation so that people voluntarily engage in climate action over and again (Steg, 2016). Endorsement of mitigation and adaptation actions are positively related (Brügger et al., 2015; Carrico et al., 2015); both are positively related to concern about climate change (Brügger et al., 2015). Strategies that target general antecedents that affect a wide range of actions, such as values, identities, worldviews, climate change beliefs, awareness of climate impacts of one’s actions and feelings of responsibility to act on climate change, can encourage consistent actions on climate change (van Der Werff and Steg, 2015; Hornsey et al., 2016; Steg, 2016). Initial climate actions can lead to further commitment to climate action (Juhl et al., 2017), when people learn that such actions are easy and effective (Lauren et al., 2016), when they engaged in the initial behaviour for environmental reasons (Peters et al., 2018), hold strong pro-environmental values and norms (Thøgersen, J., Ölander, 2003), and when initial actions make them realise they are an environmentally-sensitive person, motivating them to act on climate change in subsequent situations so as to be consistent (van der Werff et al., 2014a; Lacasse, 2015, 2016). Yet, some studies suggest that people may feel licensed not to engage in further mitigation actions when they believe they already did their bit (Truelove et al., 2014).

4.4.3.3 Acceptability of Policy and System Changes

Public acceptability can shape, enable or prevent policy and system changes. Acceptability reflects the extent to which policy or system changes are evaluated (un) favourably. Acceptability is higher when people expect more positive and less negative effects of policy and system changes (Perlaviciute and Steg, 2014; Demski et al., 2015; Drews and Van den Bergh, 2016), including climate impacts (Schuitema et al., 2010b). Because of this, policy ‘rewarding’ climate actions is more acceptable than policy ‘punishing’ actions that increase climate risks (Steg et al., 2006; Eriksson et al., 2008). Pricing policy is more acceptable when revenues are earmarked for environmental purposes (Steg et al., 2006; Sælen and Kallbekken, 2011), or redistributed towards those affected (Schuitema and Steg, 2008). Acceptability can increase when people experience
positive effects after a policy has been implemented (Schuitema et al., 2010a; Eliasson, 2014; Weber, 2015); effective policy trials can thus build public support for climate policy.

Climate policy and renewable energy systems are more acceptable when people strongly value other people and the environment, or support egalitarian worldviews, left-wing or green political ideologies (Drews and Van den Bergh, 2016), and less acceptable when people strongly endorse self-enhancement values, or support individualistic and hierarchical worldviews (Dietz et al., 2007; Perlaviciute and Steg, 2014; Drews and Van den Bergh, 2016). Solar radiation modification is more acceptable when people strongly endorse self-enhancement values, and less acceptable when they strongly value other people and the environment (Visschers et al., 2017). Climate policy is more acceptable when people believe climate change is real, when they are concerned about climate change (Hornsey et al., 2016), when they think their actions may reduce climate risks, and when they feel responsible to act on climate change (Steg et al., 2005; Eriksson et al., 2006; Jakovcevic and Steg, 2013; Drews and Van den Bergh, 2016; Kim and Shin, 2017). Stronger environmental awareness is associated with a preference for governmental regulation and behaviour change, rather than free market and technological solutions (Poortinga et al., 2002).

Climate policy is more acceptable when costs and benefits are distributed equally, when nature and future generations are protected (Sjöberg and Drottz-Sjöberg, 2001; Schuitema et al., 2011; Drews and Van den Bergh, 2016), and when fair procedures have been followed, including participation by the public (Dietz, 2013; Bernauer et al., 2016a; Bidwell, 2016) or public society organisations (Bernauer and Gampfer, 2013). Providing benefits to compensate affected communities for losses due to policy or systems changes enhanced public acceptability in some cases (Perlaviciute and Steg, 2014), although people may disagree on what would be a worthwhile compensation (Aitken, 2010; Cass et al., 2010), or feel they are being bribed (Cass et al., 2010; Perlaviciute and Steg, 2014).

Public support is higher when individuals trust responsible parties (Perlaviciute and Steg, 2014; Drews and Van den Bergh, 2016). Yet, public support for multilateral climate policy is not higher than for unilateral policy (Bernauer and Gampfer, 2015); public support for unilateral, non-reciprocal climate policy is rather strong and robust (Bernauer et al., 2016b). Public opposition may result from a culturally valued landscape being affected by adaptation or mitigation options, such as renewable energy development (Warren et al., 2005; Devine-Wright and Howes, 2010) or coastal protection measures (Kimura, 2016), particularly when people have formed strong emotional bonds with the place (Devine-Wright, 2009, 2013).

Climate actions may reduce human wellbeing when such actions involve more costs, effort or discomfort. Yet, some climate actions enhance wellbeing, such as technology that improves daily comfort and nature-based solutions for climate adaptation (Wamsler and Brink, 2014b). Further, climate action may enhance wellbeing (Kasser and Sheldon, 2002; Xiao et al., 2011; Schmitt et al., 2018) because pursuing meaning by acting on climate change can make people feel good (Venhoeven et al., 2013, 2016; Taufik et al., 2015), more so than merely pursuing pleasure.

4.4.4 Enabling Technological Innovation

This section focuses on the role of technological innovation in limiting warming to 1.5ºC, and how innovation can contribute to strengthening implementation to move towards or to adapt to 1.5ºC worlds. This assessment builds on information of technological innovation and related policy debates in and after AR5 (Somanathan et al., 2014).

4.4.4.1 The Nature of Technological Innovations

Technological systems have their own dynamics. New technologies have been described as emerging as part of a ‘socio-technical system’ that is integrated with social structures and that itself evolves over time (Geels and Schot, 2007). This progress is cumulative and accelerating (Kauffman, 2002; Arthur, 2009). To illustrate such a process of co-evolution: the progress of computer simulation enables us to understand climate,
agriculture, and material sciences better, contributing to upgrading food production and quality, microscale manufacturing techniques, and leading to much faster computing technologies, resulting for instance in better performing Photovoltaic (PV) cells.

A variety of technological developments have and will, contribute to 1.5°C-consistent climate action or the lack of it. They can do this, e.g., in the form of applications such as smart lighting systems, more efficient drilling techniques making fossil fuels cheaper, or precision agriculture. As discussed in Section 4.3.1, costs of PV (IEA, 2017f) and batteries (Nykvist and Nilsson, 2015) have sharply dropped. In addition, costs of fuel cells (Iguma and Kidoshi, 2015; Wei et al., 2017) and shale gas and oil (Wang et al., 2014; Mills, 2015) have come down as a consequence of innovation.

4.4.4.2 Technologies as Enablers of Climate Action

Since AR5, literature has emerged as to how much future GHG emission reductions can be enabled by the rapid progress of General Purpose Technologies (GPTs), consisting of Information and Communication Technologies (ICT) including Artificial Intelligence (AI) and Internet-of-Things (IoT), nanotechnologies, biotechnologies, robotics, and so forth (World Economic Forum, 2015; OECD, 2017c). Although these may contribute to limiting warming to 1.5°C, the potential environmental, social and economic impacts of new technologies are uncertain.

Rapid improvement of performance and cost reduction is observed for many GPTs. They include AI, sensors, internet, memory storage and micro-electro mechanical systems. The latter GPTs are not usually categorised as climate technologies, but they can impact GHG emissions.

Progress of GPT could help reducing GHG emissions more cost-effectively. Examples are shown in Table 4.9. It may however, result in more emissions by increasing the volume of economic activities, with unintended negative consequence on sustainable development. While ICT increases electricity consumption (Aebischer and Hilty, 2015), the energy consumption of ICT is usually dwarfed by the energy saving by ICT (Koomey et al., 2013; Malmodin et al., 2014), but rebound effects and other sustainable development impacts may be significant. An appropriate policy framework that accommodates such impacts and their uncertainties could address the potential negative impacts by GPT (Jasanoff, 2007).

GHG emission reduction potentials in relation to GPTs were estimated for passenger cars using a combination of three emerging technologies: electric vehicles, car sharing, and self-driving. GHG emission reduction potential is reported, assuming generation of electricity with low GHG emissions (Greenblatt and Saxena, 2015; ITF, 2015; Viegas et al., 2016; Fulton et al., 2017). It is also possible that GHG emissions increase due to an incentive to car use. Appropriate policies such as urban planning and efficiency regulations could contain such rebound effects (Wadud et al., 2016).

Estimating emission reductions by GPT is difficult due to substantial uncertainties, including projections of future technological performance, costs, penetration rates, and induced human activity. Even if a technology is available, the establishment of business models might not be feasible (Linder and Williander, 2017). Indeed, studies show a wide range of estimates, ranging from deep emission reductions to possible increases in the emissions due to the rebound effect (Larson and Zhao, 2017).

GPT could also enable climate adaptation, in particular through more effective climate disaster risk management and improved weather forecasting.
Table 4.9: Examples of technological innovations relevant to 1.5°C enabled by General Purpose Technologies (GPT). Note: Lists of enabling GPT or adaptation/mitigation options are not exhaustive, and the GPTs by themselves do not reduce emissions or increase climate change resilience.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Examples of mitigation/adaptation technological innovation</th>
<th>Enabling GPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buildings</td>
<td>Energy and CO₂ efficiency of logistics, warehouse and shops (GeSI, 2015; IEA, 2017a)</td>
<td>IoT, AI</td>
</tr>
<tr>
<td></td>
<td>Smart lighting and air conditioning (IEA, 2016b, 2017a)</td>
<td>IoT, AI, nanotechnology</td>
</tr>
<tr>
<td>Industry</td>
<td>Energy efficiency improvement by industrial process optimisation (IEA, 2017a)</td>
<td>Robots, IoT</td>
</tr>
<tr>
<td></td>
<td>Bio-based plastic production by bio-refinery (OECD, 2017c)</td>
<td>Biotechnology</td>
</tr>
<tr>
<td></td>
<td>New materials from bio-refineries (Fornell et al., 2013; McKay et al., 2016)</td>
<td>ICT, Biotechnology</td>
</tr>
<tr>
<td>Transport</td>
<td>Electric vehicles, car sharing, automation (Greenblatt and Saxena, 2015; Fulton et al., 2017)</td>
<td>IoT, AI, nanotechnology</td>
</tr>
<tr>
<td></td>
<td>Bio-based diesel fuel by bio-refinery (OECD, 2017c)</td>
<td>Biotechnology</td>
</tr>
<tr>
<td></td>
<td>Second Generation Bioethanol potentially coupled to Carbon Capture Systems (de Souza et al., 2014; Rochedo et al., 2016)</td>
<td>ICT, Biotechnology</td>
</tr>
<tr>
<td></td>
<td>Logistical optimisation, and electrification of trucks by overhead line (IEA, 2017e)</td>
<td>IoT, AI</td>
</tr>
<tr>
<td></td>
<td>Reduction of transport needs by remote education, health, and other services (GeSI, 2015; IEA, 2017a)</td>
<td>ICT</td>
</tr>
<tr>
<td></td>
<td>Energy saving by lightweight aircraft components (Beyer, 2014; Faludi et al., 2015; Verhoef et al., 2018)</td>
<td>Additive manufacturing (3D printing)</td>
</tr>
<tr>
<td>Electricity</td>
<td>Solar PV manufacturing (Nemet, 2014)</td>
<td>Nanotechnology</td>
</tr>
<tr>
<td></td>
<td>Smart grids and grid flexibility to accommodate intermittent renewables (Heard et al., 2017)</td>
<td>IoT, AI</td>
</tr>
<tr>
<td></td>
<td>Plasma confinement for nuclear fusion (Baltz et al., 2017)</td>
<td>AI</td>
</tr>
<tr>
<td>Agriculture</td>
<td>Precision agriculture (improvement of energy and resource efficiency including reduction of fertiliser use and N₂O emissions) (Pierpaoli et al., 2013; Brown et al., 2016; Schimmelpfennig and Ebel, 2016)</td>
<td>Biotechnology, ICT, AI</td>
</tr>
<tr>
<td></td>
<td>Methane inhibitors (methanogenic vaccines) that reduce dairy livestock emissions (Wollenberg et al., 2016)</td>
<td>Biotechnology</td>
</tr>
<tr>
<td></td>
<td>Engineering C3 into C4 photosynthesis to improve agricultural production and productivity (Schuler et al., 2016)</td>
<td>Biotechnology</td>
</tr>
<tr>
<td></td>
<td>Genome editing using CRISPR to improve/adapt crops to a changing climate (Gao, 2018)</td>
<td>Biotechnology</td>
</tr>
<tr>
<td>Disaster</td>
<td>Weather forecasting and early warning systems, in combination with user knowledge (Hewitt et al., 2012; Lourenço et al., 2016)</td>
<td>ICT</td>
</tr>
<tr>
<td>reduction</td>
<td>Climate risk reduction (Upadhyay and Bjalwan, 2015)</td>
<td>ICT</td>
</tr>
<tr>
<td>and adaptation</td>
<td>Rapid assessment of disaster damage (Kryvasheyeu et al., 2016)</td>
<td>ICT</td>
</tr>
</tbody>
</table>

Government policy usually plays a role in promoting or limiting GPTs, or science and technology in general. It has impacts on climate action, because the performance of further climate technologies will partly depend on the progress of GPTs. Governments have established institutions for achieving many social, and sometimes conflicting goals, including economic growth and addressing climate change (OECD, 2017c), which include investment in basic R&D that can help develop game changing technologies (Shayegh et al., 2017). Governments are also needed to create an enabling environment for the growth of scientific and technological ecosystems necessary for GPT development (Tassey, 2014).

4.4.4.3 The Role of Government in 1.5°C-Consistent Climate Technology Policy

While literature on 1.5°C-specific innovation policy is absent, a growing body of literature indicates that governments aim to achieve social, economic and environmental goals by promoting science and a broad range of technologies through ‘mission-driven’ innovation policies, based on differentiated national priorities.
Governments can play a role in advancing climate technology via a ‘technology push’ policy on the technology supply side (e.g., R&D subsidies), and by ‘demand pull’ policy on the demand side (e.g., energy efficiency regulation), and these policies can be complemented by enabling environments (Somanathan et al., 2014). Governments may also play a role in removing existent support for incumbents (Kivimaa and Kern, 2016). A growing literature indicates that policy mixes, rather than single policy instruments, are more effective in addressing climate innovation challenges ranging from technologies in the R&D phase to those ready for diffusion (Veugelers, 2012; Quitzow, 2015; Rogge et al., 2017; Rosenow et al., 2017). Such innovation policies can help address two kinds of externalities: environmental externalities and proprietary problems (GEA, 2012; IPCC, 2014b; Mazzucato and Semieniuk, 2017). To avoid ‘picking winners’, governments often maintain a broad portfolio of technological options (Kverndokk and Rosendahl, 2007) and work in close collaboration with the industrial sector and society in general. Some governments have achieved relative success in supporting innovation policies (Grubler et al., 2012; Mazzucato, 2013) that addressed climate-related R&D (see Box 4.7 on bioethanol in Brazil).

[START BOX 4.7 HERE]

**Box 4.7: Bioethanol in Brazil: Innovation and Lessons for Technology Transfer**

The use of sugarcane as a bioenergy source started in Brazil in the 1970s. Government and multinational car factories modified car engines nationwide so that vehicles running only on ethanol could be produced. As demand grew, production and distribution systems matured and costs came down (Soccol et al., 2010). After a transition period in which ethanol-only and gasoline-only cars were used, the flex-fuel era started in 2003, when all gasoline was blended with 25% ethanol (de Freitas and Kaneko, 2011). By 2010, around 80% of the car fleet in Brazil had been converted to use flex-fuel (Goldemberg, 2011; Su et al., 2015).

More than forty years of combining technology push and market pull measures led to the deployment of ethanol production, transportation and distribution systems across Brazil, leading to a significant decrease in CO₂ emissions (Macedo et al., 2008). Examples of innovations include: 1) the development of environmentally well-adapted varieties of sugarcane; 2) the development and scaling up of sugar fermentation in a non-sterile environment, and 3) the development of adaptations of car engines to use ethanol as a fuel isolated or in combination with gasoline (Amorim et al., 2011; de Freitas and Kaneko, 2011; de Souza et al., 2014). Public procurement, public investment in R&D and mandated fuel blends accompanying these innovations were also crucial (Hogarth, 2017). In the future, innovation could lead to viable partial carbon dioxide removal through deployment of BECCS associated with the bioethanol refineries (Fuss et al., 2014; Rochedo et al., 2016) (see Section 4.3.7).

Ethanol appears to reduce urban car emission of health-affecting ultrafine particles by 30% compared to gasoline-based cars, but increases ozone (Salvo et al., 2017). During the 1990s, when sugarcane burning was still prevalent, particulate pollution had negative consequences for human health and the environment (Ribeiro, 2008; Paraíso and Gouveia, 2015). While (Jaiswal et al., 2017) report bioethanol’s limited impact on food production and forests in Brazil, despite the large scale, and attribute this to specific agro-ecological zoning legislation, various studies report adverse effects of bioenergy production through forest substitution by croplands (Searchinger et al., 2008), as well as impacts on biodiversity, water resources, and food security (Rathore et al., 2016). For new generation biofuels, feasibility and life cycle assessment studies can provide information on their impacts on environmental, economic, and social factors (Rathore et al., 2016).

Brazil and the European Union have tried to replicate Brazil’s bioethanol experience in climatically suitable African countries. Although such technology transfer achieved relative success in Angola and Sudan, the attempts to set up bioethanol value chains did not pass the phase of political deliberations and feasibility studies elsewhere in Africa. Lessons learned include the need of political and economic stability of the donor country (Brazil) and the necessity of market creation to attract investments in first-generation biofuels alongside a safe legal and policy environment for improved technologies (Afionis et al., 2014; Favretto et al., 2017).

[END BOX 4.7 HERE]
Funding for R&D could come from various sources, including the general budget, energy or resource taxation, or emission trading schemes (see Section 4.4.5). Investing in climate-related R&D has as an additional benefit of building capabilities to implement climate mitigation and adaptation technologies (Ockwell et al., 2015). Countries regard innovation in general and climate technology specifically as a national interests issue, and addressing climate change primarily as in the global interest. Reframing part of climate policy as technology or industrial policy might therefore contribute to resolving the difficulties that continue to plague emission target negotiations (Faehn and Isaksen, 2016; Fischer et al., 2017; Lachapelle et al., 2017).

Climate technology transfer to emerging economies has happened regardless of international treaties, as these countries have been keen to acquire them, and companies have an incentive to access emerging markets to remain competitive (Glachant and Dechezleprêtre, 2016). However, the complexity of this transfer processes is high and they have to be conducted carefully by governments and institutions (Favretto et al., 2017). It is noticeable that the impact of the EU Emission Trading Scheme (EU ETS) on innovation is contested; recent work (based on lower carbon prices than anticipated for 1.5°C-consistent pathways) indicates that it is limited (Calel and Dechezleprêtre, 2016) but earlier assessments (Blanco et al., 2014) indicate otherwise.

### 4.4.4.4 Technology Transfer in the Paris Agreement

Technology development and transfer is recognised as an enabler of both mitigation and adaptation in Article 10 in the Paris Agreement (UNFCCC, 2015) as well as in Article 4.5 of the original text of the UNFCCC (UNFCCC, 1992). As previous sections have focussed on technology development and diffusion, this section focuses on technology transfer. Technology transfer can adapt technologies to local circumstances, reduce financing costs, develop indigenous technology, and build capabilities to operate, maintain, adapt and innovate on technology globally (Ockwell et al., 2015; de Coninck and Sagar, 2017). Technology cooperation could decrease global mitigation cost, and enhance developing countries’ mitigation contributions (Huang et al., 2017a).

The international institutional landscape around technology development and transfer includes the UNFCCC (via its technology framework and technology mechanism including the Climate Technology Centre and Network (CTCN)), the United Nations (a technology facilitation mechanism for the SDGs) and a variety of non-UN multilateral and bilateral cooperation initiatives such as the Consultative Group on International Agricultural Research (CGIAR, founded in the 1970s), and numerous initiatives of companies, foundations, governments and non-governmental and academic organisations. Moreover, in 2015, twenty countries launched an initiative called ‘Mission Innovation’, seeking to double their energy R&D funding. At this point it is difficult to evaluate whether Mission Innovation achieved its objective (Sanchez and Sivaram, 2017). At the same time, the private sector started an initiative called the ‘Breakthrough Energy Coalition’.

Most technology transfer is driven by through markets by the interests of technology seekers and technology holders, in particular in regions with well-developed institutional and technological capabilities such as developed and emerging nations (Glachant and Dechezleprêtre, 2016). However, the current international technology transfer landscape has gaps, in particular in reaching out to least-developed countries, where institutional and technology capabilities are limited (de Coninck and Puig, 2015; Ockwell and Byrne, 2016). On the one hand, literature suggests that the management or even monitoring of all these UN, bilateral, private and public initiatives may fail to lead to better results. On the other hand, it is probably more cost-effective to adopt a strategy of ‘letting a thousand flowers bloom’, by challenging and enticing researchers in the public and the private sector to direct innovation towards low-emission and adaptation options (Haselip et al., 2015). This can be done at the same time as mission-oriented research is adopted in parallel by the scientific community (Mazzucato, 2018).

At COP 21, the UNFCCC requested the Subsidiary Body for Scientific and Technological Advice (SBSTA) to initiate the elaboration of the technology framework established under the Paris Agreement (UNFCCC, 2015). Among other things, the technology framework would ‘provide overarching guidance for the work of
the Technology Mechanism in promoting and facilitating enhanced action on technology development and transfer in order to support the implementation of this Agreement (this Agreement being the Paris Agreement). An enhanced guidance issued by the Technology Executive Committee (TEC) for preparing a Technology Action Plan (TAP) supports the new technology framework as well as Parties’ long-term vision on technology development and transfer, reflected in the Paris Agreement (TEC, 2016).

4.4.5 Strengthening Policy Instruments and Enabling Climate Finance

Triggering rapid and far-reaching change in technical choices and institutional arrangements, consumption and lifestyles, infrastructure, land use and spatial patterns implies the ability to scale-up policy signals to enable the decoupling of GHGs emission, and economic growth and development (Section 4.2.2.3). Such a scale-up would also imply that potential short-term negative responses by populations and interest groups, that could block these changes from the outset, would need to be prevented or overcome. This section describes the size and nature of investment needs and the financial challenge over the coming two decades in the context of 1.5°C warmer worlds, assesses the potential and constraints of three categories of policy instruments that respond to the challenge, and explains the conditions for using them synergistically. The policy and finance instruments discussed in this section relate to Section 4.4.1 (on governance) and other Sections in 4.4.

4.4.5.1 The Core Challenge: Cost Efficiency, Coordination of Expectations and Distributive Effects

Box 4.8 shows that the average estimates by seven models of annual investments needs in the energy system is around 2.38 trillion USD\textsubscript{2010} (1.38 to 3.25) between 2016 and 2035. This represents between 2.53% (1.6% to 4%) of the world GDP in Market Exchange Rates (MER) and 1.7% of the world GDP in purchasing power parity (PPP). OECD investment assessments for a 2°C-consistent transition suggest that including investments in transportation and in other infrastructure would increase the investment needs by a factor of three. Other studies not included in Box 4.8, in particular by the World Economic Forum (World Economic Forum, 2013) and the Global Commission on the Economy and Climate (GCEC, 2014) confirm these orders of magnitude of investment.

[START BOX 4.8 HERE]

**Box 4.8: Investment Needs and the Financial Challenge of Limiting Warming to 1.5°C**

The peer-reviewed literature that estimates the investment needs to scale up the response to limit warming to 1.5°C is limited (see Section 4.6). This box attempts to bring together available estimates of the order of magnitude of these investments to provide the context for global and national financial mobilisation policy and related institutional arrangements.

Table 1 in this box presents mean annual investments up to 2035, based on three studies (after clarifying their scope and harmonising their metrics): an ensemble of six integrated assessment models (See Chapter 2); an OECD (Organisation for Economic Co-operation and Development) scenario for a 2°C limit (OECD, 2017a) and scenarios from the International Energy Agency (IEA) (IEA, 2016c). All three sources provide estimates for the energy sector for various for mitigation scenarios. The OECD estimate also covers transportation and other infrastructure (water, sanitation, and telecommunication), which are essential to deliver the Sustainable Development Goals (SDGs), including SDG7 on clean energy access, and enhance the adaptive capacity to climate change.
Box 4.8, Table 1: Estimated annualised mitigation investment needed to stay well below 2°C (2015–2035 in trillion USD at market exchange rates)

<table>
<thead>
<tr>
<th></th>
<th>Energy investments</th>
<th>Of which demand side</th>
<th>Transport</th>
<th>Other infrastructures</th>
<th>Total</th>
<th>Ratio to MER GDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAM Baseline (mean)</td>
<td>1.96</td>
<td>0.24</td>
<td></td>
<td></td>
<td>1.96</td>
<td>1.8%</td>
</tr>
<tr>
<td>IAM NDC (mean)</td>
<td>2.04</td>
<td>0.28</td>
<td></td>
<td></td>
<td>2.04</td>
<td>1.9%</td>
</tr>
<tr>
<td>IAM 2°C (mean)</td>
<td>2.19</td>
<td>0.38</td>
<td></td>
<td></td>
<td>2.19</td>
<td>2.1%</td>
</tr>
<tr>
<td>IAM 1.5°C (mean)</td>
<td>2.32</td>
<td>0.45</td>
<td></td>
<td></td>
<td>2.32</td>
<td>2.2%</td>
</tr>
<tr>
<td>IEA NDC</td>
<td>2.40</td>
<td>0.72</td>
<td>0.35</td>
<td></td>
<td>2.40</td>
<td>2.3%</td>
</tr>
<tr>
<td>IEA 1.5°C</td>
<td>2.76</td>
<td>1.13</td>
<td>0.55</td>
<td></td>
<td>2.76</td>
<td>2.7%</td>
</tr>
<tr>
<td><strong>Mean IAM-IEA, 1.5°C</strong></td>
<td><strong>2.38</strong></td>
<td><strong>0.54</strong></td>
<td></td>
<td></td>
<td><strong>2.38</strong></td>
<td><strong>2.53%</strong></td>
</tr>
<tr>
<td>Min IAM-IEA, 1.5°C</td>
<td>1.38</td>
<td>0.38</td>
<td></td>
<td></td>
<td>1.38</td>
<td>1.6%</td>
</tr>
<tr>
<td>Max IAM-IEA, 1.5°C</td>
<td>3.25</td>
<td>1.13</td>
<td></td>
<td></td>
<td>3.25</td>
<td>4.0%</td>
</tr>
<tr>
<td><strong>OECD Baseline</strong></td>
<td>1.91</td>
<td>0.36</td>
<td>2.46</td>
<td>1.37</td>
<td>5.74</td>
<td>5.4%</td>
</tr>
<tr>
<td>OECD 2°C</td>
<td>2.13</td>
<td>0.40</td>
<td>2.73</td>
<td>1.52</td>
<td>6.38</td>
<td>6.0%</td>
</tr>
</tbody>
</table>

The mean incremental share of annual mitigation investments to stay well below 2°C is 0.36% (between 0.2–1%) of global Gross Domestic Product (GDP) over 2015–2035. Since Gross Fixed Capital Formation (GFCF) is about 24% of global GDP, the estimated incremental energy investments between a baseline and a 1.5°C transition would be approximately 1.5% (between 0.8–4.2%) of projected total world investments. Given the uncertainty in these estimates, decision-makers could lower the probability of the most pessimistic assumptions by implementing policies to accelerate technical change (Section 4.4.5).

While total incremental investment for a 2°C-consistent pathway, including for transportation and other infrastructure, is estimated at 2.5% of global GFCF, there is no comprehensive study or estimate of these investments for a 1.5°C limit. For a 1.5°C-consistent pathway, the anticipated incremental ‘other investments’ might be lower thanks to lower investment needs in adaptation.

The issue, from a macroeconomic perspective, is whether these investments would be funded by higher savings at the costs of lower consumption. This would mean a 0.5% reduction in consumption for the energy sector for 1.5°C. Note that for a 2°C scenario, this reduction would be 0.8% if we account for the investment needs of all infrastructure sectors. Assuming a constant saving ratio, this can be enabled by reallocating existing capital flows towards infrastructure. In addition to these incremental investments, the amount of redirected investments is relevant from a financial perspective. In the reported Integrated Assessment Model (IAM) energy sector scenarios, about three times the incremental investments is redirected. There is no such assessment for the other sectors. The OECD report suggests that these ratios might be higher.

These orders of magnitude of investment can be compared to the available statistics of the global stock of 386 trillion USD of financial capital, which consists of 100 trillion USD in bonds (SIFMA, 2017), around 60 trillion USD in equity (The World Bank Data, 2018), and 226 trillion USD of loans managed by the banking system (IIF, 2017)(World Bank, 2018a). The long term rate of return (interest plus increase of shareholder value) is about 3% on bonds, 5% on bank lending, 7% on equity, leading to a weighted mean cost of capital of 3.4% in real terms (5.4% in nominal terms). Using 3.4% as a lower bound and 5% as a higher bound (following (Piketty, 2014)) and taking a conservative assumption that global financial capital grows at the same rate as global GDP, the estimated financial capital revenues would be between 16.8 and 25.4 trillion USD.

Assuming that a quarter of these investments comes from public funds (as estimated by the World Bank (World Bank, 2018a)), the amount of private resources needed to enable an energy sector transition is between 3.3% and 5.3% of annual capital income and between 5.6% and 8.3% of these revenues for all
infrastructure to meet the 2°C target and the SDGs.

Since the financial system has limited fungibility across budget lines, changing the partitioning of investments is not a zero-sum game. An effective policy regime could encourage investment managers to change their asset allocation. Part of the challenge may lie in increasing the pace of financing of low-emission assets to compensate for a possible 38% decrease, by 2035, in the value of fossil fuel assets (energy sector and indirect holdings in downstream uses like automobiles) (Mercure et al., 2018).

[END BOX 4.8 HERE]

The average increase of investment in the energy sector resulting from Box 4.8 represents a mean value of 1.5% of the global Gross Fixed Capital Formation (GFCF) compared with the baselines scenario in Market Exchange Rate (MER) and a little over 1% in Purchasing Power Parity (PPP). Including infrastructure investments would raise this to 2.5% and 1.7% respectively⁹.

These incremental investments could be funded through a drain on consumption (Bowen et al., 2017) which would necessitate between 0.68% and 0.45% lower global consumption than in the baseline. But, consumption at constant savings/consumption ratio can alternatively be funded by shifting savings towards productive adaptation and mitigation investments, instead of real-estate sector and liquid financial products. This response depends upon whether it is possible to close the global investment funding gap for infrastructure that potentially inhibits growth, through structural changes in the global economy. In this case, investing more in infrastructures would not be an incremental cost in terms of development and welfare (IMF, 2014; Gurara et al., 2017)

Investments in other (non-energy system) infrastructure to meet development and poverty reduction goals can strengthen the adaptive capacity to address climate change, and is difficult to separate from overall sustainable development and poverty alleviation investments (Hallegatte and Rozenberg, 2017). The magnitude of potential climate change damages is related to pre-existing fragility of impacted societies (Hallegatte et al., 2007). Enhancing infrastructure and service provision would lower this fragility, for example through the provision of universal (water, sanitation, telecommunication) service access (Arezki et al., 2016).

The main challenge is thus not just a lack of mobilisation of aggregate resources but of redirection of savings towards infrastructure, and the further redirection of these infrastructure investments towards low-emission options. If emission-free assets emerge fast enough to compensate for the devaluation of high-emission assets, the sum of the required incremental and redirected investments in the energy sector would (up to 2035) be equivalent to between 3.3% and 5.3% of the average annual revenues of the private capital stock (see Box 4.8) and to 5.6% and 8.3%, including all infrastructure investments.

The interplay between mechanisms of financial intermediation and the private risk-return calculus is a major barrier to realising these investments (Sirkis et al., 2015). This obstacle is not specific to climate mitigation investments but also affects infrastructure and has been characterised as the gap between the ‘propensity to save’ and the ‘propensity to invest’ (Summers, 2016). The issue is whether new financial instruments could close this gap and inject liquidity into the low-emission transition, thereby unlocking new economic opportunities (GCEC, 2014; NCE, 2016). By offsetting the crowding-out of other private and public investments (Pollitt and Mercure, 2017) the ensuing ripple effect could reinforce growth and the sustainability of development (King, 2011; Teulings and Baldwin, 2014) and potentially triggering a new growth cycle (Stern, 2013, 2015). In this case, a massive mobilisation of low-emission investments would

⁹ FOOTNOTE: A calculation in MER tends indeed to underestimate the world GDP and its growth by giving a lower weight to fast growing developing countries whereas a calculation in PPP tends to overestimate it. The difference between the value of two currencies in PPP and MER should vanish as the gap of the income levels of the two concerned countries decreases. Accounting for this trend in modelling is challenging.
require a significant effort, but may be complementary to sustainable development investments.

This uncertain but potentially positive outcome might be constrained by the higher energy costs of low-emission options in the energy and transportation sectors. The price envelope of worldwide marginal abatement costs for 1.5°C-consistent pathways reported in Chapter 2 is 135–475 USD tCO₂⁻¹ in 2030 and 245–1100 USD tCO₂⁻¹ in 2050, which is between two or three times higher than for a 2°C limit.

These figures are consistent with the dramatic reduction in the unit costs of some low-emission technical options (for example solar PV, LED lighting) over the past decade (OECD, 2017c) (see Section 4.3.1). Yet, there are multiple constraints to a system-wide energy transition. Lower costs of some supply and demand-side options does not always result in a proportional decrease in energy system costs. The adoption of alternative options can be slowed down by increasing costs of decommissioning existing infrastructure, inertia of market structures, cultural habits and by risk-adverse user behaviour (see Sections 4.4.1 to 4.4.3). Learning-by-doing processes and R&D can accelerate the cost-efficiency of low-emission technology but often imply higher early-phase costs. The German energy transition resulted in high consumer prices for electricity in Germany (Kreuz and Müsgens, 2017) and needed strong accompanying measures to succeed.

One key issue is that energy costs can propagate across sectors amplifying overall production costs. During the early stage of a low-emission transition, an increase in the prices of non-energy goods could cause lower consumer purchasing power and final demand. A rise of energy prices has a proportionally greater impact in developing countries that are in a catch-up phase, with strong dependence on energy-intensive sectors (Crassous et al., 2006; Luderer et al., 2012) and a higher ratio of energy to labour cost (Waisman et al., 2012). This explains why with lower carbon prices, similar emission reductions are reached in South Africa (Altieri et al., 2016) and Brazil (La Rovere et al., 2017a) compared to developed countries. However, three distributional issues emerge.

First, in the absence of countervailing policies, higher energy costs have an adverse effect on the distribution of welfare (see also Chapter 5). The negative impact is inversely correlated with the level of income (Harberger, 1984; Fleurbaey and Hammond, 2004) and positively correlated with the share of energy in the households budget, which is high for low- and middle-income households (Proost and Van Regemorter, 1995; Barker and Kohler, 1998; West and Williams, 2004; Chiroleu-Assouline and Fodha, 2011). Moreover, climatic conditions and the geographical conditions of human settlements matter for heating and mobility needs (see Chapter 5). Medium-income populations in the suburbs, remote and low-density regions can be as vulnerable as residents of low-income urban areas. Poor households with low levels of energy consumption are also impacted by price increases of non-energy goods caused by the propagation of energy costs (Combet et al., 2010; Dubois, 2012). These impacts are generally not offset by non-market co-benefits of climate policies for the poor (Baumgartner et al., 2017).

A second matter of concern is the distortion of international competition and employment implications in case of uneven carbon constraints, especially for energy-intensive industries (Demailly and Quirion, 2008). Some of these industries are not highly exposed to international competition because of their very high transportation costs per unit value added (Sartor, 2013; Branger et al., 2016), but other industries could suffer severe shocks, generate ‘carbon leakage’ through cheaper imports from countries with lower carbon constraints (Branger and Quirion, 2014) and weaken the surrounding regional industrial fabric with economy-wide and employment implications.

A third challenge is the depreciation of assets whose value is based on the valuation of fossil energy resources of which future revenues may decline precipitously with higher carbon prices (Waisman et al., 2013; Jakob and Hilaire, 2015; McGlade and Ekins, 2015) and on emission-intensive capital stocks (Guivarch and Hallegatte, 2011; OECD/IEA/NEA/ITF, 2015; Pfeiffer et al., 2016). This raises issues of changes in industrial structure, adaptation of worker skills and of stability of financial, insurance and social security systems. These systems are in part based on current holdings of carbon-based assets whose value might decrease by 38% by the mid-2030s (Mercure et al., 2018). This stranded asset challenge may be exacerbated by a decline of export revenues of fossil fuel producing countries and regions (Waisman et al., 2013; Jakob and Hilaire, 2015; McGlade and Ekins, 2015).
These distributional issues, if addressed carefully and expeditiously, could affect popular sensitivity towards climate policies. Addressing them could mitigate adverse macroeconomic effects on economic growth and employment that could undermine the potential benefits of a redirection of savings and investments towards 1.5°C-consistent pathways.

Strengthening policy instruments for a low-emission transition would thus need to reconcile three objectives: i) handling the short-term frictions inherent to this transition in an equitable way, ii) minimising these frictions by lowering the cost of avoided GHGs emissions, and iii) coordinating expectations of multiple stakeholders at various decision-making levels to accelerate the decline in costs of emission reduction, efficiency and decoupling options and maximising their co-benefits (see the practical example of lowering car use in cities in Box 4.9).

Three categories of policy tools would be available to meet the distributional challenges: carbon pricing, regulatory instruments and information and financial tools,. Each of them has its own strength and weaknesses, and in a 1.5°C perspective, policy tools would have to be both upscale and better coordinated in packages in a synergistic manner.

[START BOX 4.9 HERE]

**Box 4.9: Emerging cities and ‘peak car use’: Evidence of decoupling in Beijing**

The phenomenon of ‘peak car use’, or reductions in per capita car use, provides hope for continuing reductions in greenhouse gas from oil consumption (Millard-Ball and Schipper, 2011; Newman and Kenworthy, 2011; Goodwin and Van Dender, 2013). The phenomenon has been mostly associated with developed cities apart from some early signs in Eastern Europe, Latin America and China (Newman and Kenworthy, 2015). New research indicates that peak car is now also underway in China (Gao and Newman, 2018).

China’s rapid urban motorisation has resulted from strong economic growth, fast urban development and the prosperity of the Chinese automobile industry (Gao and Kenworthy, 2015). However, recent data (Gao and Newman, 2018) suggest the first signs of a break in the growth of car use expressed in percentage of daily trips as the growth in mass transit, primarily caused by the expansion of Metro systems, is becoming more significant (see Box 4.9, Figure 1).

![Modal split of daily trips (%)](image-url)
Chinese urban fabrics, featuring traditional dense linear forms and mixed land use, favour mass transit systems over automobiles (Gao and Newman, 2018). The data show that the decline in car use did not impede economic development but Vehicle Kilometres of Travel (VKT) growth has decoupled absolutely from GDP as shown in Box 4.9, Figure 2 below.

Box 4.9, Figure 1: The modal split data in Beijing between 1986 and 2014. Source: (Gao and Newman, 2018).

Box 4.9, Figure 2: Peak car in Beijing: relationships between economic performance and private automobile use in Beijing from 1986 to 2014. VKT is Vehicle Kilometres of Travel. Source: (Gao and Newman, 2018).

4.4.5.2 Carbon Pricing: Necessity and Constraints

For long, economic literature has argued that climate and energy policy only grounded in regulation, standards and public funding of R&D is at risk of being influenced by political and administrative arbitrariness, which could raise the costs of implementation. This literature has argued that it may be more efficient to make these costs explicit through carbon taxes and carbon trading, securing the abatement of emissions in places and sectors where it is cheapest (IPCC, 1995, 2001; Gupta et al., 2007; Somanathan et al., 2014).

In a frictionless world, a unique world carbon price could minimise the social costs of the low carbon transition by equating the marginal costs of abatement across all sources of emissions. This implies that investors will be able to make the right choices under perfect foresight and that domestic and international compensatory transfers offset the adverse distributional impacts of higher energy prices and their consequences on economic activity. In the absence of transfers targeted in function of countries market structures (Boeters, 2014), carbon prices are no longer optimal (Böhringer et al. 2009; Böhringer and Alexeeva-Talebi 2013) and need to be differentiated by jurisdiction (Chichilnisky and Heal, 2000; Sheeran, 2006) in function of the countries’ social welfare function. This differentiation could in turn raise concerns of distortions in international competition (Hourcade et al., 2001; Stavins et al., 2014).

Obstacles to enforcing a unique world carbon price in the short-run would not necessarily crowd out explicit national carbon pricing, for three reasons. First, it could restrain an emissions rebound due to a higher consumption of energy services enabled by efficiency gains, if energy prices do not change (Greening et al., 2000; Fleurbaey and Hammond, 2004; Sorrell et al., 2009; Guivarch and Hallegatte, 2011; Chitnis and Sorrell, 2015; Freire-González, 2017). Second, it could hedge against the arbitrariness of regulatory policies. Third, ‘revenue neutral’ recycling, at a constant share of taxes on GDP, into lowering some existing taxes.
compensates at least part of the propagation effect of higher energy costs (Stiglitz et al., 2017). The substitution by carbon taxes of taxes that cause distortions on the economy can counteract the regressive effect of higher energy prices. For example, offsetting increased carbon prices with lower labour taxes can potentially decrease labour costs (without affecting salaries), enhance employment and reduce the attractiveness of informal economic activity (Goulder, 2013).

The conditions under which an economic gain along with climate benefit (a ‘double dividend’) can be expected are well documented (Goulder, 1995; Bovenberg, 1999; Mooij, 2000). In the context of OECD countries, the literature examines how carbon taxation could substitute for other taxes to fund the social security system (Combret, 2013). The same general principles apply for countries that are building their social welfare system such as China (Li and Wang, 2012) or Brazil (La Rovere et al., 2017a) but an optimal recycling scheme could differ based on the structure of the economy (Lefèvre et al. 2018).

In every country the design of carbon pricing policy implies a balance between incentivising low-carbon behaviour and mitigating the adverse distributional consequences of higher energy prices (Combret et al., 2010). Carbon taxes can offset these effects if their revenues are redistributed through rebates to poor households. Other options include the reduction of value added taxes for basic products or direct benefit transfers to enable poverty reduction (see Winkler et al., 2017) for South Africa and (Grottera et al., 2016) for Brazil. This is possible because higher income households pay more in absolute terms, even though their carbon tax burden is a relatively smaller share of their income (Arze del Granado et al., 2012).

Ultimately, the pace of increase of carbon prices would depend on the pace at which they can be embedded in a consistent set of fiscal and social policies. This is why, after a quarter century of academic debate and experimentation (see IPCC WGIII reports since the SAR), a gap persists with respect to ‘switching carbon prices’ needed to trigger rapid changes. In 2016, only 15% of global emissions are covered by carbon pricing, three-quarters of which with prices below 10 USD tCO₂⁻¹ (World Bank, 2016). This is too low to outweigh the ‘noise’ from the volatility of oil markets (in the range of 100 USD tCO₂⁻¹ over the past decade), of other price dynamics (interest rates, currency exchange rates and real estate prices) and of regulatory policies in energy, transportation and industry. For example, the dynamics of mobility depend upon a trade-off between housing prices and transportation costs in which the price of real estate and the inert endowments in public transport play as important a role as liquid fuel prices (Lampin et al., 2013).

These considerations apply to attempts to secure a minimum price in carbon trading systems (Wood and Jotzo, 2011; Fell et al., 2012; Fuss et al., 2018) and to the reduction of fossil fuel subsidies. Estimated at 650 billion USD in 2015 (Coady et al., 2017), they represent 25–30% of government revenues in forty (mostly developing) countries (IEA, 2014b). Reducing these subsidies would contribute to reaching 1.5°C-consistent pathways, but raises similar issues as carbon pricing around long-term benefits and short-term costs (Jakob et al., 2015; Zeng and Chen, 2016), as well as social impacts.

Explicit carbon prices are thus a necessary ‘lubricant’ to accommodate the general equilibrium effects of higher energy prices but may not suffice to trigger the low-carbon transition because of a persistent ‘implementation gap’ between the aspirational carbon prices and those that can practically be enforced. When systemic changes, such as those needed for 1.5°C-consistent pathways, are at play on many dimensions of development, price levels ‘depend on the path and the path depends on political decisions’ (Dréze and Stern, 1990).

4.4.5.3 Regulatory measures and information flows

Regulatory instruments are a common tool for improving energy efficiency and enhancing renewable energy in OECD countries (e.g., US, Japan, Korea, Australia, the EU) and, more recently, in developing countries (M.H. Scott et al., 2015; Brown et al., 2017) including constraints on the import of products banned in other countries (Knoop and Lechtenböhmer, 2017).
For energy efficiency, these instruments include end-use standards and labelling for domestic appliances, lighting, electric motors, water heaters and air-conditioners. They are often complemented by mandatory efficiency labels to attract consumers’ attention and stimulate the manufacture of more efficient products (Girod et al., 2017). Experience shows that these policy instruments are effective only if they are regularly reviewed to follow technological developments, as in the ‘Top Runner’ programme for domestic appliances in Japan (Sunikka-Blank and Iwafune, 2011).

In four countries, efficiency standards (e.g. miles/gallon or level of CO₂ emission per km) have been used in the transport sector, for light and heavy-duty vehicles, which have spill-overs for the global car industry. In the EU (Ajanovic and Haas, 2017) and the US (Sen et al., 2017) vehicle manufacturers need to meet an annual CO₂ emission target for their entire new vehicle fleet. This allows them to compensate through the introduction of low-emission vehicles for the high-emission ones in the fleet. This leads to increasingly efficient fleets of vehicles over time, but does not necessarily limit the driven distance.

Building codes that prescribe efficiency requirements for new and existing buildings have been adopted in many OECD countries (Evans et al., 2017) and are regularly revised to increase their efficiency per unit of floor space. Building codes can avoid the lock-in of rapidly urbanising countries to poorly performing buildings that remain in use for the next 50–100 years (Ürge-Vorsatz et al., 2014). In OECD countries, however, their main role is to incentivise the retrofit of existing buildings. In addition of the convergence of these codes to Net Zero Energy Buildings (D’Agostino, 2015), a new focus should be placed, in the context of 1.5°C-consistent pathways, on public and private co-ordination to achieve better integration of building policies with the promotion of low-emission transportation modes (Bertoldi, 2017).

The efficacy of regulatory instruments can be reinforced by economic incentives, such as feed-in tariffs based on the quantity of renewable energy produced, subsidies or tax exemptions for energy savings (Bertoldi et al., 2013; Ritzenhofen and Spinler, 2016; García-Alvarez et al., 2017; Pablo-Romero et al., 2017), fee-bates, and ‘bonus-malus’ that foster the penetration of low-emission options (Butler and Neuhoff, 2008). Economic incentives can also be combined with direct use market-based instruments, for example combining, in the United States and, in some EU countries, carbon trading schemes with Energy Savings Obligations for energy retailers ( Haoqi et al., 2017), or with Green Certificates for renewable energy portfolio standards ( Upton and Snyder, 2017). Scholars have investigated caps on utilities’ energy sales (Thomas et al., 2017) and emission caps at a personal level (Fawcett et al., 2010).

In combination with the funding of public research institutes, grants or subsidies also support R&D, where risk and the uncertainty about long-term perspectives can reduce the private sector’s willingness to invest in low-emission innovation (see also Section 4.4.4). Subsidies can take the form of rebates on Value-Added Tax (VAT), of direct support to investments (e.g. renewable energy or refurbishment of buildings) or feed-in tariffs (Mir-Artigues and del Rio, 2014). They can be provided by the public budget, via consumption levies, or via the revenues of carbon taxes or pricing. Fee-bates, introduced in some countries (for example for cars), have had a neutral impact on public budgets by incentivising low-emission products and penalising high-emission ones (de Haan et al., 2009).

All policy instruments can benefit from information campaigns (e.g., TV ads) tailored to specific end-users. A vast majority of public campaigns on energy and climate have been delivered through mass-media channels, and advertising-based approaches (Corner and Randall, 2011; Doyle, 2011). Although some authors report large savings obtained by such campaigns, most agree that the effects are short-lived and decrease over time (Bertoldi et al., 2016). Recently, focus has been placed on the use of social norms to motivate behavioural changes (Allcott, 2011; Alló and Loureiro, 2014). More on strategies to change behaviour can be found in section 4.4.3.

4.4.5.4 Scaling-up Climate Finance and De-Risking Low-Emission Investments

The redirection of savings towards low-emission investments may be constrained by enforceable carbon prices, implementation of technical standards and the short-term bias financial systems (Miles, 1993;
Bushee, 2001; Black and Fraser, 2002). The many causes of this bias are extensively analysed in economic literature (Tehranian and Waegelein, 1985; Shleifer and Vishny, 1990; Bikhchandani and Sharma, 2000) including their link with prevailing patterns of economic globalisation (Krugman, 2009; Rajan, 2011) and the chronic under-investment in long-term infrastructure (IMF, 2014). Emerging literature explores how to overcome this through reforms targeted to bridge the gap between short-term cash balances and long-term low-emission assets and to reduce the risk-weighted capital costs of climate-resilient investments. This gap was qualified by the Governor of the Bank of England as a Tragedy of the Horizons (Carney, 2016) that constitutes a threat to the stability of the financial system, is confirmed by the literature (Arezki et al., 2016; Christophers, 2017). This potential threat would encompass the impact of climate events on the value of assets (Battiston et al., 2017), liability risks (Heede, 2014) and the transition risk due to devaluation of certain classes of assets (Platinga and Scholtens, 2016).

The financial community’s attention to climate change grew after COP 15 (ESRB ASC, 2016). This led to the introduction of climate-related risk disclosure in financial portfolios (UNEP, 2015) placing it on the agenda of G20 Green Finance Study Group and of the Financial Stability Board. This led to the creation of low-carbon financial indices that investors could consider as a ‘free option on carbon’ to hedge against risks of stranded carbon intensive assets (Andersson et al., 2016). This could also accelerate the emergence of climate-friendly financial products such as green or climate bonds, The estimated value of the Green bonds market in 2017 is USD 200 billion (BNEF, 2017). The bulk of these investments are in renewable energy, energy efficiency and low-emission transport (Lazurko and Venema, 2017), with only 4% for adaptation (OECD, 2017b). One major issue is whether individual strategies based on improved climate-related information alone will enable the financial system to allocate capital in an optimal way (Christophers, 2017) since climate change is a systemic risk (Schoenmaker and van Tilburg, 2016) (CISL, 2015).

The readiness of financial actors to reduce investments in fossil fuels is a real trend (Platinga and Scholtens, 2016; Aylung and Gunningham, 2017) but they may not resist the attractiveness of carbon-intensive investments in many regions. Hence, decarbonising an investment portfolio is not synonymous with investing massively in low-emission infrastructure. Scaling up climate-friendly financial products may depend upon a business context conducive to the reduction of the risk-weighted capital costs of low-emission projects. The typical leverage of public funding mechanisms for low-emission investment is low (2 to 4) compared with (10 to 15) in other sectors (Maclean et al., 2008; Ward et al., 2009; MDB, 2016). This is due to the interplay of the uncertainty of emerging low-emission technologies in the midst of their learning-by-doing cycle, and of uncertain future revenues due to volatility of fossil fuel prices (Roques et al., 2008; Gross et al., 2010) and of uncertainty around regulatory policies. This inhibits low-emission investments by corporations functioning under a ‘shareholder value business regime’ (Berle and Means, 1932; Froud et al., 2000; Roe, 2001) and actors with restricted access to capital (e.g. cities, local authorities, SMEs and households).

De-risking policy instruments to enable low-emission investment encompass interest rate subsidies, fee-bates, tax breaks, concessional loans from development banks, and public investment funds, including revolving funds. Given the constraints on public budgets, public guarantees can be used to secure high leverage of public financing. They imply a full direct burden on public budgets only in case of default of the project. They could back for example various forms of Green Infrastructure Funds (De Gouvello and Zelenko, 2010; Emin et al., 2014; Studart and Gallagher, 2015)10.

The risk of defaulting can be mitigated by strong Measurement, Reporting and Verifying (MRV) systems (Belllassen et al., 2015) and by the use of notional prices recommended in public economics and currently in use in France and the UK, to calibrate public support to the provision of public goods in case of persisting distortions in pricing (Stiglitz et al., 2017). Some suggest linking these notional prices to ‘social, economic and environmental value of voluntary mitigation actions’ recognised by the COP21 Decision accompanying the Paris Agreement (paragraph 108) (Hourcade et al., 2015; La Rovere et al., 2017b; Shukla et al., 2017), in order to incorporate the co-benefits of mitigation.

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10 FOOTNOTE: One prototype is the World Bank’s Pilot Auction Facility on Methane and Climate Change
Such public guarantees ultimately amount to money issuance backed by low-emission projects as collateral. This explains the potentially strong link between global climate finance and the evolution of the financial and monetary system. Amongst suggested mechanisms for this evolution are the use of International Monetary Fund’s (IMF’s) Special Drawing Rights to fund the paid-in capital of the Green Climate Fund (Bredenkamp and Pattillo, 2010) and the creation of carbon remediation assets at a predetermined face value per avoided tonne of emissions (Aglietta et al., 2015a, b). Such a predetermined value could hedge against the fragmentation of climate finance initiatives and support the emergence of financial products backed by a new class of long-term assets.

Combining public guarantees at a predetermined value of avoided emissions, in addition to improving the consistency of non-price measures, could support the emergence of financial products backed by a new class of certified assets to attract savers in search of safe and ethical investments (Aglietta et al., 2015b). It could hedge against the fragmentation of climate finance initiatives and provide a mechanism to compensate for the ‘stranded’ assets caused by divestment in carbon-based activities and in lowering the systemic risk of stranded assets (Safarzyńska and van den Bergh, 2017). These new assets could also facilitate a low-carbon transition for fossil-fuel producers and help them to overcome the ‘resource curse’ (Ross, 2015; Venables, 2016).

Blended injection of liquidity has monetary implications. Some argue that this questions the premise that money should remain neutral (Annicchiarico and Di Dio, 2015, 2016; Nikiforos and Zezza, 2017). Central Banks or financial regulators could act as a facilitator of last resort for low-emission financing instruments, that could in turn lower the systemic risk of stranded assets (Safarzyńska and van den Bergh, 2017). This may, in time, lead to the use of carbon-based monetary instruments to diversify reserve currencies (Jaeger et al., 2013) and differentiate reserve requirements (Rozenberg et al., 2013) in the perspective of a Climate Friendly Bretton Woods (Sirkis et al., 2015; Stua, 2017).

### 4.4.5.5 Financial Challenge for Basic Needs and Adaptation Finance

Adaptation finance is difficult to quantify for two reasons. The first is that it is very difficult to isolate specific investment needs to enhance climate resilience from the provision of basic infrastructure that are currently underinvested (IMF, 2014; Gurara et al., 2017). The UNEP (2016) estimate of investment needs on adaptation in developing countries between 140–300 billion USD yr⁻¹ in 2030, a major part being investment expenditures that are complementary with SDG-related investments focussed on universal access to infrastructure and services and meeting basic needs. Many climate adaptation-centric financial incentives are relevant to non-market services, offering fewer opportunities for market revenues while they contribute to creating resilience to climate impacts.

Hence, adaptation investments and the provision of basic needs would typically have to be supported by national and sub-national government budgets together with support from overseas development assistance and multilateral development banks (Fankhauser and Schmidt-Traub, 2011; Adenle et al., 2017; Robinson and Dornan, 2017), and a slow increase of dedicated NGO and private climate funds (Nakhooda and Watson, 2016). Even though the UNEP estimates of the costs of adaptation might be lower in a 1.5°C world (Climate Analytics, 2015) they would be higher than the UNEP 22.5 USD billion estimates of the bilateral and multilateral funding for climate change adaptation in 2014. Currently, 18–25% of climate finance flows to adaptation in developing countries (OECD, 2015, 2016a; Shine and Campillo, 2016). It remains fragmented, with small proportions flowing through UNFCCC channels (AdaptationWatch, 2015; Roberts and Weikmans, 2017).

Means of raising resources for adaptation, achieving the SDG and meeting basic needs (Durand et al., 2016; Roberts et al., 2017) include the reduction of fossil fuel subsidies (Jakob et al., 2016), increasing revenues from carbon taxes (Jakob et al., 2016), levies on international aviation and maritime transport and share of the proceeds of financial arrangements supporting mitigation activities (Keen et al., 2013). Each have different redistribution implications. Challenges, however, include the efficient use of resources, the emergence of long-term assets using infrastructure as collateral and the capacity to implement small-scale
adaptation and the mainstreaming of adaptation in overall development policies. There is thus a need for greater policy coordination (Fankhauser and McDermott, 2014; Morita and Matsumoto, 2015; Sovacool et al., 2015, 2017; Lemos et al., 2016; Adene et al., 2017; Peake and Ekins, 2017) that includes robust mechanisms for tracking, reporting, and ensuring transparency of adaptation finance (Donner et al., 2016; Pauw et al., 2016a; Roberts and Weikmans, 2017; Trabacchi and Buchner, 2017) and its consistency with the provision of basic needs (Hallegatte et al, 2016).

4.4.5.6  Towards Integrated Policy Packages and Innovative Forms of Financial Cooperation

Carbon prices, regulation and standards, improved information and appropriate financial instruments can work synergestically to meet the challenge of ‘making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development’, as in Article 2 in the Paris Agreement.

There is growing attention to combine the use of policy instruments that actually address three domains of action: the behavioural changes, the economic optimisation and the long-term strategies (Grubb et al., 2014). For example, de-risking low-emission investments would result in higher volumes of low-emission investments, and would in turn lead to a lower switching price for the same climate ambition (Hirth and Steckel, 2016). In the reverse direction, higher explicit carbon prices may generate more low-emission projects for a given quantum of de-risking. For example, efficiency standards for housing can increase the efficacy of carbon prices and overcome the barriers coming from the high discount rates used by households (Parry et al., 2014), while explicit and notional carbon prices can lower the risk of arbitrary standards. The calibration of innovative financial instruments to notional carbon prices could encourage large multinational companies to increase their level of internal carbon prices (UNEP, 2016). These notional prices could be higher than explicit carbon prices because they redirect new hardware investments without an immediate impact on existing capital stocks and associated interests.

Literature however shows that conflicts between poorly articulated policy instruments can undermine their efficiency (Lecuyer and Quirion, 2013; Bhattacharya et al., 2017; García-Álvarez et al., 2017). As has been illustrated in Europe, commitment uncertainty and lack of credibility of regulation have consistently led to low carbon prices in the case of the EU Emission Trading System (ETS; Koch et al., 2014; 2016). A comparative study shows how these conflicts can be avoided by policy packages that integrate many dimensions of public policies and are designed to match institutional and social context of each country and region (Bataille et al., 2015).

Even though policy packages depend upon domestic political processes, they might not reinforce the NDCs at a level consistent with the 1.5°C transition without a conducive international setting where international development finance plays a critical role. Section 4.4.1 explores the means of mainstreaming climate finance in the current evolution of the lending practices of national and multilateral bank (Badré, 2018). This could facilitate the access of developing countries to loans via bond markets at low interest rates, encouragement of the emergence of new business models for infrastructure, and encouragement of financial markets to support small-scale investments (Déau and Touati, 2017).

These financial innovations may involve non-state public actors like cities and regional public authorities that govern infrastructure investment, enable energy and food systems transitions and manage urban dynamics (Cartwright, 2015). They would help for example in raising USD 4.5–5.4 trillion yr⁻¹ from 2015 to 2030 announced by the Cities Climate Finance Leadership Alliance (CCFLA, 2016) to achieve the commitments by the Covenant of Mayors of many cities to long-term climate targets (Kona et al., 2018).

The evolution of global climate financial cooperation may involve Central Banks, financial regulatory authorities, multilateral and commercial banks. There are still knowledge gaps about the form, structure and potential of these arrangements. They could be viewed as a form of a burden-sharing between high, medium and low-income countries to enhance, the deployment of ambitious Nationally
Determined Contributions (NDCs), and new forms of Common But Differentiated Responsibility and Respective Capabilities (Edenhofer et al., 2015; Hourcade et al., 2015; Ji and Sha, 2015).

4.5 Integration and Enabling Transformation

4.5.1 Assessing Feasibility of Options for Accelerated Transitions

Chapter 2 shows that 1.5°C-consistent pathways involve rapid, global climate responses to reach net-zero emissions by mid-century or earlier. Chapter 3 identifies climate change risks and impacts to which the world would need to adapt to, during these transitions and additional risks and impacts during potential 1.5°C overshoot pathways. The feasibility of these pathways is contingent upon systemic change (Section 4.3) and enabling conditions (Section 4.4), including policy packages. This section assesses the feasibility of options (technologies, actions and measures) that form parts of global systems under transition that make up 1.5°C-consistent pathways (Section 4.3).

Following the assessment framework developed in Chapter 1, economic and technological; institutional and socio-cultural; and environmental and geophysical feasibility are considered, and applied to system transitions (Sections 4.3.1–4.3.4), overarchin adaptation options (Section 4.3.5) and to Carbon Dioxide Removal (CDR) options (Section 4.3.7). This is done to assess the multi-dimensional feasibility of mitigation and adaptation options that have seen considerable development and change since AR5. In the case of adaptation, the assessed AR5 options are typically clustered, for example, all options related to energy infrastructure resilience, independently of the generation source, are categorised as ‘resilience of power infrastructure’.

Table 4.10 presents sets of indicators against which the multi-dimensional feasibility of individual adaptation options relevant to limiting warming of 1.5°C, and mitigation options along 1.5°C-consistent pathways, are assessed.

Table 4.10: Sets of indicators against which the feasibility of adaptation and mitigation are assessed, for each feasibility dimension (in Sections 4.3.1-4.3.4, 4.3.5 and 4.3.7)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Adaptation indicators</th>
<th>Mitigation indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>Micro-economic viability</td>
<td>Cost-effectiveness</td>
</tr>
<tr>
<td></td>
<td>Macro-economic viability</td>
<td>Absence of distributional effects</td>
</tr>
<tr>
<td></td>
<td>Socio-economic vulnerability</td>
<td>Employment &amp; productivity</td>
</tr>
<tr>
<td></td>
<td>reduction potential</td>
<td>enhancement potential</td>
</tr>
<tr>
<td></td>
<td>Employment &amp; productivity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>enhancement potential</td>
<td></td>
</tr>
<tr>
<td>Technological</td>
<td>Technical resource availability</td>
<td>Technical scalability</td>
</tr>
<tr>
<td></td>
<td>Risks mitigation potential</td>
<td>Maturity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simplicity</td>
</tr>
<tr>
<td>Institutional</td>
<td>Political acceptability</td>
<td>Absence of risk</td>
</tr>
<tr>
<td></td>
<td>Legal &amp; regulatory feasibility</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Institutional capacity &amp; administrative feasibility</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transparency &amp; accountability potential</td>
<td></td>
</tr>
<tr>
<td>Socio-cultural</td>
<td>Social co-benefits (health, education)</td>
<td>Social co-benefits (health, education)</td>
</tr>
<tr>
<td></td>
<td>Socio-cultural acceptability</td>
<td>Public acceptance</td>
</tr>
<tr>
<td></td>
<td>Social &amp; regional inclusiveness</td>
<td>Social &amp; regional inclusiveness</td>
</tr>
<tr>
<td></td>
<td>Intergenerational equity</td>
<td>Intergenerational equity</td>
</tr>
<tr>
<td></td>
<td>Human capabilities</td>
<td>Human capabilities</td>
</tr>
</tbody>
</table>
The feasibility assessment takes the following steps. First, each of the mitigation and adaptation options is assessed along the relevant indicators grouped around six feasibility dimensions: economic, technological, institutional, socio-cultural, environmental/ecological and geophysical. Three types feasibility groupings were assessed from the underlying literature: first, if the indicator could block the feasibility of this option, second, if the indicator has neither a positive, nor a negative effect on the feasibility of the option or the evidence is mixed, and third if the indicator does not pose any barrier to the feasibility of this option. The full assessment of each option under each indicator, including the literature references on which the assessment is based, can be found in supplementary materials D.2 and D.3. When appropriate, it is indicated that there is no evidence (NE), limited evidence (LE) or that the indicator is not applicable to the option (NA).

Next, for each feasibility dimension and option, the overall feasibility for a given dimension is assessed as the mean of combined scores of the relevant underlying indicators, and classified into ‘insignificant barriers’ (2.5 to 3), ‘mixed or moderate but still existent barriers’ (1.5 to 2.5) or ‘significant barriers’ (below 1.5) to feasibility. Indicators assessed as NA, LE or NE are not included in this overall assessment (see supplementary material D.1 for the averaging and weighing guidance).

The results are summarised in Table 4.11 (for mitigation options) and Table 4.12 (for adaptation options) for each of the six feasibility dimensions: where dark shading indicates few feasibility barriers; moderate shading indicates that there are some barriers and light shading that multiple barriers, in this dimension, may block implementation.

A three-step process of independent validation and discussion by authors and reviewers was undertaken to make this assessment as robust as possible within the scope of this special report. It must however, be recognised that this is an indicative assessment at global scale, and both policy and implementation at regional, national and local level would need to adapt and build on this knowledge, within the particular local context and constraints.

### 4.5.2 Implementing Mitigation

This section builds on the insights on mitigation options in Section 4.3, applies the assessment methodology along feasibility dimensions and indicators explained in Section 4.5.1, and synthesises the assessment of the enabling conditions in Section 4.4.

#### 4.5.2.1 Assessing of Mitigation Options for Limiting Warming to 1.5°C Against Feasibility Dimensions

An assessment of the degree to which examples of 1.5°C-relevant mitigation options face barriers to implementation, and on which contexts this depends, is summarised in Table 4.11. An explanation of the approach is given in Section 4.5.1 and in supplementary material D.1. Selected options were mapped onto system transitions and clustered through an iterative process of literature review, expert feedback, and responses to reviewer comments. The detailed assessment and the literature underpinning the assessment can be found in supplementary material D.2.
The feasibility framework in Cross-Chapter Box 3 in Chapter 1 highlights that the feasibility of mitigation and adaptation options depends on many factors. Many of those are captured in the indicators in Table 4.10, but many depend on the specific context in which an option features. Since this Special Report did not have the mandate, space nor the literature base to undertake a regionally specific assessment. Hence the assessment is caveated as providing a broad indication of where the global barriers are likely to ignoring significant regional diversity. Regional and context-specific literature is also just emerging as recorded in knowledge gaps (Section 4.6). Nevertheless, in Table 4.11, an indicative attempt has been made to capture some relevant contextual information. The ‘context’ column indicates what contextual factors may affect the feasibility of an option, including regional differences. For instance, solar irradiation in an area impacts the cost-effectiveness of solar Photovoltaic (PV), so solar irradiation is mentioned in this column.
**Table 4.11:** Feasibility assessment of examples of 1.5°C-relevant mitigation options with dark shading signifying the absence of barriers in the feasibility dimension, moderate shading that on average, the dimension does not have a positive, nor a negative effect on the feasibility of the option, and faint shading the presence of potentially blocking barriers. No shading means that not sufficient literature could be found to make the assessment. Evidence and agreement assessment is undertaken at the option level. The context column on the far right indicates how the assessment might change if contextual factors are different. For the methodology and literature basis, see supplementary material D.1 and D.2.

<table>
<thead>
<tr>
<th>System</th>
<th>Mitigation option</th>
<th>Evidence</th>
<th>Agreement</th>
<th>Ec</th>
<th>Tec</th>
<th>Inst</th>
<th>Soc</th>
<th>Env</th>
<th>Geo</th>
<th>Context</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy system transitions</strong></td>
<td>Wind energy (on-shore &amp; off-shore)</td>
<td>Robust</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Wind regime, economic status, space for windfarms and enhanced by legal framework for independent power producers affect uptake; cost-effectiveness affected by incentive regime.</td>
</tr>
<tr>
<td></td>
<td>Solar PV</td>
<td>Robust</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cost-effectiveness affected by solar irradiation and incentive regime. Also enhanced by legal framework for independent power producers affect uptake.</td>
</tr>
<tr>
<td></td>
<td>Bioenergy</td>
<td>Robust</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Depends on availability of biomass and land and capability to manage sustainable land use. Distributional effects depend on the agrarian (or other) system used to produce feedstock.</td>
</tr>
<tr>
<td></td>
<td>Electricity storage</td>
<td>Robust</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Batteries universal but grid flexible resources vary with area’s level of development.</td>
</tr>
<tr>
<td></td>
<td>Power sector CCS</td>
<td>Robust</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Varies with local CO2 storage capacity, presence of legal framework, level of development and quality of public engagement.</td>
</tr>
<tr>
<td></td>
<td>Nuclear energy</td>
<td>Robust</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Electricity market organisation, legal framework, standardisation &amp; know-how, country’s ‘democratic fabric’, institutional and technical capacity, and safety culture of public and private institutions.</td>
</tr>
<tr>
<td><strong>Land &amp; ecosystem transitions</strong></td>
<td>Reduced food wastage &amp; efficient food production</td>
<td>Robust</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Will depend on the combination of individual and institutional behaviour.</td>
</tr>
<tr>
<td></td>
<td>Dietary shifts</td>
<td>Medium</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Depends on individual behaviour, education, cultural factors and institutional support.</td>
</tr>
<tr>
<td></td>
<td>Sustainable intensification of agriculture</td>
<td>Medium</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Depends on development and deployment of new technologies.</td>
</tr>
<tr>
<td></td>
<td>Ecosystems restoration</td>
<td>Medium</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Depends on location and institutional factors.</td>
</tr>
<tr>
<td>Ur ba n</td>
<td>Land-use &amp; urban planning</td>
<td>Robust</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Varies with urban fabric, not geography or economy; requires capacitated local government and legitimate tenure system.</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Technology</th>
<th>Final Government Draft</th>
<th>IPCC SR1.5</th>
<th>Chapter 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric cars and buses</td>
<td>Medium</td>
<td>High</td>
<td>Varies with degree of government intervention; requires capacity to retrofit “fuelling” stations</td>
</tr>
<tr>
<td>Sharing schemes</td>
<td>Limited Medium</td>
<td>Medium</td>
<td>Historic schemes universal new ones depend on ICT status; undermined by high crime and low levels of law enforcement</td>
</tr>
<tr>
<td>Public transport</td>
<td>Robust</td>
<td>Medium</td>
<td>Depends on presence of existing ‘informal’ taxi systems, which may be more cost effective and affordable than capital intensive new build schemes, as well as (local) government capabilities</td>
</tr>
<tr>
<td>Non-motorised transport</td>
<td>Robust</td>
<td>High</td>
<td>Viability rests on linkages with public transport, cultural factors, climate and geography</td>
</tr>
<tr>
<td>Aviation &amp; shipping</td>
<td>Medium</td>
<td>Medium</td>
<td>Varies with technology, governance and accountability</td>
</tr>
<tr>
<td>Smart Grids</td>
<td>Medium</td>
<td>Medium</td>
<td>Varies with economic status and presence or quality of existing grid</td>
</tr>
<tr>
<td>Efficient appliances</td>
<td>Medium</td>
<td>High</td>
<td>Adoption varies with economic status and policy framework</td>
</tr>
<tr>
<td>Low/zero-energy buildings</td>
<td>Medium</td>
<td>High</td>
<td>Depends on size of existing building stock and growth of building stock</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>Robust</td>
<td>High</td>
<td>Potentials and adoption depends on existing efficiency, energy prices and interest rates, as well as government incentives.</td>
</tr>
<tr>
<td>Bio-based &amp; circularity</td>
<td>Medium</td>
<td>Medium</td>
<td>Faces barriers in terms of pressure on natural resources and biodiversity. Product substitution depends on market organisation and government incentivisation.</td>
</tr>
<tr>
<td>Electrification &amp; hydrogen</td>
<td>Medium</td>
<td>High</td>
<td>Depends on availability of large-scale, cheap, emission-free electricity (electrification, hydrogen) or CO2 storage nearby (hydrogen). Manufacturers’ appetite to embrace disruptive innovations</td>
</tr>
<tr>
<td>Industrial CCUS</td>
<td>Robust</td>
<td>High</td>
<td>High concentration of CO2 in exhaust gas improve economic and technical feasibility of CCUS in industry. CO2 storage or reuse possibilities.</td>
</tr>
<tr>
<td>BECCS</td>
<td>Robust</td>
<td>Medium</td>
<td>Depends on biomass availability, CO2 storage capacity, legal framework, economic status and social acceptance</td>
</tr>
<tr>
<td>DACCs</td>
<td>Medium</td>
<td>Medium</td>
<td>Depends on CO2-free energy, CO2 storage capacity, legal framework, economic status and social acceptance</td>
</tr>
<tr>
<td>Afforestation &amp; reforestation</td>
<td>Robust</td>
<td>High</td>
<td>Depends on location, mode of implementation, and economic and institutional factors</td>
</tr>
<tr>
<td>Soil carbon sequestration &amp; biochar</td>
<td>Robust</td>
<td>High</td>
<td>IPCC SR1.5</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>--------</td>
<td>------</td>
<td>------------</td>
</tr>
<tr>
<td>Enhanced weathering</td>
<td>Medium</td>
<td>Low</td>
<td></td>
</tr>
</tbody>
</table>
4.5.2.2 Enabling Conditions for Implementation of Mitigation Options Towards 1.5°C

The feasibility assessment highlights six dimensions that could help inform an agenda that could be addressed by the areas discussed in Section 4.4: governance, behaviour and lifestyles, innovation, enhancing institutional capacities, policy and finance. For instance, Section 4.4.3 on behaviour offers strategies for addressing public acceptance problems, and how changes can be more effective when communication and the actions relate to people’s values. This section synthesises the findings in Section 4.4 in an attempt to link them to the assessment in Table 4.11. The literature on which the discussion is based is found in Section 4.4.

From Section 4.4, including the case studies presented in the Boxes 4.1 to 4.10, several main messages can be constructed. For instance, governance would have to be multi-level and engaging different actors, while being efficient, and choosing the type of cooperation based on the specific systemic challenge or option at hand. If institutional capacity for financing and governing the various transitions is not urgently built, many countries would lack the ability to change pathways from a high-emission scenario to a low- or zero-emission scenario. In terms of innovation, governments, both national and multilateral, can contribute to the mitigation-oriented application of general purpose technologies. If this is not managed, some emission reduction could happen autonomously, but it may not lead to a 1.5°C-consistent pathway. International cooperation on technology, including technology transfer where this does not happen autonomously, is needed and can help creating the innovation capabilities in all countries to be able to operate, maintain, adapt and regulate a portfolio of mitigation technologies. Case studies in the various sub-sections highlight the opportunities and challenges of doing this in practice. They indicate that it can be done in specific circumstances.

A combination of behaviour-oriented pricing policies and financing options can help change technologies and social behaviour as it challenges the existing, high-emission socio-technical regime on multiple levels across feasibility characteristics. For instance, for dietary change, a combination of supply-side measures with value-driven communication and economic instruments may help make a lasting transition, while only an economic instrument, such as enhanced prices or taxation, may not be as robust.

Governments could benefit from enhanced carbon prices, as a price and innovation incentive and also source of additional revenue to correct distributional effects and subsidise the development of new, cost-effective negative-emission technology and infrastructure. However, there is high evidence and medium agreement that pricing alone is insufficient. Even if prices rise significantly, they typically incentivise incremental change, but typically fail to provide the impetus for private actors to take the risk of engaging in the transformational changes that would be needed to limit warming to 1.5°C. Apart from the incentives to change behaviour and technology, financial systems are an indispensable element of a systemic transition. If financial markets do not acknowledge climate risk and the risk of transitions, they could be organised by regulatory financial institutions, such as central banks.

Strengthening implementation revolves around more than addressing barriers to feasibility. A system transition, be it in energy, industry, land or a city, requires changing the core parameters of a system. These relate, as introduced in Section 4.2 and further elaborated in Section 4.4, to how actors cooperate, how technologies are embedded, how resources are linked, how cultures relate and what values people associate with the transition and the current regime.

4.5.3 Implementing Adaptation

Article 7 of the Paris Agreement provides an aspirational global goal for adaptation, of ‘enhancing adaptive capacity, strengthening resilience, and reducing vulnerability’ (UNFCCC, 2015). Adaptation implementation is gathering momentum in many regions, guided by national NDC’s and National Adaptation Plans (see Cross-Chapter Box 11 in this Chapter).

Operationalising adaptation in a set of regional environments on pathways to a 1.5°C world, requires strengthened global and differentiated regional and local capacities. It also needs rapid and decisive
adaptation actions to reduce the costs and magnitude of potential climate impacts (Vergara et al., 2015).

This could be facilitated by: i) enabling conditions, especially improved governance, economic measures and financing (Section 4.4); ii) enhanced clarity on adaptation options to help identify strategic priorities, sequencing and timing of implementation (Section 4.3); iii) robust monitoring and evaluation frameworks; and iv) political leadership (Magnan et al., 2015; Magnan and Ribera, 2016; Lesnikowski et al., 2017; UNEP, 2017a).

4.5.3.1 Feasible Adaptation Options

This section summarises the feasibility (defined in Cross-Chapter Box 3, Table 1 in Chapter 1 and Table 4.4) of select adaptation options using evidence presented across this chapter and in supplementary material D.3 and the expert-judgement of its authors (Table 4.12). The options assessed respond to risks and impacts identified in Chapter 3. They were selected based on options identified in AR5 (Noble et al., 2014), focusing on those relevant to 1.5°C-compatible pathways, where sufficient literature exists. Selected options were mapped onto system transitions and clustered through an iterative process of literature review, expert feedback, and responses to reviewer comments.

Besides gaps in the literature around crucial adaptation questions on the transition to a 1.5°C world (Section 4.6), there is inadequate current literature to undertake a spatially differentiated assessment (Cross-Chapter Box 3 in Chapter 1). There are also limited baselines for exposure, vulnerability and risk to help policy and implementation prioritisation. Hence, the compiled results can at best provide a broad framework to inform policymaking. Given the bottom-up nature of most adaptation implementation evidence, care needs to be taken in generalising these findings.

Options are considered as part of a systemic approach, recognising that no single solution to exits to limit warming to 1.5°C and adapting to its impacts. To respond to the local and regional context, and synergies and trade-offs between adaptation, mitigation and sustainable development, packages of options suited to local enabling conditions, can be implemented.

Table 4.12 summarises the feasibility assessment through its six dimensions with levels of evidence and agreement, and indicates how the feasibility of an adaptation option may be differentiated by certain contextual factors (last column).
Table 4.12: Feasibility assessment of examples of 1.5°C-relevant adaptation options with dark shading signifying the absence of barriers in the feasibility dimension, moderate shading that on average, the dimension does not have a positive, nor a negative effect on the feasibility of the option, and light shading the presence of potentially blocking barriers. No shading means that not sufficient literature could be found to make the assessment. NA signifies that the dimension is not applicable to that adaptation option. For methodology and literature basis, see supplementary material D.

<table>
<thead>
<tr>
<th>System</th>
<th>Adaptation option</th>
<th>Evidence</th>
<th>Agreement</th>
<th>Ec</th>
<th>Tec</th>
<th>Inst</th>
<th>Soc</th>
<th>Env</th>
<th>Geo</th>
<th>Context</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy system transitions</td>
<td>Power infrastructure, including water</td>
<td>Medium</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Depends on existing power infrastructure, all generation sources and with intensive water requirements</td>
</tr>
<tr>
<td></td>
<td>Conservation agriculture</td>
<td>Medium</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Depends on irrigated/rainfed system, ecosystem characteristics, crop type, other farming practices</td>
</tr>
<tr>
<td></td>
<td>Efficient irrigation</td>
<td>Medium</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Depends on agricultural system, technology used, regional institutional and biophysical context</td>
</tr>
<tr>
<td></td>
<td>Efficient livestock</td>
<td>Limited</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dependent on livestock breeds, feed practices, and biophysical context (e.g. carrying capacity)</td>
</tr>
<tr>
<td>Land &amp; ecosystem transitions</td>
<td>Agroforestry</td>
<td>Medium</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Depends on knowledge, financial support, and market conditions</td>
</tr>
<tr>
<td></td>
<td>Community-based adaptation</td>
<td>Medium</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Focus on rural areas and combined with ecosystems-based adaptation, does not include urban settings</td>
</tr>
<tr>
<td></td>
<td>Ecosystem restoration &amp; avoided deforestation</td>
<td>Robust</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mostly focused on existing and evaluated REDD+ projects</td>
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<tr>
<td></td>
<td>Biodiversity management</td>
<td>Medium</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Focus on hotspots of biodiversity vulnerability and high connectivity</td>
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<tr>
<td></td>
<td>Coastal defense &amp; hardening</td>
<td>Robust</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Depends on locations that require it as a first adaptation option</td>
</tr>
<tr>
<td>Urban &amp; infrastructure system transitions</td>
<td>Sustainable land-use &amp; urban planning</td>
<td>Medium</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Depends on nature of planning systems and enforcement mechanisms</td>
</tr>
<tr>
<td></td>
<td>Sustainable water management</td>
<td>Robust</td>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Balancing sustainable water supply and rising demand especially in low-income countries</td>
</tr>
<tr>
<td></td>
<td>Green infrastructure &amp; ecosystem services</td>
<td>Medium</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Depends on reconciliation of urban development with green infrastructure</td>
</tr>
<tr>
<td>Building codes &amp; standards</td>
<td>Limited</td>
<td>Medium</td>
<td>Adoption requires legal, educational, and enforcement mechanisms to regulate buildings</td>
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<tr>
<td>Intensive industry infrastructure resilience and water management</td>
<td>Limited</td>
<td>High</td>
<td>Depends on intensive industry, existing infrastructure and using or requiring high demand of water</td>
<td></td>
<td></td>
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<tr>
<td>Disaster risk management</td>
<td>Medium</td>
<td>High</td>
<td>Requires institutional, technical, and financial capacity in frontline agencies and government</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Risk spreading and sharing</td>
<td>Medium</td>
<td>Medium</td>
<td>Requires well developed financial structures and public understanding</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Climate services</td>
<td>Medium</td>
<td>High</td>
<td>Depends on climate information availability and usability, local infrastructure and institutions, national priorities</td>
<td></td>
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<tr>
<td>Indigenous knowledge</td>
<td>Medium</td>
<td>High</td>
<td>Dependent on recognition of Indigenous rights, laws, and governance systems</td>
<td></td>
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<tr>
<td>Education and learning</td>
<td>Medium</td>
<td>High</td>
<td>Existing education system, funding</td>
<td></td>
<td></td>
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<tr>
<td>Population health and health system</td>
<td>Medium</td>
<td>High</td>
<td>Requires basic health services and infrastructure</td>
<td></td>
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</tr>
<tr>
<td>Social safety nets</td>
<td>Medium</td>
<td>Medium</td>
<td>Type and mechanism of safety net, political priorities, institutional transparency</td>
<td></td>
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<tr>
<td>Human migration</td>
<td>Medium</td>
<td>Low</td>
<td>Hazard exposure, political and socio-cultural acceptability (in destination), migrant skills and social networks</td>
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</tbody>
</table>

Overarching adaptation options

| Disaster risk management | Medium | High | Requires institutional, technical, and financial capacity in frontline agencies and government |
| Risk spreading and sharing | Medium | Medium | Requires well developed financial structures and public understanding |
| Climate services | Medium | High | Depends on climate information availability and usability, local infrastructure and institutions, national priorities |
| Indigenous knowledge | Medium | High | Dependent on recognition of Indigenous rights, laws, and governance systems |
| Education and learning | Medium | High | Existing education system, funding |
| Population health and health system | Medium | High | Requires basic health services and infrastructure |
| Social safety nets | Medium | Medium | Type and mechanism of safety net, political priorities, institutional transparency |
| Human migration | Medium | Low | Hazard exposure, political and socio-cultural acceptability (in destination), migrant skills and social networks |
When considered jointly, the description of adaptation options (Section 4.3), the feasibility assessment (summarised in Table 4.12), and discussion of enabling conditions (Section 4.4) show us how options can be implemented and lead towards transformational adaptation if and when needed.

The adaptation options for energy system transitions focus on existing power infrastructure resilience and water management, when required, for any type of generation source. These options are not sufficient for the far-reaching transformations required in the energy sector, which have tended to focus on technologies to shift from a fossil-based to a renewable energy system (Erlinghagen and Markard, 2012; Muench et al., 2014; Brand and von Gleich, 2015; Monstadt and Wolff, 2015; Child and Breyer, 2017; Hermwille et al., 2017). There is also need for integration of this with social-ecological systems transformations to increase the resilience of the energy sector, for which appropriate enabling conditions, such as for technological innovations, are fundamentally important. Institutional capacities can be enhanced by expanding the role of actors as transformation catalysts (Erlinghagen and Markard, 2012). The integration of ethics and justice within these transformations can help attain the SDG7 on clean energy access (Jenkins et al., 2018), while inclusion of the cultural dimension and cultural legitimacy (Amars et al., 2017) can provide a more substantial base for societal transformation. Strengthening policy instruments and regulatory frameworks and enhancing multi-level governance that focusses on resilience components can help secure these transitions (Exner et al., 2016).

For land and ecosystem transitions, conservation agriculture, efficient irrigation, agroforestry, ecosystem restoration and avoided deforestation, and coastal defence and hardening have between medium and robust evidence with medium to high agreement. The other options assessed have limited or no evidence across one or more of the feasibility dimensions. Community-based adaptation is assessed as an option many opportunities with medium evidence and high agreement though faces scaling barriers. Given the structural changes these options may require, transformational adaptation may be implied in some regions, involving enhanced multi-level governance and institutional capacities by enabling anticipatory and flexible decision-making systems that access and develop collaborative networks (Dowd et al., 2014), tackling root causes of vulnerability (Chung Tiam Fook, 2017), and developing synergies between development and climate change (Burch et al., 2017). Case studies show the use of transformational adaptation approaches for fire management (Colloff et al., 2016a), floodplain and wetland management (Colloff et al., 2016b), and forest management (Chung Tiam Fook, 2017), in which the strengthening of policy instruments and climate finance are also required.

There is growing recognition of the need for transformational adaptation within the agricultural sector but limited evidence on how to facilitate processes of deep, systemic change (Dowd et al., 2014). Case studies demonstrate that transformational adaptation in agriculture requires a sequencing and overlap between incremental and transformational adaptation actions (Hadarits et al., 2017; Termeer et al., 2017), e.g., incremental improvements to crop management while new crop varieties are being researched and field tested (Rippke et al., 2016). Broader considerations include addressing stakeholder values and attitudes (Fleming et al., 2015a), understanding and leveraging the role of social capital, collaborative networks, and information (Dowd et al., 2014), and being inclusive with rural and urban communities, and the social, political, and cultural environment (Rickards and Howden, 2012). Transformational adaptation in agriculture systems could have significant economic and institutional costs (Mushtaq, 2016), along with potential unintended negative consequences (Davidson, 2016; Rippke et al., 2016; Gajjar et al., 2018; Mushtaq, 2018), and a need to focus on the transitional space between incremental and transformational adaptation (Hadarits et al., 2017), as well as the timing of the shift from one to the other (Läderach et al., 2017).

Within urban and infrastructure transitions, green infrastructure and sustainable water management are assessed as the most feasible options, followed by sustainable land-use and urban planning. The need for transformational adaptation in urban settings arises from the root causes of poverty, failures in sustainable development, and a lack of focus on social justice (Revi et al., 2014a; Parnell, 2015; Simon and Leck, 2015; Shi et al., 2016; Ziervogel et al., 2016a; Burch et al., 2017), with the focus on governance structures and the inclusion of equity and justice (Bos et al., 2015; Shi et al., 2016; Hölscher et al., 2018).
Current implementation of Urban Ecosystems-based Adaptation (EbA) lacks a systems perspective of transformations and consideration of the normative and ethical aspects of EbA (Brink et al., 2016). Flexibility within urban planning could help deal with the multiple uncertainties of implementing adaptation (Radhakrishnan et al., 2018) (Rosenzweig and Solecki, 2014), for example, urban adaptation pathways were implemented in the aftermath of Hurricane Sandy in New York, which is considered as tipping point that led to the implementation of transformational adaptation practices.

Adaptation options for industry focus on infrastructure resilience and water management. Like with energy system transitions, technological innovation would be required, but also the enhancement of institutional capacities. Recent research illustrates transformational adaptation within industrial transitions focusing on the role of different actors and tools driving innovation, and points to the role of Nationally Appropriate Mitigation Actions in avoiding lock-ins and promoting system innovation (Boodoo and Olsen, 2017), the role of private sector in sustainability governance in the socio-political context (Burch et al., 2016), and of green entrepreneurs driving transformative change in the green economy (Gibbs and O’Neill, 2014). (Lim-Camacho et al., 2015) suggest an analysis of the complete lifecycle of supply chains as a means of identifying additional adaptation strategies, as opposed to the current focus on a part of the supply chain. Chain-wide strategies can modify the rest of the chain and present a win-win with commercial objectives. The assessed adaptation options also have mitigation synergies and tradeoffs (assessed in Section 4.5.4) that need to be carefully considered, while planning climate action.

4.5.3.2 Monitoring and Evaluation

Monitoring and Evaluation (M&E) in adaptation implementation can promote accountability and transparency of adaptation financing, facilitate policy learning and the share good practices, pressure laggards, and guide adaptation planning. The majority of research on M&E focuses on specific policies or programmes, and has typically been driven by the needs of development organisations, donors, and governments to measure the impact and attribution of adaptation initiatives (Ford and Berrang-Ford, 2016). There is growing research examining adaptation progress across nations, sectors, and scales (Austin et al. 2016; Heidrich et al. 2016; Lesnikowski et al. 2016; Reckien et al. 2014; Robinson 2017; Araos et al. 2016a,b). Responding to need for global, regional and local adaptation, developing indicators and standardised approaches to evaluate and compare adaptation over time and across regions, countries, and sectors would enhance comparability and learning. A number of constrains continue to hamper progress on adaptation M&E, including a debate on what actually constitutes adaptation for purposes of assessing progress (Dupuis and Biesbroek 2013; Biesbroek et al. 2015), absence of comprehensive and systematically collected data on adaptation to support longitudinal assessment and comparison (Lesnikowski et al. 2016; Ford et al. 2015), lack of agreement on indicators to measure (Lesnikowski et al. 2015; Bours et al. 2015; Brooks et al. 2013), and challenges of attributing altered vulnerability to adaptation actions (UNEP 2017; Bours et al. 2015; Ford et al. 2013).

4.5.4 Synergies and Trade-Offs Between Adaptation and Mitigation

Implementing a particular mitigation or adaptation option may affect the feasibility and effectiveness of other mitigation and adaptation options. Supplementary Material E.1 provides examples of possible positive impacts (synergies) and negative impacts (trade-offs) of mitigation options for adaptation. For example, renewable energy sources such as wind energy and solar PV combined with electricity storage can increase resilience due to distributed grids, thereby enhancing both mitigation and adaptation. Yet, as another example, urban densification may reduce Greenhouse Gas (GHG) emissions, enhancing mitigation, but can also intensify heat island effects and inhibit restoration of local ecosystems if not accounted for, thereby increasing adaptation challenges.

The table in Supplementary Material E.2 provides examples of synergies and trade-offs of adaptation options for mitigation. It shows, for example, that conservation agriculture can reduce some GHG emissions and thus...
enhance mitigation, but at the same time increase other GHG emissions thereby reducing mitigation potential. As another example, agroforestry can reduce GHG emissions through reduced deforestation and fossil fuel consumption, but has a lower carbon sequestration potential compared with natural and secondary forest.

Maladaptive actions could increase the risk of adverse climate-related outcomes, for example, biofuel targets could lead to indirect land use change and influence local food security, through a shift in land use abroad in response to increased domestic biofuel demand, increasing global GHG emissions, rather than decreasing it.

Various options enhance both climate change mitigation and adaptation, and would hence serve two 1.5°C-related goals: reducing emissions while adapting to the associated climate change. Examples of such options are reforestation, urban and spatial planning, and land and water management.

Synergies between mitigation and adaptation may be enhanced, and trade-offs reduced, by considering enabling conditions (Section 4.4), while trade-offs can be amplified when enabling conditions are not considered (C.A. Scott et al., 2015). For example, information that is tailored to the personal situation of individuals and communities, including climate services, that are credible and targeted at the point of decision making, can enable and promote both mitigation and adaptation actions (Section 4.4.3). Similarly, multi-level governance and community participation, respectively, can enable and promote both adaptation and mitigation actions (Section 4.4.1). Governance, policies and institutions can facilitate the implementation of the Water-Energy-Food (WEF) nexus (Rasul and Sharma, 2016). The WEF can enhance food, water and energy security, particularly in cities with agricultural production areas (Biggs et al., 2015), electricity generation with intensive water requirements (Conway et al. 2015), and in agriculture (El Gafy et al., 2017) and livelihoods (Biggs et al., 2015). Such a nexus approach can reduce the transport energy that is embedded in food value chains (Villarrello Walker et al., 2014), providing diverse sources of food in the face of changing climates (Tacoli et al., 2013). Urban agriculture, where integrated, can mitigate climate change and support urban flood management (Angotti, 2015; Bell et al., 2015; Biggs et al., 2015; Gwedla and Shackleton, 2015; Lwasa et al., 2015; Y.C.E. Yang et al., 2016; Sanesi et al., 2017). In the case of electricity generation, enabling conditions through a combination of carefully selected policy instruments can maximize the synergic benefits between low GHG energy production and water for energy (Shang et al., 2018).

Despite the multiple benefits of maximising synergies between mitigation and adaptations options through the WEF nexus approach (Chen and Chen, 2016), there are implementation challenges given institutional complexity, political economy, and interdependencies between actors (Leck et al., 2015).

[START BOX 4.10 HERE]

Box 4.10: Bhutan: Synergies and Trade-Offs in Economic Growth, Carbon Neutrality and Happiness

Bhutan has three national goals, improving: its Gross National Happiness Index (GNHI), economic growth (Gross Domestic Product, GDP) and carbon neutrality. These goals increasingly interact and raise questions about whether they can be sustainably maintained into the future. Interventions in this enabling environment are required to comply with all three goals.

Bhutan is well known for its GNHI, which is based on a variety of indicators covering psychological well-being, health, education, cultural and community vitality, living standards, ecological issues and good governance (RGoB, 2012; Schroeder and Schroeder, 2014; Ura, 2015). The GNHI is a precursor to the Sustainable Development Goals (SDGs) (Allison, 2012; Brooks, 2013) and reflects local enabling environments. The GNHI has been measured twice, in 2010 and 2015, and this showed an increase of 1.8% (CBS, 2016). Like most emerging countries, Bhutan wants to increase its wealth and become a middle-income country (RGoB, 2013, 2016), while it remains carbon-neutral, a goal which has been in place since 2011 at COP 19 and was reiterated in its Intended Nationally Determined Contribution (NEC, 2015). Bhutan achieves its current carbon-neutral status through hydropower and forest cover (Yangka and Diesendorf, 2016) which are part of their resilience and adaptation strategy.

Nevertheless, Bhutan faces rising Greenhouse Gas (GHG) emissions. Transport and industry are the largest...
growth areas (NEC, 2011). Bhutan’s carbon-neutral status would be threatened by 2037 by business-as-usual approaches to economic growth (Yangka and Newman, 2018). Increases in hydropower are being planned based on climate change scenarios that suggest sufficient water supply will be available (NEC, 2011). Forest cover is expected to remain sufficient to maintain co-benefits. The biggest challenge is to electrify both freight and passenger transport (ADB, 2013). Bhutan wants to be a model for achieving economic growth consistent with limiting climate change to 1.5°C and improving its Gross National Happiness (Michaelowa et al., 2018) through synthesizing all three goals and improving its adaptive capacity.

[END BOX 4.10 HERE]
4.6 Knowledge Gaps and Key Uncertainties

The global response to limiting warming to 1.5°C is a new knowledge area, that has emerged after the Paris Agreement. This sections presents a number of knowledge gaps that have emerged from the assessment of mitigation, adaptation and Carbon Dioxide Removal (CDR) options and Solar Radiation Modification (SRM) measures, enabling conditions, and synergies and tradeoffs. Illustrative questions that emerge synthesising the more comprehensive Table 4.14 below include: how much can be realistically expected from innovation, behaviour and systemic political and economic change in improving resilience, enhancing adaptation and reducing GHG emissions? How can rates of changes be accelerated and scaled up? What is the outcome of realistic assessments of mitigation and adaptation land transitions that are compliant with sustainable development, poverty eradication and addressing inequality? What are life-cycle emissions and prospects of early-stage CDR options? How can climate and sustainable development policies converge, and how can they be organised within a global governance framework and financial system, based on principles of justice and ethics (CBDR-RC), reciprocity and partnership? To what extent limit warming to 1.5°C needs a harmonization of macro-financial and fiscal policies, that could include Central banks? How can different actors and processes in climate governance reinforce each other, and hedge against the fragmentation of initiatives?

These knowledge gaps are highlighted in Table 4.13 along with a cross-reference to the respective sections in the last column.

Table 4.13: Knowledge gaps and uncertainties

<table>
<thead>
<tr>
<th>Knowledge area</th>
<th>Mitigation</th>
<th>Adaptation</th>
<th>Reference</th>
</tr>
</thead>
</table>
| 1.5°C pathways and ensuing change | • Lack of literature specific to 1.5°C on investment costs with detailed breakdown by technology.  
• Lack of literature specific to 1.5°C on mitigation costs in terms of GDP and welfare.  
• Lack of literature on distributional implications of 1.5°C compared to 2°C or business-as-usual at sectoral and regional levels.  
• Limited 1.5°C-specific case studies for mitigation  
• Limited knowledge on the systemic and dynamic aspects of transitions to 1.5°C, including how vicious or virtuous circles might work, how self-reinforcing aspects can be actively introduced and managed. | • Lack of literature specific to 1.5°C on adaptation costs and need  
• Lack of literature on what overshoot means for adaptation  
• Lack of knowledge on avoided adaptation investments associated with limiting warming to 1.5°C, 2°C or business-as-usual  
• Limited 1.5°C-specific case studies for adaptation  
• Scant literature examining current or future adaptation options, or examining what different climate pathways mean for adaptation success  
• Need for transformational adaptation at 1.5°C and beyond remains largely unexplored | 4.2 |
| Options to achieve and | Energy | • The shift to variable renewables that many countries are implementing is just reaching a level where large-scale storage systems or other grid | • Relatively little literature on individual adaptation options since AR5 | 4.3.1 |
### adapt to 1.5°C

| | flexibility options, e.g., demand response, are required to enable resilient grid systems, thus, new knowledge on the opportunities and issues associated with scaling up zero carbon grids would be needed including knowledge about how zero carbon electric grids can integrate with the full scale electrification of transport systems. |
| | - CCS suffers mostly from uncertainty about the feasibility of timely upscaling, both due to lack of regulatory capacity and concerns about storage safety and cost. |
| | - There is not much literature on the distributional implications of large-scale bioenergy deployment, the assessment of environmental feasibility is hampered by a diversity of contexts of individual studies (type of feedstock, technology, land availability), which could be improved through emerging meta-studies. |
| | - No evidence on socio-cultural acceptability of adaptation options |
| | - Lack of regional research on the implementation of adaptation options. |

### Land & ecosystems

| | More knowledge would be needed on how land-based mitigation can be reconciled with land demands for adaptation and development. |
| | - While there is now more literature on the underlying mechanisms of land transitions, data is often insufficient to draw robust conclusions, and uncertainty about land availability |
| | - The lack of data counts on social and institutional information (largest knowledge gap indicated for ecosystems restoration in Table 4.11), which is therefore not widely integrated in land use modelling. |
| | - Examples of successful policy implementation and institutions related to land-based mitigation leading to co-benefits for adaptation and development are missing from the literature |
| | - Regional information on some options does not exist, especially in the case of land use transitions. |
| | - Limited research examining socio-cultural perspectives and impacts of adaptation options, especially for efficient irrigation, coastal defense and hardening, agroforestry and biodiversity management |
| | - Lack of longitudinal, regional studies assessing the impacts of certain adaptation options such as conservation agriculture and shifting to efficient livestock systems. |
| | - More knowledge is needed on the cost-effectiveness and scalability of various adaptation options. For example, there is no evidence for the macro-economic viability of Community-based Adaptation (CbA) and biodiversity management, nor on employment and productivity enhancement |

| Do Not Cite, Quote or Distribute | 4-112 | Total pages: 198 |
| Urban systems & infrastructure | • Limited evidence of effective land use planning in low income cities where tenure and land zoning is contested, and the risks of trying to implement land use planning under communal tenure.  
• Limited evidence on the governance of public transport from an accountability and transparency perspective  
• Limited evidence on relationship between toxic waste and public transport.  
• Limited evidence on the impacts of electric vehicles and non-motorised urban transport as most schemes are too new.  
• As changes in shipping and aviation have been limited to date, limited evidence of social impacts.  
• Knowledge about how to facilitate disruptive, demand-based innovations that may be transformative in urban systems, is needed. | • Regional and sectoral adaptation cost assessments are missing, particularly in the context of welfare losses of households, across time and space.  
• More knowledge is needed on the political economy of adaptation, particularly on how to impute different types of cost and benefit in a consistent manner, on adaptation performance indicators that could stimulate investment, and the impact of adaptation interventions on socio-economic, and other types, of inequality.  
• More evidence would be needed on hot-spots, for example the growth of peri-urban areas populated by large informal settlements.  
• Major uncertainties emanate from the lack of knowledge on the integration of climate adaptation and mitigation, disaster risk management, and urban poverty alleviation.  
• There is limited evidence on the institutional, technological and economic feasibility of green agriculture. | 4.3.3 |
| Industry                          | • The urban form implications of combined changes from electric, autonomous and shared/public mobility systems, is needed.  
• Considering distributional consequences of climate responses is an on-going need.  
• Knowledge gaps in the application and scale-up of combinations of new smart technologies, sustainable design, advanced construction techniques and new insulation materials, renewable energy and behaviour change in urban settlements.  
• The potential for leapfrog technologies to be applied to slums and new urban developments in developing countries is weak.  
• Lack of knowledge on potential for scaling up and global diffusion of zero- and low-emission technologies in industry  
• Questions remain on the socio-cultural feasibility of industry options, including human capacity and private sector acceptance of new, radically different technologies from current well-developed practices, as well as distributional effects of potential new business models  
• As the industrial transition unfolds, lack of knowledge on its dynamic interactions with other sectors, in particular with the power sector (and infrastructure) for electrification of industry, with food production and other users of biomass in case of bio-based industry developments, and with CDR technologies in the case of CC(U)S.  
• Life-cycle assessment-based comparative analysis of CCUS options are missing, as well as life-cycle information on electrification and hydrogen.  
• Impacts of industrial system transitions are not well understood, especially on employment, identity and well-being, in particular in the case of substitution.  
| IPC CC SR1.5                     | • In general, there is no evidence for the employment and productivity enhancement potential of most adaptation options.  
• There is limited evidence on the economic feasibility of sustainable water management.  
• Very limited evidence on how industry would adapt to the consequences of 1.5 or 2°C temperature increases, in particular large and immobile industrial clusters in low-lying areas and availability of transportation and (cooling) water resources and infrastructure.  
• There is limited evidence on the economic, institutional and socio-cultural feasibility of adaptation options available to industry.  

<p>| 4.3.4                           |</p>
<table>
<thead>
<tr>
<th>Short-lived climate forcers</th>
<th>CDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Limited evidence of co-benefits and trade-offs of SLCF reduction (e.g., better health outcomes, agricultural productivity improvements).</td>
<td>• A bottom-up analysis of CDR options, indicates that there are still key uncertainties around the individual technologies. This – includes Ocean-based options will be assessed in depth in the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC). Assessments of environmental aspects are missing, especially for ‘newer’ options like Enhanced Weathering or Direct Air Carbon Capture.</td>
</tr>
<tr>
<td>• Integration of SLCFs into emissions accounting and international reporting mechanisms enabling a better understanding of the links between black carbon, air pollution, climate change and agricultural productivity.</td>
<td>• In order to obtain more information on realistically available and sustainable removal potentials, more bottom-up, regional studies, also taking into account also social issues, would be needed. These can better inform the modeling of 1.5°C pathways.</td>
</tr>
<tr>
<td></td>
<td>• Knowledge gaps on issues of governance and public acceptance, the impacts of large-scale removals on the carbon cycle, the potential to accelerate deployment and upscaling, and means of incentivisation.</td>
</tr>
<tr>
<td></td>
<td>• Knowledge gaps on integrated systems of renewable energy and CDR technologies such as enhanced weathering and DACCS</td>
</tr>
<tr>
<td>Enabling conditions</td>
<td>Governance</td>
</tr>
<tr>
<td>---------------------</td>
<td>------------</td>
</tr>
<tr>
<td>- Knowledge gaps on the use of captured CO₂ is generating negative emissions and as mitigation option.</td>
<td>- There is no evidence on technical and institutional feasibility of educational options</td>
</tr>
<tr>
<td>- There is evidence on employment and productivity enforcement potential of climate services</td>
<td>- There is limited evidence on socio-cultural acceptability of social safety nets</td>
</tr>
<tr>
<td>- There is a small but growing literature on human migration as an adaptation strategy. Scant literature on the cost effectiveness of migration.</td>
<td>- There is limited evidence on employment and productivity enforcement potential of climate services</td>
</tr>
<tr>
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<tr>
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<td>- There is a small but growing literature on human migration as an adaptation strategy. Scant literature on the cost effectiveness of migration.</td>
</tr>
</tbody>
</table>

4.3.5
- The ability to identify explanatory factors affecting the progress of climate policy is constrained by a lack of data on adaptation actions across nations, regions, and sectors, compounded by an absence of frameworks for assessing progress. Most hypotheses on what drives adaptation remain untested.
- Limited empirical assessment of how governance affects adaptation across cases
- Focus on ‘success’ stories and leading adaptors overlooks lessons from situations where no or unsuccessful adaptation is taking place

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4.4.2
whether and why an adaptation initiative has been effective. One of the challenges of M&E for both mitigation and adaptation is a lack of high quality information for modellings. Adaptation M&E is additionally challenged by limited understanding on what indicators to measure and how to attribute altered vulnerability to adaptation actions.

| Lifestyle and behavioural change | Whereas mitigation pathways studies address (implicitly or explicitly) the reduction or elimination of market failures (e.g., external costs, information asymmetries) via climate or energy policies, no study addresses behavioural change strategies in the relationship with mitigation and adaptation actions in the 1.5°C context. | Limited knowledge on GHG emission reduction potential of diverse mitigation behaviour across the world.  
Most studies on factors enabling lifestyle changes have been conducted in high income countries, more knowledge needed from low- and middle-income countries, and the focus in typically on enabling individual behavior change, far less on enabling change in organisations and political systems  
Limited understanding and treatment of behavioural change and the potential effects of related policies in ambitious mitigation pathways, e.g., in Integrated Assessment Models. | Knowledge gaps on factors enabling adaptation behaviour, except for behaviour in agriculture.  
Little is known about cognitive and motivational factors promoting adaptive behavior.  
Little is known about how potential adaptation actions might affect behavior to influence vulnerability outcomes | 4.4.3 |
| Lack of insight on what can enable changes in adaptation and mitigation behaviour in organisations and political systems. |
| Technological innovation | Quantitative estimates for mitigation and adaptation potentials at economy or sector scale as a result of the combination of general purpose technologies and mitigation technologies have been scarce, except for some evidence in the transport sector.  
Evidence on the role of international organisations, including the UNFCCC, in building capabilities and enhancing technological innovation for 1.5°C, except for some parts of the transport sector.  
Technology transfer trials to enable leapfrog applications in developing countries have limited evidence | 4.4.4 |
| Policy | More empirical research would be needed to derive robust conclusions on effectiveness of policies for | Understanding of what polices work (and do not work) is limited for adaptation in general and for | 4.4.5 |
### Enabling transition to 1.5°C and on which factors aid decision-makers seeking to ratchet up their NDCs

<table>
<thead>
<tr>
<th>Finance</th>
<th>Knowledge gaps persist with respect to the instruments to match finance to its most effective use in mitigation and adaptation.</th>
</tr>
</thead>
</table>

### 4.4.5 Synergies and tradeoffs between adaptation and mitigation

- Strong claims are made with respect to synergies and trade-offs, but there is little knowledge to underpin these, especially of co-benefits by region.
- Water-energy conservation relationships of individual conservation measures in industries other than the water and energy sectors have not been investigated in detail.
- There is no evidence on synergies with adaptation of CCS in the power sector and of enhanced weathering under carbon dioxide removal.
- There is no evidence on trade-offs with adaptation of low and zero-energy buildings, and circularity and substitution and bio-based industrial system transitions.
- There is no evidence of synergies or trade-offs with mitigation of CbA
- There is no evidence of trade-offs with mitigation of the built environment, on adaptation options for industrial energy, and climate services

### 4.3.8 SRM

- In spite of increasing attention to the different SRM measures and their potential to keep global temperature below 1.5°C, knowledge gaps remain not only with respect to the physical understanding of SRM options, but also concerning ethical issues.
- We do not know how to govern SRM in order to avoid unilateral action and how to prevent possible reductions in mitigation (‘moral hazard’).
Frequently Asked Questions

FAQ 4.1: What transitions could enable limiting global warming to 1.5°C?

**Summary:** In order to limit warming to 1.5°C above preindustrial levels, the world would need to transform in a number of complex and connected ways. While transitions towards lower greenhouse gas emissions are underway in some cities, regions, countries, businesses and communities, there are few that are currently consistent with limiting warming to 1.5°C. Meeting this challenge would require a rapid escalation in the current scale and pace of change, particularly in the coming decades. There are many factors that affect the feasibility of different adaptation and mitigation options that could help limit warming to 1.5°C and adapting to the consequences.

There are actions across all sectors can substantially reduce greenhouse gas emissions. This Special Report assesses energy, land and ecosystems, urban and infrastructure, and industry in developed and developing nations to see how they would need to be transformed to limit warming to 1.5°C. Examples of actions include shifting to low- or zero-emission power generation, such as renewables; changing food systems, such as diet changes away from land-intensive animal products; electrifying transport and developing ‘green infrastructure’, such as building green roofs, or improving energy efficiency by smart urban planning, which will change the layout of many cities.

Because these different actions are connected, a ‘whole systems’ approach would be needed for the type of transformations that could limit warming to 1.5°C. This means that all relevant companies, industries and stakeholders would need to be involved to increase the support and chance of successful implementation. As an illustration, the deployment of low-emission technology (e.g., renewable energy projects or a bio-based chemical plants) would depend upon economic conditions (e.g., employment generation or capacity to mobilise investment), but also on social/cultural conditions (e.g., awareness and acceptability) and institutional conditions (e.g., political support and understanding).

To limit warming to 1.5°C, mitigation would have to be large-scale and rapid. Transitions can be transformative or incremental, and they often, but not always, go hand in hand. Transformative change can arise from growth in demand for a new product or market, such that it displaces an existing one. This is sometimes called ‘disruptive innovation’. For example, high demand for LED lighting is now making more energy-intensive, incandescent lighting near-obsolete, with the support of policy action that spurred rapid industry innovation. Similarly, smart phones have become global in use within ten years. But electric cars, which were released around the same time, have not been adopted so quickly because the bigger, more connected transport and energy systems are harder to change. Renewable energy, especially solar and wind, is considered to be disruptive by some as it is rapidly being adopted and is transitioning faster than predicted. But its demand is not yet uniform. Urban systems that are moving towards transformation are coupling solar and wind with battery storage and electric vehicles in a more incremental transition, though this would still require changes in regulations, tax incentives, new standards, demonstration projects and education programmes to enable markets for this system to work.

Transitional changes are already underway in many systems but limiting warming to 1.5°C would require a rapid escalation in the scale and pace of transition, particularly in the next 10-20 years. While limiting warming to 1.5°C would involve many of the same types of transitions as limiting warming to 2°C, the pace of change would need to be much faster. While the pace of change that would be required to limit warming to 1.5°C can be found in the past, there is no historical precedent for the scale of the necessary transitions, in particular in a socially and economically sustainable way. Resolving such speed and scale issues would require people’s support, public-sector interventions and private-sector cooperation.

Different types of transitions carry with them different associated costs and requirements for institutional or governmental support. Some are also easier to scale up than others, and some need more government support than others. Transitions between, and within, these systems are connected and none would be sufficient on its own to limit warming to 1.5°C.
The ‘feasibility’ of adaptation and mitigation options or actions within each system that together can limit warming to 1.5°C within the context of sustainable development and efforts to eradicate poverty requires careful consideration of multiple different factors. These factors include: (i) whether sufficient natural systems and resources are available to support the various options for transitioning (known as environmental feasibility); (ii) the degree to which the required technologies are developed and available (known as technological feasibility); (iii) the economic conditions and implications (known as economic feasibility); (iv) what are the implications for human behaviour and health (known as social/cultural feasibility); and (v) what type of institutional support would be needed, such as governance, institutional capacity and political support (known as institutional feasibility). An additional factor (vi - known as the geophysical feasibility) addresses the capacity of physical systems to carry the option, for example whether it is geophysically possible to implement large-scale afforestation consistent with 1.5°C.

Promoting enabling conditions, such as finance, innovation and behaviour change, would reduce barriers to the options, make the required speed and scale of the system transitions more likely, and therefore would increase the overall feasibility limiting warming to 1.5°C.

**FAQ4.1, Figure 1:** The different feasibility dimensions towards limiting warming to 1.5°C

Assessing the feasibility of different adaptation and mitigation options/actions requires consideration across six dimensions.
FAQ 4.2: What are Carbon Dioxide Removal and negative emissions?

Summary: Carbon Dioxide Removal (CDR) refers to the process of removing CO₂ from the atmosphere. Since this is the opposite of emissions, practices or technologies that remove CO₂ are often described as achieving ‘negative emissions’. The process is sometimes referred to more broadly as Greenhouse Gas Removal if it involves removing gases other than CO₂. There are two main types of CDR: either enhancing existing natural processes that remove carbon from the atmosphere (e.g., by increasing its uptake by trees, soil, or other ‘carbon sinks’) or using chemical processes to, for example, capture CO₂ directly from the ambient air and storing it elsewhere (i.e., underground). All CDR methods are at different stages of development and some are more conceptual than others, as they have not been tested at scale.

Limiting warming to 1.5°C above preindustrial levels would require unprecedented rates of transformation in many areas, including in the energy and industrial sectors, for example. Conceptually, it is possible that techniques to draw CO₂ out of the atmosphere (known as Carbon Dioxide Removal, or CDR) could contribute to limiting warming to 1.5°C. One use of CDR could be to compensate for greenhouse gas emissions from sectors that cannot completely decarbonise, or which may take a long time to do so.

If global temperature temporarily overshoots 1.5°C, CDR would be required to reduce the atmospheric concentration of CO₂ to bring global temperature back down. To achieve this temperature reduction, the amount of CO₂ drawn out of the atmosphere would need to be greater than the amount entering the atmosphere, resulting in ‘net negative emissions’. This would involve a greater amount of CDR than stabilising atmospheric CO₂ concentration – and, therefore, global temperature – at a certain level. The larger and longer an overshoot, the greater the reliance on practices that remove CO₂ from the atmosphere.

There are a number of CDR methods, each with different potentials for achieving negative emissions, as well as different associated costs and side effects. They are also at differing levels of development, with some more conceptual than others. One example of a CDR method in the demonstration phase is a process known as Bioenergy with Carbon Capture and Storage (BECCS), in which atmospheric CO₂ is absorbed by plants and trees as they grow and then the plant material (biomass) is burned to produce bioenergy. The CO₂ released in the production of bioenergy is captured before it reaches the atmosphere and stored in geological formations deep underground on very long timescales. Since the plants absorb CO₂ as they grow and the process does not emit CO₂, the overall effect can be to reduce atmospheric CO₂.

Afforestation (planting new trees) and reforestation (replanting trees where they previously existed) are also considered forms of CDR because they enhance natural CO₂ ‘sinks’. Another category of CDR techniques uses chemical processes to capture CO₂ from the air and store it away on very long timescales. In a process known as Direct Air Carbon Capture and Storage (DACCS), CO₂ is extracted directly from the air and stored in geological formations deep underground. Converting waste plant material into a charcoal-like substance called biochar and burying it in soil can also be used to store carbon away from the atmosphere for decades to centuries.

There can be beneficial side effects of some types of CDR, other than removing CO₂ from the atmosphere. For example, restoring forests or mangroves can enhance biodiversity and protect against flooding and storms. But there could also be risks involved with some CDR methods. For example, deploying BECCS at large scale would require a large amount of land to cultivate the biomass required for bioenergy. This could have consequences for sustainable development if the use of land competes with producing food to support a growing population, biodiversity conservation, or land rights. There are also other considerations. For example, there are uncertainties about how much it would cost to deploy DACCS as a CDR technique, given that removing CO₂ from the air requires considerable energy.
FAQ4.2: Carbon dioxide removal and negative emissions
Examples of some CDR / negative emissions techniques and practices

**Bioenergy with Carbon Capture and Storage (BECCS)**
Atmospheric CO$_2$ is absorbed by plants and trees as they grow and then the plant material (biomass) is turned into bioenergy.

...the CO$_2$ released in the production of bioenergy is captured before it reaches the atmosphere and stored underground.

**Afforestation and re-forestation**
Afforestation (planting trees) and reforestation (restoring trees where they previously existed) enhance natural CO$_2$ 'sinks'.

**FAQ4.2, Figure 1:** Carbon Dioxide Removal (CDR) refers to the process of removing CO$_2$ from the atmosphere. There are a number of CDR techniques, each with different potential for achieving 'negative emissions', as well as different associated costs and side effects.
FAQ 4.3: Why is adaptation important in a 1.5°C warmer world?

**Summary:** Adaptation is the adjustment process to current or expected changes in climate and its effects. Even though climate change is a global problem, its impacts are experienced differently across the world. This means that responses are often specific to the local context, and so people in different regions are adapting in different ways. A rise in global temperature from 1°C to 1.5°C, and beyond, increases the need for adaptation. Therefore, stabilising global temperatures at 1.5°C above pre-industrial levels would require a smaller adaptation effort than for 2°C. Despite many successful examples around the world, progress in adaptation is, in many regions, in its infancy and unevenly distributed globally.

Adaptation refers to the process of adjustment to actual or expected changes in climate and its effects. Since different parts of the world are experiencing the impacts of climate change differently, there is similar diversity in how people in a given region are adapting to those impacts.

The world is already experiencing the impacts from 1°C of global warming above preindustrial levels and there are many examples of adaptation to impacts associated with this warming. Examples of adaptation efforts taking place around the world include investing in flood defences such as building sea walls or restoring mangroves, efforts to guide development away from high risk areas, modifying crops to avoid yield reductions, and using social learning (social interactions that changes understanding on the community level) to modify agricultural practices, amongst many others. Adaptation also involves building capacity to respond better to climate change impacts, including making governance more flexible and strengthening financing mechanisms such as providing different types of insurance.

In general, an increase in global temperature from present day to 1.5°C or 2°C (or higher) above preindustrial temperatures would increase the need for adaptation. Therefore, stabilising global temperature increase at 1.5°C would require a smaller adaptation effort than for 2°C.

Since adaptation is still in early stages in many regions, this raises questions about the capacity of vulnerable communities to cope with any amount of further warming. Successful adaptation can be supported at the national and sub-national levels, with national governments playing an important role in coordination, planning, determining policy priorities, and distributing resources and support. Given that the need for adaptation can be very different from one community to the next, the kinds of measures that can successfully reduce climate risks will also depend heavily on the local context.

When done successfully, adaptation can allow individuals to adjust to the impacts of climate change in ways that minimise negative consequences and maintain their livelihoods. This could involve, for example, a farmer switching drought-tolerant crops to deal with increasing occurrences of heat waves. In some cases, however, the impacts of climate change could result in entire systems changing significantly, such as moving to an entirely new agricultural system in areas where the climate is no longer suitable for current practices. Constructing sea walls to stop flooding due to sea level rising from climate change is another example of adaptation, but developing city planning to change how flood water is managed throughout the city would be an example of transformational adaptation. These actions require significantly more institutional, structural, and financial support. While this kind of transformational adaptation wouldn’t be needed everywhere in a 1.5°C world, the scale of change needed would be challenging to implement, as it requires additional support such as through financial assistance and behavioural change. Few empirical examples exist to date.

Examples from around the world show that adaptation is an iterative process. Adaptation pathways describe how communities can make decisions about adaptation in an ongoing and flexible way. Such pathways allow for pausing, evaluating the outcomes of specific adaptation actions, and modifying the strategy as appropriate. Due to their flexible nature, adaptation pathways can help to identify the most effective ways to minimise the impacts of present and future climate change for a given local context. This is important since adaptation can sometimes exacerbate vulnerabilities and existing inequalities if poorly designed. The unintended negative consequences of adaptation that can sometimes occur is known as ‘maladaptation’. Maladaptation can be seen if a particular adaptation option has negative consequences for some (e.g.,
rainwater harvesting upstream might reduce water availability downstream) or if an adaptation intervention in the present has trade-offs in the future (e.g., desalination plants may improve water availability in the present but have large energy demands over time).

While adaptation is important to reduce the negative impacts from climate change, adaptation measures on their own are not enough to prevent climate change impacts entirely. The more global temperature rises, the more frequent, severe, and erratic the impacts will be, and adaptation may not protect against all risks. Examples of where limits may be reached include substantial loss of coral reefs, massive range losses for terrestrial species, more human deaths from extreme heat, and losses of coastal-dependent livelihoods in low lying islands and coasts.

**FAQ4.3: Adaptation in a warming world**

Adapting to further warming requires action at national & sub-national levels and can mean different things to different people in different contexts.

**ADAPTATION**

Responding to and preparing for the impacts of climate change

- Improved infrastructure, i.e. efficient irrigation systems to deal with drought
- Flood protection and safeguarding of fresh water supply

**TRANSFORMATIONAL ADAPTATION**

Deep, systemic change that requires reconfiguration of social and ecological systems

- Alternative lifestyles of employment
- Change of farming type i.e. from crop to livestock
- New city planning to safeguard people and infrastructure

**FAQ4.3, Figure 1:** Examples of adaptation and transformational adaptation. Adapting to further warming requires action at national & sub-national levels and can mean different things to different people in different contexts. While transformational adaptation wouldn’t be needed everywhere in a world limited to 1.5°C warming, the scale of change needed would be challenging to implement.


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## Contents

Supplementary Material 4.A Benchmark indicators for sectoral changes in emissions as presented in Table 4.1 (Section 4.2.1) ................................................................. 2
Supplementary Material 4.B Enabling conditions and constraints of overarching adaptation options as discussed in Section 4.3.5 .............................................................. 5
Supplementary Material 4.C Carbon dioxide removal costs, deployment and side-effects: literature basis for Figure 4.2 (Section 4.3.7) ................................................................. 10
Supplementary Material 4.D Guidance and assessment for feasibility assessment ................................................................. 12
  Supplementary Material 4.D.1 Guidance for feasibility assessment in Section 4.5.1 ......................................................................................................................... 12
  Supplementary Material 4.D.2 Feasibility assessment of mitigation options as presented in Section 4.5.2 ................................................................. 14
    Supplementary Material 4.D.2.i Feasibility assessment of mitigation options in energy system transitions ............................................................................................ 14
    Supplementary Material 4.D.2.ii Feasibility assessment of mitigation options in land & ecosystem transitions ................................................................. 23
    Supplementary Material 4.D.2.iii Feasibility assessment of mitigation options in urban & infrastructure system transitions ................................................................. 28
    Supplementary Material 4.D.2.iv Feasibility assessment of mitigation options in industrial system transitions ................................................................. 38
  Supplementary Material 4.D.2.v Feasibility assessment of carbon dioxide removal mitigation options ................................................................. 42
  Supplementary Material 4.D.3 Feasibility assessment of adaptation options as presented in Section 4.5.3 ................................................................. 51
    Supplementary Material 4.D.3.i Feasibility assessment of adaptation options in energy system transitions ............................................................................................ 51
    Supplementary Material 4.D.3.iii Feasibility assessment of adaptation options in urban & infrastructure system transitions ................................................................. 61
    Supplementary Material 4.D.3.iv Feasibility assessment of adaptation options in industrial system transitions ................................................................. 67
    Supplementary Material 4.D.3.v Feasibility assessment of overarching adaptation options ................................................................. 69
Supplementary Material 4.E Adaptation and mitigation synergies and trade-offs as discussed in Section 4.5.4 ................................................................. 81
  Supplementary Material 4.E.1 Mitigation options with adaptation synergies and trade-offs ......................................................................................................................... 81
  Supplementary Material 4.E.2 Adaptation options with mitigation synergies and trade-offs ......................................................................................................................... 87
Supplementary Material 4.A Benchmark indicators for sectoral changes in emissions as presented in Table 4.1 (Section 4.2.1)

Integrated Assessment Models (IAMs) and other sector scenarios provide sectoral detail underpinning the declines in Greenhouse Gas (GHG) emissions by the middle of the century (Section 2.3 and Section 2.4). Supplementary Material 4.A, Table 1 indicates the pace of the transitions that are deemed necessary in 2020, 2030 and 2050 at the sector level for 1.5°C-consistent pathways, and complements this with bottom-up studies from literature that give actionable policy targets (the lines in white). A summary of this table is presented in Section 4.2.1.

**Supplementary Material 4.A, Table 1:** Benchmark indicators indicating the sectoral changes in emissions, fuels and technologies that would need to take place in 1.5°C-consistent pathways, based on selected IAM 1.5°C pathways assessed in Chapter 2 (with high and low overshoot (OS)) (dark grey rows), four archetype scenarios (light grey rows), and bottom-up studies (white rows).

<table>
<thead>
<tr>
<th></th>
<th>Energy</th>
<th>Buildings</th>
<th>Transport</th>
<th>Industry</th>
</tr>
</thead>
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<tr>
<td><strong>2020</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5°C low OS</td>
<td>15.31</td>
<td>26.26</td>
<td>61.08</td>
<td>-10.86</td>
</tr>
<tr>
<td>(Figuero et al., 2017)</td>
<td>14.03</td>
<td>28.83</td>
<td>63.17</td>
<td>(-7.53)</td>
</tr>
<tr>
<td>1.5°C high OS</td>
<td>15.08</td>
<td>28.37</td>
<td>61.38</td>
<td>(-14.83)</td>
</tr>
<tr>
<td>(Kuramochi et al., 2017)</td>
<td>14.44</td>
<td>29.24</td>
<td>63.83</td>
<td>(-9.44)</td>
</tr>
<tr>
<td>S1</td>
<td>12.46</td>
<td>23.24</td>
<td>63.72</td>
<td>-9.20</td>
</tr>
<tr>
<td>S2</td>
<td>16.61</td>
<td>27.00</td>
<td>60.11</td>
<td>-16.20</td>
</tr>
<tr>
<td>S5</td>
<td>13.46</td>
<td>17.38</td>
<td>71.03</td>
<td>-8.78</td>
</tr>
<tr>
<td>LED</td>
<td>15.63</td>
<td>24.61</td>
<td>54.11</td>
<td>-7.63</td>
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<tr>
<td><strong>2030</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5°C low OS</td>
<td>28.75</td>
<td>52.63</td>
<td>31.54</td>
<td>-2.61</td>
</tr>
<tr>
<td>(IEA, 2017a)</td>
<td>25.31</td>
<td>58.90</td>
<td>38.14</td>
<td>(5.41, 7.73)</td>
</tr>
<tr>
<td>1.5°C high OS</td>
<td>23.65</td>
<td>42.73</td>
<td>42.02</td>
<td>-16.64</td>
</tr>
<tr>
<td>(Kuramochi et al., 2017)</td>
<td>20.03</td>
<td>53.78</td>
<td>47.27</td>
<td>(-12.07, 20.01)</td>
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<tr>
<td>S1</td>
<td>28.79</td>
<td>57.89</td>
<td>27.84</td>
<td>-7.63</td>
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<tr>
<td>S2</td>
<td>15</td>
<td>31</td>
<td>58</td>
<td>5</td>
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<td>S5</td>
<td>15</td>
<td>31</td>
<td>58</td>
<td>5</td>
</tr>
<tr>
<td>LED</td>
<td>15</td>
<td>31</td>
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<td>Total</td>
<td>28.72</td>
<td>37.42</td>
<td>13.78</td>
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<td>20</td>
<td>20</td>
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<th>47.89</th>
<th>59.64</th>
<th>25.11</th>
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<th>47</th>
<th>47</th>
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</thead>
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<td></td>
<td>35.37</td>
<td>17.14</td>
<td>57.38</td>
<td>30.02</td>
<td>59.01</td>
<td>59.81</td>
<td>59.81</td>
<td>59.81</td>
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<tr>
<td></td>
<td>-14.12</td>
<td>30.42</td>
<td>47.92</td>
<td>5.17</td>
<td>3.43</td>
<td>4.46</td>
<td>20.93</td>
<td>1.93</td>
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<tr>
<td>Notes:</td>
<td></td>
<td></td>
<td></td>
<td>Values for ‘1.5°C low OS’ and ‘1.5°C high OS’ indicate the median and the interquartile ranges for indicators for 1.5°C-consistent pathways distinguishing high and low overshoot, collected in the scenario database established for the assessment of this Special Report (see Section 2.1 and Annex 2.3). Four illustrative pathway archetypes were selected for comparison: S1 (AIM 2.0, SSP1-19), S2 (MESSAGE-GLOBIOM 1.0, SSP2-19), S5 (REMIND-MAgPIE 1.5, SSP5-19) and LED (MESSAGEix-GLOBIOM 1.0, LowEnergyDemand) (see Section 2.1) The selected studies indicate mitigation transitions in key sectors consistent with limiting warming to 1.5°C (Figuere et al., 2017; Kuramochi et al., 2017).</td>
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</tbody>
</table>
et al., 2017; Löffler et al., 2017; Rockström et al., 2017) or below 2°C (IEA, 2017a; WBCSD, 2017), grounded in published scenarios combined with expert judgment.
## Supplementary Material 4.B Enabling conditions and constraints of overarching adaptation options as discussed in Section 4.3.5

### Supplementary Material 4.B, Table 1: Overarching adaptation options: enabling conditions and constraints. This table is underpinning Section 4.3.5.

<table>
<thead>
<tr>
<th>Adaptation option</th>
<th>Feasibility</th>
<th>Enabling conditions</th>
<th>Constraints</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Disaster risk management (DRM)</strong></td>
<td><em>Medium evidence (high agreement)</em></td>
<td>Pools resources and expertise for risk reduction (Howes et al., 2015; Kelman et al., 2015; Wallace, 2017) Integrates adaptation into existing management (Howes et al., 2015) Supports post-disaster recovery and reconstruction (Kelman et al., 2015; Kull et al., 2016) Engagement of local and Indigenous knowledge can improve preparedness and response (McNamara and Prasad, 2014; Mawere and Mubaya, 2015; Kaya et al., 2016; Chambers et al., 2017; Granderson, 2017)</td>
<td>Uncertainty over projected climate impacts, absence of downscaled climate projections (van der Keur et al., 2016; de Leon and Pittock, 2017; Wallace, 2017) Limited institutional, technical, and financial capacity in frontline agencies (de Leon and Pittock, 2017; Kita, 2017; Wallace, 2017) Adaptation and DRM communities operate separately (Kelman et al., 2015; Serra-Neumann et al., 2015; de Leon and Pittock, 2017)</td>
<td><strong>Glacial lake outburst floods (GLOFs)</strong> 1.5°C will increase risk of GLOFs (Cogley, 2017; Kraaijenbrink et al., 2017). Infrastructural measures technically and economically unfeasible in many regions (Muñoz et al., 2016; Schwanghart et al., 2016; Watanabe et al., 2016; Haebeler et al., 2017) Early warning systems (Anacona et al., 2015), and monitoring of dangerous lakes and surrounding slopes (including using remote sensing) offer DRM opportunities (Emmer et al., 2016; Milner et al., 2017) Institutional leadership and community engagement essential for effectiveness (Anacona et al., 2015; Watanabe et al., 2016)</td>
</tr>
<tr>
<td><strong>Risk sharing and spreading: insurance</strong></td>
<td><em>Medium evidence (medium agreement)</em></td>
<td>Buffers climate risk (Wolfrom and Yokoi-Arai, 2015; O’Hare et al., 2016; Glaas et al., 2017; Jenkins et al., 2017; Patel et al., 2017). Shifts the mobilization of financial resources towards strategic approaches (Surminski et al., 2016) Incentivises investments and behavior that reduce exposure (Linnerooth-Bayer and Hochrainer-Stigler, 2015; Shapiro, 2016; Jenkins et al., 2017).</td>
<td>Can provide disincentives for reducing risk and can distort incentives for adaptation strategies (Annan and Schlenker, 2015; Nicola, 2015) Underwrites a return to the ‘status-quo’ rather than enabling adaptive behavior (O’Hare et al., 2016) Financial, social, and institutional barriers to implementation and uptake, especially in low income nations (García Romero and Molina, 2015; Joyette et al., 2015; Lashley and Warner, 2015; Jin et al., 2016)</td>
<td><strong>Crop insurance</strong> In Kenya during the 2011 drought, index-based insurance pay-outs for livestock reduced distress sales by 64% among better-off pastoralist households and reduced the likelihood of rationing food intake by 43% among poorer households (Hansen et al., 2017) In USA, (Annan and Schlenker, 2015) found insured crops were significantly more sensitive to extreme heat because insured farmers were disincentivised from investing in costly adaptation strategies since their insurance compensated for potential losses</td>
</tr>
<tr>
<td>Risk sharing and spreading: social protection programmes</td>
<td>Medium evidence (medium agreement)</td>
<td>Builds generic adaptive capacity and reduces social vulnerability (Weldegebriel and Prowse, 2013; Eakin et al., 2014; Lemos et al., 2016; Schwan and Yu, 2017). Must be complemented with a comprehensive climate risk management approach (Schwan and Yu, 2017) that also takes into account disaster risk management, adaptation, and vulnerability reduction goals (Davies et al., 2013).</td>
<td>Inadequate targeting, leakages, and lack of institutional architecture, especially in LDCs (Ravi and Engler, 2015; Schwan and Yu, 2017) Uncertainties about effectiveness of processes of delivering social protection (e.g. cash or “in-kind”). Necessary but insufficient to decrease households’ vulnerability if standalone (Lemos et al., 2016) When delivered without emphasis on vulnerability reduction, investments may be maladaptive in long run (Nelson et al., 2016)</td>
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<td></td>
</tr>
<tr>
<td>Education and learning</td>
<td>Medium evidence (high agreement)</td>
<td>Co-production of solutions strengthens adaptation implementation (Butler et al., 2016a; Thi Hong Phuong et al., 2017; Ford et al., 2018)</td>
<td>Not appropriate in all circumstances (e.g., highly marginalized locations) (Ford et al., 2016, 2018)</td>
<td></td>
</tr>
</tbody>
</table>

**In Bangladesh low institutional trust and financial literacy means that fewer women enrol in weather-based crop insurance (Akter et al., 2016)**

**World Bank Cat bond issuance in Caribbean**
In 2007, the Caribbean Catastrophe Risk Insurance Facility was formed to pool risk from tropical cyclones, earthquakes, and excess rainfalls (Murphy et al., 2012; CCRIF, 2017)
36 payouts have been made to 13 governments, totalling 130.5 million USD and partially funded by CCRIF, within 14 days of the event (CCRIF, 2017). Speed of payment allows countries to finance immediate needs (Murphy et al., 2012)

Though widely perceived to be successful, evidence of success remains limited (Teh, 2015)

**Cash transfer programmes**
In sub-Saharan Africa, cash transfer programmes targeting poor communities have proven successful in smoothing household welfare and food security during droughts, strengthening community ties, and reducing debt levels (del Ninno et al., 2016; Asfaw et al., 2017; Asfaw and Davis, 2018).

In Brazil, higher levels of income due to cash transfer programs have been linked to food security, as households are able to invest in irrigation, but there have been limited long-term investments in reducing vulnerability among the poorest households (Lemos et al., 2016; Mesquita and Bursztyn, 2016; Nelson et al., 2016).

**Participatory scenario planning (PSP)**
PSP is a process by which multiple stakeholders work together to envision future scenarios under a range of climatic conditions (Flynn et al., 2018).
Social learning strengthens adaptation and affects longer-term change (Clemens et al., 2015; Enser and Harvey, 2015; Henly-Shepard et al., 2015).

International learning and cooperation mechanisms, supranational organizations (Vinke-de Kruijf and Pahl-Wostl, 2016), and international, collaborative projects (Cochrane et al., 2017; Harvey et al., 2017) can build adaptive capacity.

Education and learning on their own may not provide “enough adaptive capacity to respond to climate change” (Thi Hong Phuong et al., 2017)

Participation in and of itself does not necessarily build capacity (Ford et al., 2016)

PSP has been observed to facilitate the interaction of multiple knowledge systems, resulting in learning and the co-production of knowledge on adaptation (Tschakert et al., 2014; Oteros-Rozas et al., 2015; Star et al., 2016; Flynn et al., 2018).

1.5°C will primarily exacerbate existing health challenges (Smith et al., 2014a), which can be targeted by enhancing health services.

Age, pre-existing medical conditions and social deprivation are found to be the key (but not the only) factors that make people vulnerable and lead to more adverse health outcomes related to climate change impacts. This can be mainstreamed through existing health programming and service delivery (WHO, 2015; Paavola, 2017)

Governance challenges: e.g. absence of coordination across scales, lack of mandate for action on adaptation (Austin et al., 2016; Ebi and del Barrio, 2017; Shimamoto and McCormick, 2017)

Absence of information and understanding on climate impacts (Nigatu et al., 2014; Xiao et al., 2016; Sheehan et al., 2017)

Many health services currently don’t consider climate change (Hess and Ebi, 2016).

Adaptation strategies based on individual preparedness, action and behaviour change may aggravate health and social inequalities due to their selective uptake, unless they are coupled with broad public information campaigns and financial support for undertaking adaptive measures (Paavola, 2017)

Indigenous knowledge underpins the adaptive capacity of Indigenous

Cultural programming
| Human migration | (high agreement) | Revising and adopting migration issues in national DRR policies, NAPs, and INDCs/NDCs (Kuruppu and Willie, 2015; Yamamoto et al., 2017). Utilizing existing social protection programmes to manage climate-induced migration (Schwan and Yu, 2017). Moving away from ad hoc approaches to migration and displacement (Thomas and Benjamin, 2018). Migration can serve as an important risk management strategy, leading to increased incomes (Cattaneo and Peri, 2016). | Research conducted on a “case by case” approach fails to provide the effective scaling of policy to national or international levels (Gemenne and Blocher, 2017; Grecequet et al., 2017). Few policies on migration exist at the national or sub-national scales (Yamamoto et al., 2017). Financial, social and ecological costs (Grecequet et al., 2017) Stress on urban system resources and services (Bhagat, 2017) | Autonomous and planned relocation in SIDS and semi-arid regions Migration is improving access to financial and social capital and reducing risk exposure in some locations (e.g., in the Solomon Islands (Birk and Rasmussen, 2014)). The ad hoc nature of migration and displacement can be overcome by integrating disaster risk reduction and climate change adaptation into national sustainable development plans (Thomas and Benjamin, 2018). In dryland India, populations in rural regions already experiencing 1.5°C warming are migrating to cities (Gajjar et al., 2018) but are inadequately covered by existing policies (Bhagat, 2017). |
Migration might become the only feasible adaptation option in highly vulnerable areas (Betzold, 2015; Wilkinson et al., 2016)

Migrants at risk of insecure tenure, unsafe living conditions, and exclusion in their destinations (Bettini et al., 2016; Gioli et al., 2016; Bhagat, 2017; Schwan and Yu, 2017)

Rapid technical development, due to increased financial inputs and growing demand is enabling improved quality of climate information (Rogers and Tsirkunov, 2010; Clements et al., 2013; Perrels et al., 2013; Gasc et al., 2014; WMO, 2015; Roudier et al., 2016).

Multiple stakeholder engagement and participatory processes to interpret climate information are effective to improve uptake and use (Mantilla et al., 2014; Sivakumar et al., 2014; Coulibaly et al., 2015; Gebru et al., 2015; Brasseur and Gallardo, 2016; Lourenço et al., 2016; Singh et al., 2016; Vaughan et al., 2016; Kihila, 2017; Lobo et al., 2017).

Scaling climate services may occur through leveraging capacities of project champions, knowledge brokers, and intermediaries (Mantilla et al., 2014; Coulibaly et al., 2015), co-production of knowledge (Kirchhoff et al., 2013) that enables users to actively participate with valid expertise of the particularities of their decision-making context (Vaughan and Dessai, 2014), developing clear financial models to ensure sustainability (Webber and Donner, 2017), which includes multi-stakeholder engagement through iterative participatory processes (Girvetz et al., 2014; Dorward et al., 2015), and leveraging appropriate

Issues of timing of information provision and scale of information remain barriers (Dinku et al., 2014; Jancoes et al., 2014; Gebru et al., 2015; Weisse et al., 2015; Brasseur and Gallardo, 2016; Cortekar et al., 2016; Singh et al., 2016; Snow et al., 2016; Vaughan et al., 2016; Kihila, 2017)

Lower uptake by women, remote communities, those without technical support (Carr and Onzere, 2017; Singh et al., 2017)

Issues of trust and usability of information provided (Jones et al., 2016b; Singh et al., 2017; White et al., 2017a)

Continued focus on supply-driven provision of climate in-formation rather than specific needs of end users (Lourenço et al., 2016)

Semi-arid regions in India and sub-Saharan Africa facing 1.5°C warming are seeing benefits of climate services in the agriculture planning, drought management, and flood warning (Vincent et al., 2015; Lobo et al., 2017; Singh et al., 2017; Vaughan et al., 2018a)

Climate services are seeing wide application in sectors such as agriculture, health, disaster management, insurance (Lourenço et al., 2016; Vaughan et al., 2018a) with implications for adaptation decision-making.

Several programmes aimed at using climate services for better decision making are showing signs of success: from various actors, at various scales, and using different forms of information delivery and uptake. These involve participatory analysis of seasonal forecasts in East Africa (Dorward et al., 2015), NGO-driven weather advisories in India (Lobo et al., 2017), innovations in government-led agriculture extension in various countries across sub-Saharan Africa and South Asia (Singh et al., 2016), and broadening the scope of climate services to directly inform spatial planning and adaptation interventions in the Netherlands (Goosen et al., 2013).
communication channels such as mobile technology (Hampson et al., 2014; Gebru et al., 2015).

**Supplementary Material 4.C Carbon dioxide removal costs, deployment and side-effects: literature basis for Figure 4.2 (Section 4.3.7)**

**Supplementary Material 4.C, Table 1: References supporting Figure 4.2 in Section 4.3.7: Evidence on Carbon Dioxide Removal (CDR) abatement costs, 2050 deployment potentials, and side effects. Based on systematic review (Fuss et al., 2018b).**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Costs</th>
<th>Potentials</th>
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</thead>
<tbody>
<tr>
<td>Afforestation and reforestation (AR)</td>
<td>(Myers and Goreau, 1991; van Kooten et al., 1992; Winjum et al., 1992; Dixon et al., 1993; Winjum et al., 1993; Swisher, 1994; Brown et al., 1995; Chang, 1999; Plantinga et al., 1999; van Kooten et al., 1999; Kooten, 2000; Sohngen and Alig, 2000; Plantinga and Mauldin, 2001; Ravindranath et al., 2001; Sohngen and Mendelsohn, 2003; van Vliet et al., 2003; Baral and Guha, 2004; Richards and Stokes, 2004; Koning et al., 2005; Lakjeda et al., 2005; Lee et al., 2005; Olschewski and Benítez, 2005; Richards and Stavins, 2005; Yemshanov et al., 2005; Benítez and Obersteiner, 2006; Han et al., 2007; Ahn, 2008; Hedenus and Azar, 2009; Dominy et al., 2010; Rootzén et al., 2010; Ryan et al., 2010; Torres et al., 2010; Winsten et al., 2011; Paterson and Bryan, 2012; Townsend et al., 2012; Nijnik et al., 2013; Paul et al., 2013; Polglase et al., 2013; Carwardine et al., 2015; Evans et al., 2015; Maraseni and Cockfield, 2015; Haim et al., 2016)</td>
<td>(Dixon et al., 1994; Nilsson and Schopfhauser, 1995; Cannell, 2003; Richards and Stokes, 2004; Houghton et al., 2015)</td>
</tr>
<tr>
<td>Bioenergy with carbon dioxide capture and storage (BECCS)</td>
<td>(Möllersten et al., 2003, 2004, 2006; Keith et al., 2006; Azar et al., 2006; Luckow et al., 2010; Abanades et al., 2011; Gough and Upham, 2011; Laude and Ricci, 2011; Laude et al., 2011; Ranjan and Herzog, 2011; Carbo et al., 2011; De Visser et al., 2011; Fabbrì et al., 2011; Koornneef et al., 2012b; Kärki et al., 2013; Fornell et al., 2013; Akgül et al., 2014; Johnson et al., 2014b; Arasto et al., 2014; Al-Quayim et al., 2015; Onarheim et al., 2015; Creutzig et al., 2015; Moreira et al., 2016; Rochedo et al., 2016; Sanchez and Callaway, 2016)</td>
<td>(Fischer and Schrattenholzer, 2001; Yamamoto et al., 2001; Hoogwijk et al., 2005; Moreira, 2006; Obersteiner et al., 2006; Smeets et al., 2007; Smeets and Faaij, 2007; Hakala et al., 2008; Hoogwijk et al., 2009; van Vuuren et al., 2009; Dornburg et al., 2010; Gregg and Smith, 2010; Thrán et al., 2010; Beringer et al., 2011; Haberl et al., 2011; Cornelissen et al., 2012; Erb et al., 2012; Rogner et al., 2012; Smith et al., 2012b; Lauri et al., 2014; Kraxner and Nordström, 2015; Searle and Malins, 2015; Buchholz et al., 2016; Calvin et al., 2016; Tokimatsu et al., 2017)</td>
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<tr>
<td>Biochar</td>
<td>(McCarl et al., 2009; Smith, 2016)</td>
<td>(Lehmann et al., 2006; Laird et al., 2009; Lee et al., 2010; Moore et al., 2010; Pratt and Moran, 2010; Woolf et al., 2010; Powell and Lentón, 2012; Hamilton et al., 2015; Lomax et al., 2015; Smith, 2016)</td>
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| Soil carbon sequestration | (Smith et al., 2008) | (Batjes, 1998; Meting et al., 2001; Lal, 2003a, 2003b, 2004a, 2004c; Lal et al., 2007; Smith et al., 2008; Lal, 2010; Salati et al., 2010; Conant, 2011; Lal, 2011; Smith, 2012; Benbi, 2013; Lal, 2013; Lorenz
<table>
<thead>
<tr>
<th>Strategy</th>
<th>References</th>
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<td>Direct air carbon dioxide capture and storage (DACCS)</td>
<td>(Zeman, 2003, 2014; Keith et al., 2006; Nikulshina et al., 2006; Stolaroff et al., 2008; Lackner, 2009; Simon et al., 2011; Socolow et al., 2011; House et al., 2011; Holmes and Keith, 2012a; Kulkarni and Sholl, 2012; Mazzotti et al., 2013; Zhang et al., 2014b; Geng et al., 2016; Sakwa-Novak et al., 2016; SEAB, 2016; Sinha et al., 2017; van der Giesen et al., 2017)</td>
</tr>
<tr>
<td>Enhanced weathering (EW)</td>
<td>(Schuiling and Krijgsman, 2006; Hartmann and Kempe, 2008; Köhler et al., 2010; Renforth, 2012; Taylor et al., 2016; Strefler et al., 2018a)</td>
</tr>
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<td>Ocean alkalinisation (OA)</td>
<td>(Rau and Caldeira, 1999; Rau et al., 2007; Harvey, 2008; Rau, 2008; Paquay and Zeebe, 2013; Renforth et al., 2013; Renforth and Kruger, 2013; Renforth and Henderson, 2017)</td>
</tr>
<tr>
<td>Reviews</td>
<td>(Lenton, 2010; McGlashan et al., 2012; McLaren, 2012; Lenton, 2014; Caldecott et al., 2015; NRC, 2015; UNEP, 2017b)</td>
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Supplementary Material 4.D Guidance and assessment for feasibility assessment

Supplementary Material 4.D.1 Guidance for feasibility assessment in Section 4.5.1

Supplementary Material 4.D.1, Table 1: Guidance for conducting the feasibility assessment of mitigation and adaptation options. See Supplementary Material 4.D.2 for the assessment and literature basis of the assessment of mitigation options and Supplementary Material 4.D.3 for the assessment and literature basis of adaptation options.

<table>
<thead>
<tr>
<th>Entry for indicator-option combination</th>
<th>Guidance for conducting the feasibility assessment of mitigation and adaptation options</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA (not applicable)</td>
<td>The indicator is not relevant to the option</td>
</tr>
<tr>
<td>NE (no evidence)</td>
<td>• No peer-reviewed literature could be located supporting an assessment of whether this indicator would limit the option’s feasibility</td>
</tr>
<tr>
<td></td>
<td>• The peer-reviewed literature that mentions the issue is not robust enough</td>
</tr>
<tr>
<td>LE (limited evidence)</td>
<td>• One or two papers make statements/present research that could be a basis for the assessment, but this evidence is considered too limited</td>
</tr>
<tr>
<td></td>
<td>• Two or more papers provide a basis for the assessment as a side-issue in the paper, not as a core issue</td>
</tr>
<tr>
<td>A</td>
<td>A feasibility assessment can be made:</td>
</tr>
<tr>
<td></td>
<td>• If there are one or two robust papers (or more) that contain references which also support the assessment</td>
</tr>
<tr>
<td>B</td>
<td>B = The indicator does not have a positive, nor a negative effect on the feasibility of the option</td>
</tr>
<tr>
<td></td>
<td>• If literature is plentiful</td>
</tr>
<tr>
<td></td>
<td>• If one or a number of meta-studies and reviews provide extensive treatment of the option/indicator combination</td>
</tr>
<tr>
<td>C</td>
<td>C = The indicator does not pose any barrier to the feasibility of this option</td>
</tr>
</tbody>
</table>

Supplementary Material 4.D.1, Table 2: Parameters used for the calculation of the overall feasibility of the dimension-option combinations

<table>
<thead>
<tr>
<th>#indicators</th>
<th>Number of indicators used to assess the overall feasibility of a dimension, typically two to five.</th>
</tr>
</thead>
<tbody>
<tr>
<td>#NA</td>
<td>Number of indicators that are not applicable (NA) to the option</td>
</tr>
<tr>
<td>#NE&amp;LE</td>
<td>Total number of indicators for which there is no evidence (NE) or limited evidence (LE)</td>
</tr>
<tr>
<td>#A</td>
<td>Number of indicators assessed as A</td>
</tr>
<tr>
<td>#B</td>
<td>Number of indicators assessed as B</td>
</tr>
<tr>
<td>#C</td>
<td>Number of indicators assessed as C</td>
</tr>
<tr>
<td>#effective indicators</td>
<td>#effective indicators = #indicators − #NA</td>
</tr>
</tbody>
</table>

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Supplementary Material 4.D.1, Table 3: Legend criteria for the overall feasibility of the dimension-option combinations as shown in Table 4.11 for mitigation options and Table 4.12 or adaptation options.

<table>
<thead>
<tr>
<th>Legend of Table 4.11 and Table 4.12</th>
<th>Legend criteria for the overall feasibility of each of the dimension-option combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>#indicators = #NA</td>
<td></td>
</tr>
<tr>
<td>#NE&amp;LE &gt; 0.5 * effective indicators</td>
<td></td>
</tr>
<tr>
<td>AVG ≤ 1.5</td>
<td>#NE&amp;LE ≤ 0.5 * effective indicators</td>
</tr>
<tr>
<td>1.5 &lt; AVG ≤ 2.5</td>
<td>#NE&amp;LE ≤ 0.5 * effective indicators</td>
</tr>
<tr>
<td>AVG &gt; 2.5</td>
<td>#NE&amp;LE ≤ 0.5 * effective indicators</td>
</tr>
</tbody>
</table>
**Supplementary Material 4.D.2 Feasibility assessment of mitigation options as presented in Section 4.5.2**

**Supplementary Material 4.D.2.i Feasibility assessment of mitigation options in energy system transitions**

**Supplementary Material 4.D.2.i, Table 1**: Feasibility assessment of energy system transition mitigation options: Wind (on-shore & off-shore); Solar PV; and Bioenergy. For methodology, see Supplementary Material 4.D.1.

<table>
<thead>
<tr>
<th></th>
<th>Wind (on-shore &amp; off-shore)</th>
<th>Solar PV</th>
<th>Bioenergy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Evidence</strong></td>
<td>Robust</td>
<td>Robust</td>
<td>Robust</td>
</tr>
<tr>
<td><strong>Agreement</strong></td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Cost-effectiveness</strong></td>
<td>(Silva Herran et al., 2016); (IRENA 2015); (IRENA, 2016); (WEC), 2016); (Shafiee et al., 2016); (Voormolen et al., 2016)</td>
<td>(Climate Council 2017b); (IRENA 2015); (IRENA, 2016); (Cengiz and Mamiş, 2015)</td>
<td>(Brown, 2015; Creutzig et al., 2015; Patel et al., 2016)</td>
</tr>
<tr>
<td><strong>Absence of</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>distributional effects</strong></td>
<td>(Greene and Geisken, 2013); (Corfee-Morlot et al., 2012)</td>
<td>(Toovey and Malin, 2016); (Corfee-Morlot et al., 2012)</td>
<td>(Arndt et al., 2011b; German and Schoneveld, 2012; Creutzig et al., 2013; Hunsberger et al., 2014; Buck, 2016; Robledo-Abad et al., 2017; Stevanović et al., 2017)</td>
</tr>
<tr>
<td><strong>Employment &amp;</strong></td>
<td>(IEA 2017d); (IRENA 2017b); (Council, 2016); (Council, 2012)</td>
<td>(IEA) 2017d); (IRENA 2017b); (Council 2017b); (Council, 2016)</td>
<td>(Parcell and Westhoff, 2006; Gohin, 2008; Wicke et al., 2009; Arndt et al., 2011a)</td>
</tr>
<tr>
<td><strong>productivity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>enhancement potential</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Do Not Cite, Quote or Distribute</td>
<td>Chapter 4 Supplementary Material</td>
<td>IPCC SR1.5</td>
<td></td>
</tr>
<tr>
<td>---------------------------------</td>
<td>----------------------------------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td><strong>Technological</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical scalability</td>
<td>(IRENA 2017b); (Al-Maghalseh and Maharmeh, 2016); (Silva Herran et al., 2016); (IRENA 2017a)</td>
<td>(IRENA 2017a)</td>
<td></td>
</tr>
<tr>
<td>Maturity</td>
<td>(UNEP 2017b); (IRENA 2017a)</td>
<td>(Despotou, 2012)</td>
<td></td>
</tr>
<tr>
<td>Simplicity</td>
<td>(IRENA, 2016)</td>
<td>(Demirbas and Demirbas, 2007; Surendra et al., 2014)</td>
<td></td>
</tr>
<tr>
<td>Absence of risk</td>
<td>(UNEP 2017b)</td>
<td>Carbon Neutrality - debate (Buchholz et al., 2016; Liu et al., 2018)</td>
<td></td>
</tr>
<tr>
<td><strong>Institutional</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Political acceptability</td>
<td>(UNEP 2017b); (WEC) 2016); (Borch et al., 2014); (Bistline, 2017); (Kar and Sharma, 2015) (Baker, 2015) (Furtado and Perrot, 2015)</td>
<td>(UNEP 2017b); (Shukla et al., 2018)(Baker, 2015)</td>
<td></td>
</tr>
<tr>
<td>Legal &amp; administrative acceptability</td>
<td>(UNEP 2017b); (Bistline, 2017); (Kar and Sharma, 2015); (Comello et al., 2017)</td>
<td>(UNEP 2017b); (Comello et al., 2017); (Shukla et al., 2018); (Shrimali and Rohra, 2012)</td>
<td></td>
</tr>
<tr>
<td>Institutional capacity</td>
<td>(UNEP 2017b); (Corfee-Morlot et al., 2012); (Goodale and Milman, 2016); (Bistline, 2017); (Kar and Sharma, 2015); (Comello et al., 2017)</td>
<td>(UNEP 2017b); (Corfee-Morlot et al., 2012); (Comello et al., 2017); (Shukla et al., 2018); (Shrimali and Rohra, 2012)</td>
<td></td>
</tr>
<tr>
<td>Transparency &amp; accountability potential</td>
<td>(UNEP 2017b); (Bistline, 2017) (Eberhard et al., 2014) (Furtado and Perrot, 2015) (Swilling et al., 2016)</td>
<td>(UNEP 2017b) (Eberhard et al., 2014) (Swilling et al., 2016)</td>
<td></td>
</tr>
<tr>
<td><strong>Legal &amp; administrative acceptability</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Institutional capacity</strong></td>
<td></td>
<td>LE</td>
<td></td>
</tr>
<tr>
<td><strong>Transparency &amp; accountability potential</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Rathmann et al., 2012; Silalertruksa et al., 2012; Augusto Horta Nogueira and Silva Capaz, 2013; Ribeiro, 2013)
| Socio-cultural | | | | NE |
|----------------|----------------|----------------|----------------|
| Social co-benefits (health, education) | (Geels et al., 2017); (IEA 2017d); (UNEP 2017a); (UNEP 2017b); (Silva Herran et al., 2016); (Geels et al., 2017) | (Geels et al., 2017); (IEA 2017d); (UNEP 2017a); (UNEP 2017b) | (Kar et al., 2012; Anenberg et al., 2013; Knoblauch et al., 2014; Porter et al., 2015; Weldu et al., 2017) |
| Public acceptance | (Geels et al., 2017); (IEA, 2017d); (UNEP 2017a); (UNEP 2017b); (Geraint and Gianluca, 2016); (Borch et al., 2014); (Kondili and Kaldellis, 2012); (Sütterlin and Siegrist, 2017); (Brennan et al., 2017); (Heidenreich, 2015) | (Geels et al., 2017); (IEA 2017d); (UNEP 2017a); (UNEP 2017b); (Sütterlin and Siegrist, 2017); (Brennan et al., 2017) | (Khanal et al., 2010; Delshad and Raymon, 2013; Dragojlovic and Einsiedel, 2015; Moula et al., 2017) (Fytiti and Zabaniotou, 2017; Goetz et al., 2017) |
| Social & regional inclusiveness | (Geels et al., 2017); (IEA) 2017d); (UNEP 2017a); (UNEP 2017b) | (Geels et al., 2017); (IEA) 2017d); (UNEP 2017a); (UNEP 2017b) | (Creutzig et al., 2013, 2015; Favretto et al., 2017; Robledo-Abad et al., 2017) |
| Intergenerational equity | (Geels et al., 2017); (IEA) 2017d); (UNEP 2017a); (UNEP 2017b) | (Geels et al., 2017); (IEA) 2017d); (UNEP 2017a); (UNEP 2017b) | NE |
| Human capabilities | (Geels et al., 2017); (IEA) 2017d); (UNEP 2017a); (UNEP 2017b); (Bistline, 2017) | (Geels et al., 2017); (IEA) 2017d); (UNEP 2017a); (UNEP 2017b); (Shrimali and Rohra, 2012); (Shukla et al., 2018) | NE |
| Environmental | Reduction of air pollution | (UNEP 2017a); (UNEP 2017b); (Council, 2012); (Kondili and Kaldellis, 2012) | (UNEP 2017a); (UNEP 2017b) | LE |

*Management (Pyörälä et al., 2014; Torssonen et al., 2016; Baul et al., 2017; Kilpeläinen et al., 2017)*

*Carbon neutrality – feedstock and time frame (Zanchi et al., 2012; Hammar et al., 2015; Daioglou et al., 2017; Booth, 2018; Sterman et al., 2018)*

*dLUC and iLUC challenges emissions (Schulze et al., 2012; Harris et al., 2015; Daioglou et al., 2017; Booth, 2018; Sterman et al., 2018) (Buchholz et al., 2014; Röder et al., 2015; Röder and Thornley, 2016; Robledo-Abad et al., 2017)*
<table>
<thead>
<tr>
<th>Topic</th>
<th>Final Government Draft</th>
<th>Chapter 4 Supplementary Material</th>
<th>IPCC SR1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction of toxic waste</td>
<td>(UNEP 2017a); (UNEP 2017b)</td>
<td>(UNEP 2017a); (UNEP 2017b)</td>
<td>(Smith et al., 2016) (Bonsch et al., 2016) (Gerbens-Leenes et al., 2009; Gheewala et al., 2011; Smith and Torn, 2013; Bonsch et al., 2016; Lampert et al., 2016; Mouratidou et al., 2016; Wei et al., 2016; Mathioudakis et al., 2017)</td>
</tr>
<tr>
<td>Reduction of water use</td>
<td>(UNEP 2017a); (UNEP 2017b); (Kondili and Kaldellis, 2012)</td>
<td>(UNEP 2017a); (UNEP 2017b)</td>
<td>(Immerzeel et al., 2014; Dale et al., 2015; Holland et al., 2015; Kline et al., 2015; Santangeli et al., 2016; Tarr et al., 2017) (Holland et al., 2015; Santangeli et al., 2016) Mixed evidence pointing more to negative impacts for first-generation and sometimes even positive for second-generation.</td>
</tr>
<tr>
<td>Improved biodiversity</td>
<td>(UNEP 2017a); (UNEP 2017b)</td>
<td>(UNEP, 2017a); (UNEP 2017b)</td>
<td>(Slade et al., 2014) (Beringer et al., 2011; Klein et al., 2014; Creutzig et al., 2015; Kraxner and Nordström, 2015; Searle and Malins, 2015; Smith et al., 2016; Boysen et al., 2017b; Tokimatsu et al., 2017; Heck et al., 2018)</td>
</tr>
<tr>
<td>Physical feasibility (physical potentials)</td>
<td>(UNEP 2017a); (UNEP 2017b); (Al-Maghelseh and Maharmeh, 2016)</td>
<td>(UNEP 2017a); (UNEP 2017b)</td>
<td>(Popp et al., 2014; Creutzig et al., 2015; Williamson, 2016; Robledo-Abad et al., 2017)</td>
</tr>
<tr>
<td>Geophysical</td>
<td></td>
<td></td>
<td>(Bonsch et al., 2016; Hammond and Li, 2016)</td>
</tr>
<tr>
<td>Limited use of land</td>
<td>(UNEP 2017a); (UNEP 2017b); (Silva Herran et al., 2016); (Mohan, 2017)</td>
<td>(UNEP 2017a); (UNEP 2017b); (Mohan, 2017)</td>
<td></td>
</tr>
</tbody>
</table>

Do Not Cite, Quote or Distribute 4-17 Total pages: 171
<table>
<thead>
<tr>
<th>Limited use of scarce (geo)physical resources</th>
<th>(UNEP 2017a); (UNEP 2017b)</th>
<th>(UNEP 2017a); (UNEP 2017b)</th>
<th>NA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global spread</td>
<td>(UNEP 2017a); (UNEP 2017b)</td>
<td>(UNEP 2017a); (UNEP 2017b)</td>
<td>(Deng et al., 2015; Daioglou et al., 2017; Robledo-Abad et al., 2017)</td>
</tr>
</tbody>
</table>
**Supplementary Material 4.D.2.i, Table 2**: Feasibility assessment of energy system transition mitigation options: Electricity storage; Power sector CCS; and Nuclear energy. For methodology, see Supplementary Material 4.D.1.

<table>
<thead>
<tr>
<th>Economic</th>
<th>Electricity storage</th>
<th>Power sector CCS</th>
<th>Nuclear energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost-effectiveness</td>
<td>(ACOLA, 2017); (Schmidt et al., 2017); (Quann, 2017); (IRENA 2015)</td>
<td>Studies indicate that CCS in the power sector is somewhere in the middle range of mitigation options. It’s a significant additional cost but the scale is usually large so much CO₂ is reduced. (Global CCS Institute, 2017) (Rubin et al., 2015) (IEA, 2017a) (Castrejón et al., 2018)</td>
<td>(Bruckner et al., 2014) (Lovering et al., 2016; Koomey et al., 2017) (Finon and Roques, 2013)</td>
</tr>
<tr>
<td>Absence of distributional effects</td>
<td>(Corfee-Morlot et al., 2012; ACOLA, 2017)</td>
<td>NE</td>
<td>NE</td>
</tr>
<tr>
<td>Employment &amp; productivity enhancement potential</td>
<td>(ACOLA, 2017); (Climate Council, 2017); (IEA 2017); (IRENA, 2017b)</td>
<td>Higher than coal/gas without CCS, on par with wind, geothermal, nuclear (IEA, 2017a) (Wei et al., 2010) (Koelbl et al., 2016)</td>
<td>(Wei et al., 2010) (Kenley et al., 2009)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technological</th>
<th>Electricity storage</th>
<th>Power sector CCS</th>
<th>Nuclear energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maturity</td>
<td>(ACOLA, 2017); (IRENA, 2017a)</td>
<td>(Zheng and Xu, 2014; Abanades et al., 2015; Bui et al., 2018; Qiu and Yang, 2018)</td>
<td>(Bruckner et al., 2014)</td>
</tr>
<tr>
<td>Simplicity</td>
<td>(ACOLA, 2017); (IRENA, 2016)</td>
<td>LE (Wei et al., 2010) (IEA GHG, 2012)</td>
<td>(Esteban and Portugal-Pereira, 2014)</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------------</td>
<td>--------------------------------------------------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Legal &amp; administrative acceptability</td>
<td>(ACOLA, 2017); (Nguyen et al., 2017); (UNEP, 2017a)</td>
<td>(Boot-Handford et al., 2014; de Coninck and Benson, 2014; Dixon et al., 2015)</td>
<td>NE</td>
</tr>
<tr>
<td>Institutional capacity</td>
<td>(ACOLA, 2017); (IEA 2017a); (Nguyen et al., 2017); (UNEP 2017b); (Corfee-Morlot et al., 2012)</td>
<td>LE</td>
<td>(Ashworth et al., 2015)</td>
</tr>
<tr>
<td>Transparency &amp; accountability potential</td>
<td>(ACOLA, 2017); (Nguyen et al., 2017); (UNEP, 2017a)</td>
<td>NE</td>
<td>NE</td>
</tr>
<tr>
<td>Socio-cultural</td>
<td>Social co-benefits (health, education)</td>
<td>(ACOLA, 2017); (Geels et al., 2017); (IEA 2017d); (UNEP 2017a); (UNEP 2017b)</td>
<td>NE</td>
</tr>
<tr>
<td></td>
<td>Public acceptance</td>
<td>(ACOLA, 2017); (Climate Council 2017a); (Geels et al., 2017); (IEA 2017d); (UNEP 2017a); (UNEP 2017b)</td>
<td>(Ashworth et al., 2015) (Aminu et al., 2017) (Seigo et al., 2014)</td>
</tr>
<tr>
<td>Social &amp; regional inclusiveness</td>
<td>(ACOLA, 2017); (Geels et al., 2017); (IEA 2017d); (UNEP 2017a); (UNEP 2017b)</td>
<td>NA</td>
<td>NE</td>
</tr>
<tr>
<td>Intergenerational equity</td>
<td>(ACOLA, 2017); (Geels et al., 2017); (IEA 2017d); (UNEP 2017a); (UNEP 2017b)</td>
<td>(Alcalde et al., 2018)</td>
<td>(Bruckner et al., 2014)</td>
</tr>
<tr>
<td>Human capabilities</td>
<td>(ACOLA, 2017; Geels et al., 2017; (IEA 2017d); (UNEP 2017a);</td>
<td>(Shackley et al., 2009; IEA GHG, 2012)</td>
<td>NE</td>
</tr>
</tbody>
</table>

**Institutional Political acceptability**
- (ACOLA, 2017); (Nguyen et al., 2017); (UNEP, 2017a)
- (de Coninck and Benson, 2014)
- (Boot-Handford et al., 2014)
- (Aminu et al., 2017)

**Legal & administrative acceptability**
- (ACOLA, 2017); (Nguyen et al., 2017); (UNEP, 2017a)
- (Boot-Handford et al., 2014)
- (de Coninck and Benson, 2014)
- (Dixon et al., 2015)

**Institutional capacity**
- (ACOLA, 2017)
- (IEA 2017a)
- (Nguyen et al., 2017)
- (UNEP 2017b)
- (Corfee-Morlot et al., 2012)
- (Ashworth et al., 2015)
- (Figueroa, 2016)
- (Juraku, 2016)
- (Tosa, 2015)
- (Vivoda and Graetz, 2015)
- (Taebi and Mayer, 2017)
- (Kim and Chung, 2018)

**Transparency & accountability potential**
- (ACOLA, 2017)
- (Nguyen et al., 2017)
- (UNEP, 2017a)
- (Bruckner et al., 2014)
- (Oe et al., 2016)
- (Suzuki et al., 2016)
- (WHO, 2011)
- (Ishikawa, 2014)
- (Nagataki et al., 2013)
- (Endo et al., 2012)
- (Kawaguchi and Yukutake, 2017)
- (Nakayachi et al., 2015)
- (Fridman et al., 2016)
- (Berenson et al., 2016)
- (Hirschberg et al., 2016)

**Socio-cultural Public acceptance**
- (ACOLA, 2017)
- (Climate Council 2017a)
- (Geels et al., 2017)
- (IEA 2017d)
- (UNEP 2017a)
- (UNEP 2017b)
- (Ashworth et al., 2015)
- (Aminu et al., 2017)
- (Seigo et al., 2014)
- (Huhtala and Remes, 2017)
- (Diaz-Maurin and Kovacic, 2015)
- (Wu, 2017)
- (Kim et al., 2014)
- (Murakami et al., 2015)
- (Ho et al., 2018)
- (Tsujikawa et al., 2016)
- (Nishikawa et al., 2016)
- (Bruckner et al., 2014)
- (IAEA, 2017)

**Social & regional inclusiveness**
- (ACOLA, 2017)
- (Geels et al., 2017)
- (IEA 2017d)
- (UNEP 2017a)
- (UNEP 2017b)
- NA
- NE

**Intergenerational equity**
- (ACOLA, 2017)
- (Geels et al., 2017)
- (IEA 2017d)
- (UNEP 2017a)
- (UNEP 2017b)
- (Alcalde et al., 2018)
- (Bruckner et al., 2014)

**Human capabilities**
- (ACOLA, 2017; Geels et al., 2017; (IEA 2017d); (UNEP 2017a);
- (Shackley et al., 2009; IEA GHG, 2012)
- NE
<table>
<thead>
<tr>
<th>Environmental/ecological</th>
<th>Reduction of air pollution</th>
<th>(ACOLA, 2017); (UNEP 2017a); (UNEP 2017b)</th>
<th>(Koornneef et al., 2008; Odeh and Cockerill, 2008; Pehnt and Henkel, 2009; Korre et al., 2010; Nie et al., 2011; Modahl et al., 2012; Corsten et al., 2013; Cuéllar-Franca and Azapagic, 2015; Gibon et al., 2017)</th>
<th>(Cheng and Hammond, 2017)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reduction of toxic waste</td>
<td>(ACOLA, 2017); (UNEP 2017a); (UNEP 2017b)</td>
<td>(Koornneef et al., 2008; Odeh and Cockerill, 2008; Pehnt and Henkel, 2009; Korre et al., 2010; Nie et al., 2011; Modahl et al., 2012; Corsten et al., 2013; Cuéllar-Franca and Azapagic, 2015; Gibon et al., 2017)</td>
<td>(Bruckner et al., 2014)</td>
</tr>
<tr>
<td></td>
<td>Reduction of water use</td>
<td>(ACOLA, 2017); (UNEP 2017a); (UNEP 2017b)</td>
<td>. (Cooney et al., 2015) (Koornneef et al., 2012a) (Koornneef et al., 2008; Odeh and Cockerill, 2008; Pehnt and Henkel, 2009; Korre et al., 2010; Nie et al., 2011; Modahl et al., 2012; Corsten et al., 2013; Cuéllar-Franca and Azapagic, 2015; Gibon et al., 2017)</td>
<td>(Kato et al., 2012) (Ueda et al., 2013) (Tsumune et al., 2012) (Sakaguchi et al., 2012) (Bailly du Bois et al., 2012) (Bruckner et al., 2014)</td>
</tr>
<tr>
<td></td>
<td>Improved biodiversity</td>
<td>NA</td>
<td>(Koornneef et al., 2012a) (Koornneef et al., 2008; Odeh and Cockerill, 2008; Pehnt and Henkel, 2009; Korre et al., 2010; Nie et al., 2011; Modahl et al., 2012; Corsten et al., 2013; Cuéllar-Franca and Azapagic, 2015; Gibon et al., 2017)</td>
<td>(Cheng and Hammond, 2017)</td>
</tr>
<tr>
<td>Geophysical</td>
<td>Physical feasibility (physical potentials)</td>
<td>(ACOLA, 2017); (UNEP 2017a); (UNEP 2017b)</td>
<td>(IPCC, 2005) (de Coninck and Benson, 2014) (Scott et al., 2015)</td>
<td>(Bruckner et al., 2014)</td>
</tr>
<tr>
<td></td>
<td>Limited use of land</td>
<td>(ACOLA, 2017); (UNEP 2017a); (UNEP 2017b)</td>
<td>Non-controversial so not investigated.</td>
<td>(Cheng and Hammond, 2017)</td>
</tr>
<tr>
<td>Limited use of scarce (geo)physical resources</td>
<td>(ACOLA, 2017); (UNEP 2017a); (UNEP 2017b) (Newman et al., 2017)</td>
<td>(Scott et al., 2015) (IPCC, 2005) (de Coninck and Benson, 2014) (on storage capacity, otherwise no issues)</td>
<td>(NEA, 2016) (Bruckner et al., 2014)</td>
<td></td>
</tr>
<tr>
<td>---------------------------------------------</td>
<td>---------------------------------------------------------------</td>
<td>----------------------------------------------------------------</td>
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<td></td>
</tr>
<tr>
<td>Global spread</td>
<td>(ACOLA, 2017); (UNEP 2017a); (UNEP 2017b)</td>
<td>(IPCC, 2005) (de Coninck and Benson, 2014)</td>
<td>(IAEA, 2017)</td>
<td></td>
</tr>
</tbody>
</table>
### Supplementary Material 4.D.2.ii Feasibility assessment of mitigation options in land & ecosystem transitions

**Supplementary Material 4.D.2.ii, Table 1:** Feasibility assessment of the land and ecosystem transition mitigation options: Reduced food wastage and efficient food production; Dietary shifts; Sustainable intensification of agriculture; and Ecosystems restoration. For methodology, see Supplementary Material 4.D.1.

<table>
<thead>
<tr>
<th>Evidence</th>
<th>Agreements</th>
<th>Economic</th>
<th>Absence of distributional effects</th>
<th>Employment &amp; productivity enhancement potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced food wastage and efficient food production</td>
<td>Dietary shifts</td>
<td>Sustainable intensification of agriculture</td>
<td>Ecosystems restoration</td>
<td></td>
</tr>
<tr>
<td>Robust</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>

- **Evidence:**
  - Robust (FAO, 2013a; Thyberg and Tonjes, 2016; Hebrok and Boks, 2017)
  - Medium (FAO, 2013b)
  - Medium (FAO, 2013b)
  - Medium (FAO, 2013b)

- **Agreement:**
  - High (FAO, 2013b)
  - High (FAO, 2013b)
  - High (FAO, 2013b)
  - High (FAO, 2013b)

- **Economic:**
  - (FAO, 2013a; Thyberg and Tonjes, 2016; Hebrok and Boks, 2017)
  - (FAO, 2013b)
  - (Havlik et al., 2014)
  - (Griscom et al., 2017; Phan et al., 2017)
  - AD - (Kindermann et al., 2008) (Overmars et al., 2014) (Dang Phan et al., 2014)
  - REDD+ (Rakatama et al., 2017) (Ickowitz et al., 2017)

- **Absence of distributional effects:**
  - LE (Žukiewicz-Sobczak et al., 2014)
  - LE (Smith et al., 2017a)
  - Biofuels certification (German and Schoneveld, 2012)
  - AD - (Caplow et al., 2011)
  - REDD+ tenure (Sunderlin et al., 2014) (Poudyal et al., 2016)
  - (Howson and Kindon, 2015)

- **Employment & productivity enhancement potential:**
  - LE (Haggblade et al., 2015; Tschirley et al., 2015; Berti and Mulligan, 2016; Blay-Palmer et al., 2016; Alexander et al., 2017)
  - LE (Foley et al., 2011; Harvey et al., 2014; Clark and Tilman, 2017; Griscom et al., 2017)
  - AD - (Brander et al., 2013)
  - Forest carbon (Neimark et al., 2016)
  - Yields, income and capital (Fenger et al., 2017; Jena et al., 2017)
  - Wetlands - (Brander et al., 2013)
Institutional

| Political acceptability | Clark and Tilman, 2017 | (Shepon et al., 2016) | al., 2017) but are not uncontested (Blackman and Rivera, 2011; Hidayat et al., 2015; Oya et al., 2017).

Technological

| Technical scalability | (Högy et al., 2009; DaMatta et al., 2010; Lin et al., 2013; Challinor et al., 2014; Papargyropoulou et al., 2014; De Souza et al., 2015; Hebros and Boks, 2017) | (Hallström et al., 2015; Alexander et al., 2017; Clark and Tilman, 2017) | (Harvey et al., 2014; Clark and Tilman, 2017; Griscom et al., 2017; Waldron et al., 2017; Ramankutty et al., 2018) (Pretty and Bharucha, 2014; Petersen and Snapp, 2015; Adhikari et al., 2018a) | (Smith et al., 2014b) – Table 11.2 (Houghton et al., 2015; Griscom et al., 2017; Houghton and Nassikas, 2018)

| Maturity | NE | NE | LE | (Pretty and Bharucha, 2014; Petersen and Snapp, 2015) | (McLaren, 2012; Smith et al., 2012a; Goetz et al., 2015)

| Simplicity | NE | NE | NE | Ecosystem restoration – (Smith et al., 2014b; Erb et al., 2017; Griscom et al., 2017)

| Absence of risk | (Lin et al., 2013; Papargyropoulou et al., 2014; Hebros and Boks, 2017) | (Hallström et al., 2015; Alexander et al., 2017; Clark and Tilman, 2017; Röös et al., 2017) | (Harvey et al., 2014; Clark and Tilman, 2017; Griscom et al., 2017; Waldron et al., 2017; Ramankutty et al., 2018; Sparovek et al., 2018) (Adhikari et al., 2018a) | (Smith et al., 2014b) Table 11.9 *No major breakthroughs since AR5

| Institutional | (Refgaard and Magnussen, 2009; Lin et al., 2013; Thornton and Herrero, 2014; Jones et al., 2016b; Thyberg and Tonjes, 2016; Singh et al., 2017; White et al., 2017a) | NE | (Smith and Gregory, 2013; Harvey et al., 2014; Sparovek et al., 2018) (Godfray and Garnett, 2014) | Legitimacy (Nantongo, 2017) REDD+ (Cronin et al., 2016) (Di Gregorio et al., 2017a)
<table>
<thead>
<tr>
<th>Legal &amp; administrative acceptability</th>
<th>NE</th>
<th>NE</th>
<th>(Smith and Gregory, 2013; Harvey et al., 2014)</th>
<th>(Creutzig et al., 2013; Sunderlin et al., 2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Institutional capacity</td>
<td>(Refsgaard and Magnussen, 2009; Thornton and Herrero, 2014; Briley et al., 2015; Jones et al., 2016b; Thyberg and Tonjes, 2016; Singh et al., 2017; White et al., 2017a)</td>
<td>NE</td>
<td>(Smith and Gregory, 2013; Harvey et al., 2014; Sparovek et al., 2018) (Lu et al., 2015; Petersen and Snapp, 2015; Mungai et al., 2016; Adhikari et al., 2018a)</td>
<td>(Unruh, 2011; Marion Suiseeya and Caplow, 2013; Wylie et al., 2016)</td>
</tr>
<tr>
<td>Transparency &amp; accountability potential</td>
<td>(Briley et al., 2015; Jones et al., 2016b; Thyberg and Tonjes, 2016; Singh et al., 2017; White et al., 2017a)</td>
<td>NE</td>
<td>NE</td>
<td>(Neimark et al., 2016; Strassburg et al., 2014)</td>
</tr>
<tr>
<td>Social co-benefits (health, education)</td>
<td>(Lin et al., 2013; Tilman and Clark, 2014; Wellesley et al., 2015; Thyberg and Tonjes, 2016; Hebrok and Boks, 2017; Popp et al., 2017)</td>
<td>(Alexander et al., 2016, 2017; Stoll-Kleemann and Schmidt, 2017; Ritchie et al., 2018)</td>
<td>(Smith and Gregory, 2013; Harvey et al., 2014; Ramankutty et al., 2018; Sparovek et al., 2018) (Pretty et al., 2011; Jones et al., 2012; Falconnier et al., 2018)</td>
<td>(Caplow et al., 2011; Spencer et al., 2017)</td>
</tr>
<tr>
<td>Public acceptance</td>
<td>(Lin et al., 2013; Popp et al., 2017)</td>
<td>(Alexander et al., 2016, 2017; Stoll-Kleemann and Schmidt, 2017)</td>
<td>(Smith and Gregory, 2013; Harvey et al., 2014; Ramankutty et al., 2018; Sparovek et al., 2018) (Godfray and Garnett, 2014; Adhikari et al., 2018a)</td>
<td>AR, (Braun et al., 2017) Wetlands – (Scholte et al., 2016) Ecosystem services – (Lin et al., 2012; Kragt et al., 2016; Thompson et al., 2016)</td>
</tr>
<tr>
<td>Social &amp; regional inclusiveness</td>
<td>(Lin et al., 2013; Tilman and Clark, 2014; Hebrok and Boks, 2017; Popp et al., 2017)</td>
<td>(Khoury et al., 2014; Tilman and Clark, 2014; Alexander et al., 2016, 2017; Stoll-Kleemann and Schmidt, 2017; Ritchie et al., 2018)</td>
<td>(Smith and Gregory, 2013; Harvey et al., 2014; Ramankutty et al., 2018; Sparovek et al., 2018) (Pretty et al., 2011; Franke et al., 2014; Petersen and Snapp, 2015) (Pretty and Lyons and Westoby, 2014) (Ribar and Larson, 2012; Jagger et al., 2014; Brimont et al., 2015; Howson and Kindon, 2015)</td>
<td></td>
</tr>
<tr>
<td>Intergenerational equity</td>
<td>NE</td>
<td>LE</td>
<td>(Bajželj et al., 2014)</td>
<td>NE</td>
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<tr>
<td>--------------------------</td>
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</tr>
<tr>
<td>Human capabilities</td>
<td>(Tilman and Clark, 2014; Thyberg and Tonjes, 2016; Hebrok and Boks, 2017)</td>
<td>LE</td>
<td>(Tilman and Clark, 2014; Ritchie et al., 2018)</td>
<td>LE</td>
</tr>
<tr>
<td>Reduction of air pollution</td>
<td>LE</td>
<td>(Thyberg and Tonjes, 2016)</td>
<td>(Tilman and Clark, 2014; Hallström et al., 2015; Ritchie et al., 2018)</td>
<td>NE</td>
</tr>
<tr>
<td>Reduction of toxic waste</td>
<td>NE</td>
<td>NE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduction of water use</td>
<td>(Bajželj et al., 2014; West et al., 2014; Westhoek et al., 2014)(Thyberg and Tonjes, 2016)</td>
<td>LE</td>
<td>(Bajželj et al., 2014; West et al., 2014; Westhoek et al., 2014)</td>
<td>(Pretty and Bharucha, 2014)</td>
</tr>
<tr>
<td>Improved biodiversity</td>
<td>(Ramankutty et al., 2018)(Johnson et al., 2014a)</td>
<td></td>
<td>(Ramankutty et al., 2018)(Clark and Tilman, 2017)</td>
<td>(Pretty and Bharucha, 2014; Waldron et al., 2017)</td>
</tr>
<tr>
<td>Physical feasibility</td>
<td>Physical feasibility (physical potentials)</td>
<td>(Cherubin et al., 2015; Ivy et al., 2017)</td>
<td>NE</td>
<td>NE</td>
</tr>
<tr>
<td>Topic</td>
<td>Reference</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>--------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limited use of land</td>
<td>(Ramankutty et al., 2018; Sparovek et al., 2018) (Thyberg and Tonjes, 2016)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limited use of scarce (geo)physical resources</td>
<td>NE (Ramankutty et al., 2018) (Shepon et al., 2016) (Benton et al., 2018)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limited use of scarce (geo)physical resources</td>
<td>NE (Foley et al., 2011)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global spread</td>
<td>LE (Thyberg and Tonjes, 2016)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LE (Harvey et al., 2014; Clark and Tilman, 2017)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LE (Petersen and Snapp, 2015; Mungai et al., 2016) (Havlik et al., 2014) (Tilman et al., 2011b)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Humpenöder et al., 2015) REDD+ (Strassburg et al., 2014) AD - restricts land onto which agriculture, grazing and bioenergy plantations can be deployed, which may lead to GHG emissions, increase food prices (Kreidenweis et al., 2016) (Erb et al., 2016)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increased risk from climate change – (Canadell et al 2008)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Ecosystem restoration secondary forests – (Houghton et al., 2015; Houghton and Nassikas, 2018) REDD+ (Strassburg et al., 2014)</td>
<td></td>
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</tr>
</tbody>
</table>
### Feasibility assessment of mitigation options in urban & infrastructure system transitions

#### Supplementary Material 4.D.2.iii, Table 1: Feasibility assessment of urban and infrastructure system transition mitigation options: Land-use & urban planning; Electric cars and buses; and Sharing schemes. For methodology, see Supplementary Material 4.D.1.

<table>
<thead>
<tr>
<th></th>
<th>Land-use &amp; urban planning</th>
<th>Electric cars and buses</th>
<th>Sharing schemes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evidence</td>
<td>Robust</td>
<td>Medium</td>
<td>Limited</td>
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<tr>
<td>Agreement</td>
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<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Economic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost-effectiveness</td>
<td>(Trubka et al., 2010); (Nahlka and Chester, 2014); (Lee and Erickson, 2017); (Sharma, 2018); (Ahlfeldt and Pietrostefani, 2017); (Ahlfeldt and Pietrostefani, 2017)</td>
<td>(Peterson and Micha lek, 2013); (IEA, 2017b)</td>
<td>(Ambrosino et al., 2016); (Cheyne and Imran, 2016); (Kent and Dowling, 2016)</td>
</tr>
<tr>
<td>Absence of distributional effects</td>
<td>(Wiktorowicz et al., 2018); (Teferi and Newman, 2018); (Broekhoff et al., 2018); (Lwasa, 2017) (Colenbrander et al., 2015)</td>
<td>(Glazebrook and Newman, 2018); (Sivak and Schoettle, 2018)</td>
<td>(Gomez et al., 2015); (Ambrosino et al., 2016); (Kent and Dowling, 2016)</td>
</tr>
<tr>
<td>Employment &amp; productivity enhancement potential</td>
<td>(Han et al., 2018); (Ambrosino et al., 2016); (Ambrosino et al., 2016); (Gao and Newman, 2018); (Ahlfeldt and Pietrostefani, 2017); (Broto, 2017)</td>
<td>(Whitelegg, 2016); (IEA, 2017b)</td>
<td>((Cheyne and Imran, 2016); (Sweet, 2014)</td>
</tr>
<tr>
<td><strong>Technological</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical scalability</td>
<td>(Zhang et al., 2018a) (Sharma, 2018) (Broekhoff et al., 2018)</td>
<td>(Brown et al., 2010) (IEA, 2017b)</td>
<td>(Reis et al., 2016); (Ambrosino et al., 2016); (Broch et al., 2013); (Kent and Dowling, 2016)</td>
</tr>
<tr>
<td>Maturity</td>
<td>(Newman et al., 2017); (Parnell, 2015)</td>
<td>(Whitelegg, 2016); (IEA, 2017b)</td>
<td>(Kent and Dowling, 2016); (Le Vine et al., 2014)</td>
</tr>
<tr>
<td>Simplicity</td>
<td>(Newman et al., 2017); (Lilford et al., 2017)</td>
<td>(Glazebrook and Newman, 2018); (IEA, 2017b)</td>
<td>(Ambrosino et al., 2016); (Giuliano and Hanson, 2017)</td>
</tr>
<tr>
<td>Absence of risk</td>
<td>LE (Newman et al., 2017)</td>
<td>(Whitelegg, 2016); (IEA, 2017b)</td>
<td>(Ambrosino et al., 2016); (Kent and Dowling, 2016)</td>
</tr>
<tr>
<td><strong>Institutional</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Political acceptability</td>
<td>(Grandin et al., 2018); (Broekhoff et al., 2018)</td>
<td></td>
<td>(Ambrosino et al., 2016); (Le Vine et al., 2014)</td>
</tr>
<tr>
<td>Socio-cultural</td>
<td>Legal &amp; administrative acceptability</td>
<td>Institutional capacity</td>
<td>Transparency &amp; accountability potential</td>
</tr>
<tr>
<td>----------------</td>
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<td>----------------------------------------</td>
</tr>
<tr>
<td>Social co-benefits (health, education)</td>
<td>(Grandin et al., 2018); (Broekhoff et al., 2018)</td>
<td>(Chau et al., 2018); (Geneletti et al., 2017)</td>
<td>(Moglia et al., 2018)</td>
</tr>
<tr>
<td>Public acceptance</td>
<td>(Su et al., 2016); (Nahlika and Chester, 2014); (Chava et al., 2018a); (Chava et al., 2018b); (Chava and Newman, 2016); (Jillella et al., 2015)</td>
<td>(Wirasingha et al., 2008); (IEA, 2017b)</td>
<td>(Wirasingha et al., 2008); (IEA, 2017b)</td>
</tr>
<tr>
<td>Social &amp; regional inclusiveness</td>
<td>(Endo et al., 2017); (Teferi and Newman, 2018); (Broekhoff et al., 2018); (Chava et al., 2018a); (Chava and Newman, 2016); (Jillella et al., 2015); (Lwasa, 2017); (Colenbrander et al., 2017)</td>
<td>(IEA, 2017b); (Newman et al., 2017)</td>
<td>(IEA, 2017b); (Newman et al., 2017)</td>
</tr>
<tr>
<td>Intergenerational equity</td>
<td>LE</td>
<td>LE</td>
<td>LE</td>
</tr>
<tr>
<td>Human capabilities</td>
<td>LE</td>
<td>(Newman et al., 2017)</td>
<td>(Newman et al., 2017); (Wirasingha et al., 2008)</td>
</tr>
<tr>
<td>Environmental/ecologic al</td>
<td>Reduction of air pollution</td>
<td>Reduction of toxic waste</td>
<td></td>
</tr>
<tr>
<td>Reduction of air pollution</td>
<td>(Zhang et al., 2018a); (Zubelzu et al., 2015); (Thomson and Newman, 2018); (Glazebrook and Newman, 2018); (Sharma, 2018)</td>
<td>(Thomson and Newman, 2018)</td>
<td>(Hawkins et al., 2013)</td>
</tr>
<tr>
<td>Reduction of toxic waste</td>
<td>LE</td>
<td>LE</td>
<td>LE</td>
</tr>
<tr>
<td>Geophysical</td>
<td>Reduction of water use</td>
<td>Improved biodiversity</td>
<td>Physical feasibility (physical potentials)</td>
</tr>
<tr>
<td>-------------</td>
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<td>----------------------------------------</td>
</tr>
<tr>
<td></td>
<td>(Serrao-Neumann et al., 2017)</td>
<td>(Huang et al., 2018)</td>
<td>(Hsieh et al., 2017); (Wiktorowicz et al., 2018)</td>
</tr>
<tr>
<td></td>
<td></td>
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Do Not Cite, Quote or Distribute 4-30 Total pages: 171
### Supplementary Material 4.D.2.iii, Table 2: Feasibility assessment of urban and infrastructure system transition mitigation options: Public transport; Non-motorised transport; and Aviation & shipping. For methodology, see Supplementary Material 4.D.1.

<table>
<thead>
<tr>
<th></th>
<th>Public transport</th>
<th>Non-motorised transport</th>
<th>Aviation &amp; shipping</th>
</tr>
</thead>
<tbody>
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<td>Robust</td>
<td>Robust</td>
<td>Medium</td>
</tr>
<tr>
<td>Agreement</td>
<td>Medium</td>
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<td>Medium</td>
</tr>
<tr>
<td><strong>Economic</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Cost-effectiveness</td>
<td>(Nahlika and Chester, 2014; Bouf and Faivre D’arcier, 2015; Lee and Erickson, 2017; Lin and Du, 2017; Glazebrook and Newman, 2018; Kenworthy and Schiller, 2018)</td>
<td>(Deenihan and Caulfield, 2014; Gössling and Choi, 2015; MacDonald Gibson et al., 2015; Brown et al., 2016b; Matan and Newman, 2016; Rajé and Saffrey, 2016; Litman, 2017, 2018)</td>
<td>(Corbett et al., 2009; Dessens et al., 2014; Cames et al., 2015b, 2015a)</td>
</tr>
<tr>
<td>Absence of distributional effects</td>
<td>(Kenworthy and Schiller, 2018; Linovski et al., 2018; Yangka and Newman, 2018)</td>
<td>(Jensen et al., 2017); (Litman, 2018); (Lohmann and Gasparini, 2017); (Newman and Kenworthy, 2015); (Matan and Newman, 2016)</td>
<td>LE (Cames et al., 2015a)</td>
</tr>
<tr>
<td>Employment &amp; productivity enhancement potential</td>
<td>(Hazledine et al., 2017; Gao and Newman, 2018; Kenworthy and Schiller, 2018)</td>
<td>(Rohani and Lawrence, 2017); (Litman, 2017); (Litman, 2018); (Matan and Newman, 2016)</td>
<td>(Cames et al., 2015a; Gencsü and Hino, 2015)</td>
</tr>
<tr>
<td><strong>Technological</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical scalability</td>
<td>(Kenworthy and Schiller, 2018; Yangka and Newman, 2018; Zhang et al., 2018a)</td>
<td>(Newman and Kenworthy, 2015; Matan and Newman, 2016; Reis et al., 2016; Stevenson et al., 2016)</td>
<td>(Dessens et al., 2014; Gencsü and Hino, 2015)</td>
</tr>
<tr>
<td>Maturity</td>
<td>(Kenworthy and Schiller, 2018); (Newman et al., 2017)</td>
<td>(Newman et al., 2015; Matan and Newman, 2016; Stevenson et al., 2016; Jensen et al., 2017; Newman et al., 2017)</td>
<td>(Corbett et al., 2009; Cames et al., 2015b)</td>
</tr>
<tr>
<td>Simplicity</td>
<td>(Kenworthy and Schiller, 2018); (Newman et al., 2017)</td>
<td>(Matan and Newman, 2016; Rajé and Saffrey, 2016; Stevenson et al., 2016; Litman, 2017, 2018)</td>
<td>LE (Dessens et al., 2014)</td>
</tr>
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<td>Absence of risk</td>
<td>(Kenworthy and Schiller, 2018); (Mohamed et al., 2017)</td>
<td>(Stevenson et al., 2016); (Lohmann and Gasparini, 2017); (Matan and Newman, 2016)</td>
<td>LE (Dessens et al., 2014)</td>
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<tr>
<td>Institutional</td>
<td>Political acceptability</td>
<td>(Wijaya et al., 2017); (Yangka and Newman, 2018); (Sharma, 2018); (Gao and Newman, 2018); (Glazebrook and Newman, 2018); (Kenworthy and Schiller, 2018) (Mohamed et al., 2017)</td>
<td>(Giles-Corti et al., 2016); (Jensen et al., 2017); (Litman, 2017); (Litman, 2018); (McCosker et al., 2018); (Matan and Newman, 2016); (Newman and Kenworthy, 2015)</td>
</tr>
<tr>
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<td>---------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Legal &amp; administrative acceptability</td>
<td>(Kenworthy and Schiller, 2018); (Yangka and Newman, 2018)</td>
<td>(Litman, 2018); (Lohmann and Gasparini, 2017)</td>
<td>(Zhang, 2016); (Shi, 2016); (Smale et al., 2012); (Bows-Larkin, 2015); (Sikorska, 2015).</td>
</tr>
<tr>
<td>Institutional capacity</td>
<td>(Sharma, 2018); (Newman et al., 2017)</td>
<td>(Reis et al., 2016); (Litman, 2018)</td>
<td>(Zhang, 2016); (Shi, 2016); (Smale et al., 2012); (Bows-Larkin, 2015); (Sikorska, 2015).</td>
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<td>Transparency &amp; accountability potential</td>
<td>LE</td>
<td>(Bouf and Faivre D’arcier, 2015); (Kenworthy and Schiller, 2018)</td>
<td>(Lah, 2017); (Matan and Newman, 2016); (Newman and Kenworthy, 2015)</td>
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<tr>
<td>Socio-cultural</td>
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<td>(Steg, 2003; Gatersleben and Uzzell, 2007; Nahlika and Chester, 2014; Lin and Du, 2017; Yangka and Newman, 2018)</td>
<td>(Maibach et al., 2009; Woodcock et al., 2009; Deenihan and Caulfield, 2014; Gilderbloom et al., 2015; MacDonald Gibson et al., 2015; Mansfield and Gibson, 2015; Matan et al., 2015; Brown et al., 2016b; Giles-Corti et al., 2016; Matan and Newman, 2016; Rajé and Saffrey, 2016; Stevenson et al., 2016; Jensen et al., 2017; Lah, 2017; Lohmann and Gasparini, 2017; Maizlish et al., 2017; Litman, 2018)</td>
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<td>(Jensen et al., 2017); (Lohmann and Gasparini, 2017); (Matan and Newman, 2016); (Newman et al., 2017); (Gatersleben and Uzzell, 2007)</td>
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<td>(Nahlaka and Chester, 2014); (Yangka and Newman, 2018)</td>
<td>(Stevenson et al., 2016); (Gilderbloom et al., 2015); (Jensen et al., 2017)</td>
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<td>(Zhang et al., 2018a); (Glazebrook and Newman, 2018); (Yangka and Newman, 2018); (Kenworthy and Schiller, 2018)</td>
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<td>LE (Newman et al., 2017)</td>
<td>LE</td>
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<td>Reduction of water use</td>
<td>LE (Newman et al., 2017)</td>
<td>LE (Newman et al., 2017)</td>
<td>LE</td>
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<td>LE (Newman et al., 2017)</td>
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<td>(Lah, 2017); (Panter et al., 2016)</td>
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<td>(Newman et al., 2017; Ye et al., 2018)</td>
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<td>(Bouf and Faivre D’arcier, 2015; Glazebrook and Newman, 2018; Kenworthy and Schiller, 2018)</td>
<td>(Stevenson et al., 2016; Litman, 2017; Lohmann and Gasparini, 2017)</td>
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Supplementary Material 4.D.2.iii, Table 3: Feasibility assessment of urban and infrastructure system transition mitigation options: Smart grids; Efficient appliances; and Low/zero-energy buildings. For methodology, see Supplementary Material 4.D.1.

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<th>Economic</th>
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<th>Low/zero-energy buildings</th>
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<td>(McNeil and Bojda, 2012; Garg et al., 2017; Gerke et al., 2017)</td>
<td>(Neroutsou and Croxford, 2016; Balaban and Puppim de Oliveira, 2017; Ballarini et al., 2017; Stocker and Koch, 2017; Carlson and Pressnail, 2018)</td>
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<td>(Rao, 2013; Rao et al., 2016; McInnes, 2017; Rao and Ummel, 2017)</td>
<td>(Figuš et al., 2017); (McInnes, 2017)</td>
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<td>(Naus et al., 2014); (Foxon et al., 2015); (Shomali and Pinkse, 2016).</td>
<td>(Ryan and Campbell, 2012; Cambridge Econometrics, 2015; Garrett-Peltier, 2017; Hartwig et al., 2017)</td>
<td>(Scott et al., 2008; Ryan and Campbell, 2012; Urge-Vorsatz et al., 2012; Mirasgedis et al., 2014; Cambridge Econometrics, 2015; Hartwig et al., 2017; Krarti and Dubey, 2018)</td>
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<td>Technical scalability</td>
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<td>(Roland and Wood, 2009); (Parikh and Parikh, 2016); (Rao et al., 2016); (Rao and Ummel, 2017); (Salleh et al., 2018)</td>
<td>(Hartwig et al., 2017); (Krarti et al., 2017)</td>
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<td>(Zogg et al., 2009); (Diczfalusy and Taylor, 2011); (Rao and Ummel, 2017); (Rao et al., 2016)</td>
<td>(González et al., 2017); (Diczfalusy and Taylor, 2011); (Jain et al., 2017b)</td>
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<td>Simplicity</td>
<td>(Crispim et al., 2014); (Clerici et al., 2015); (Abi Ghanem and Mander, 2014); (Zheng et al., 2014); (Ramos et al., 2016); (Otuoze et al., 2018); (Derakhshan et al., 2016); (Giannantoni, 2014).</td>
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<td>Absence of risk</td>
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<td>Political acceptability</td>
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<td>Legal &amp; administrative acceptability</td>
<td>(Crispim et al., 2014); (Bigerna et al., 2016); (Marques et al., 2014); (Foxon et al., 2015).</td>
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<td>Transparency &amp; accountability potential</td>
<td>(Naus et al., 2014); (Bigerna et al., 2016); (Otuoze et al., 2018); (Naus et al., 2014); (Hall and Foxon, 2014); (Hansen and Hauge, 2017).</td>
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<tr>
<td>Social co-benefits (health, education)</td>
<td>(Naus et al., 2014; Foxon et al., 2015; Shomali and Pinkse, 2016).</td>
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**Authors:**
- Reyna and Chester, 2017
- Salvalai et al., 2017
- Pereira and da Silva, 2017
- Ringel, 2017
- Pereira and da Silva, 2017
- Chanell et al., 2016
- Jain et al. 2017
- Pereira and da Silva, 2017
- Shah et al., 2015
- Meyers and Kromer, 2008
- Payne et al., 2015
- Ryan and Campbell, 2012
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<th>Description</th>
<th>Reference(s)</th>
<th>IPCC SR1.5</th>
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<td>(Hall and Foxon, 2014; Naus et al., 2014; Bigerna et al., 2016; Hansen and Hauge, 2017) (Green and Newman, 2017)</td>
<td>(Jain et al., 2018); (Swim et al., 2014); (Winward et al., 1998); (Boardman, 2004); (Reyna and Chester, 2017)</td>
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<td>Social &amp; regional inclusiveness</td>
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<td>(Rao and Pachauri, 2017); (Rao et al., 2016); (Rao and Ummel, 2017)</td>
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<td>Intergenerational equity</td>
<td>(Schlör et al., 2015); (Green and Newman, 2017)</td>
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<td>energy efficiency saves natural resources and therefore it is fair for future generations</td>
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<td>NE</td>
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<td>Environmental/ecological</td>
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<td>(Zhou et al., 2018); (Ryan and Campbell, 2012)</td>
<td>(Zhou et al., 2018); (Ryan and Campbell, 2012); (Balaban and Puppim de Oliveira, 2017); (Xiong et al., 2015)</td>
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<td>Reduction of toxic waste (Newman et al., 2017); (Foxon et al., 2015)</td>
<td>(Ryan and Campbell, 2012)</td>
<td>(Ryan and Campbell, 2012)</td>
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<td>Reduction of water use (Newman et al., 2017); (Wiktorowicz et al., 2018)</td>
<td>(Zhou et al., 2018)</td>
<td>(Loiola et al., 2018)</td>
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<td>Improved biodiversity (Newman et al., 2017); (Wiktorowicz et al., 2018)</td>
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<td>NA</td>
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<td>Geophysical</td>
<td>Physical feasibility (physical potentials) (Foxon et al., 2015)</td>
<td>(Heidari et al., 2018)</td>
<td>(Laitner, 2013)</td>
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</table>
| Limited use of land | (Wiktorowicz et al., 2018); (Green and Newman, 2017) | N/A | N/A energy efficient appliances do not take up more land than inefficient appliances | NA | Existing buildings refurbishment do not use additional land
New buildings use more land if not rebuilt over demolished buildings |
| Limited use of scarce (geo)physical resources | (Newman et al., 2017); (Wiktorowicz et al., 2018) | LE | (Needhidasan et al., 2014) possible that upgrades lead to landfill contamination | NA | N/A limited impact and limited use of scarce resources |
| Global spread | (Crispim et al., 2014; Foxon et al., 2015; Ramos et al., 2016) | NA | N/A efficient appliances available everywhere where access to electricity or energy is available | NA |
### Feasibility assessment of mitigation options in industrial system transitions

#### Table 1: Feasibility assessment of industrial system transition mitigation options: Energy efficiency; Bio-based & circularity; Electrification & hydrogen; and Industrial CCUS. For methodology, see Supplementary Material 4.D.1.

<table>
<thead>
<tr>
<th>Economic Factor</th>
<th>Energy efficiency</th>
<th>Bio-based &amp; circularity</th>
<th>Electrification &amp; hydrogen</th>
<th>Industrial CCUS</th>
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<td>Evidence</td>
<td>Robust</td>
<td>Medium</td>
<td>Medium</td>
<td>Robust</td>
</tr>
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<td>Agreement</td>
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<td>High</td>
<td>High</td>
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<td><strong>Cost-effectiveness</strong></td>
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<tr>
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</tr>
<tr>
<td>Agreement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Absence of distributional effects</strong></td>
<td>LE</td>
<td>NE</td>
<td>LE</td>
<td>NE</td>
</tr>
<tr>
<td>Economic</td>
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<tr>
<td>Employment &amp; productivity enhancement potential</td>
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<td></td>
<td></td>
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<tr>
<td>Evidence</td>
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<td><strong>Technical scalability</strong></td>
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<tr>
<td>Agreement</td>
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<td></td>
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<tr>
<td><strong>Simplicity</strong></td>
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- **Evidence**: Robust
- **Agreement**: High
- **Absence of distributional effects**: LE (Zha and Ding, 2015) NE (Nabernegg et al., 2017)
- **Employment & productivity enhancement potential**: (He et al., 2013; Zhang et al., 2015; Henrique and Catarino, 2016; Färe et al., 2018) (Nabernegg et al., 2017)(Fuentes-Saguar et al., 2017) LE (Nabernegg et al., 2017) (Koelbl et al., 2016)
- **Technical scalability**: (Fischedick et al., 2014; Bataille et al., 2018) (de Besi and McCormick, 2015; Wesseling et al., 2017) (Fischedick et al., 2014; Bataille et al., 2018)(Wang et al., 2017b) (Boot-Handford et al., 2014; Global CCS Institute, 2017; Bui et al., 2018)
- **Maturity**: (Hasanbeigi et al., 2014; Napp et al., 2014; Forman et al., 2016; Wesseling et al., 2017) (Quader et al., 2016)(Wesseling et al., 2017) (Quader et al., 2016; Philibert, 2017) (Boot-Handford et al., 2014; Mikunda et al., 2014; Abanades et al., 2015; Global CCS Institute, 2017; Bui et al., 2018)
- **Simplicity**: (Fernández-Viñé et al., 2010; Wakabayashi, 2013) (Wesseling et al., 2017) (Henry et al., 2006) NE (IEA GHG, 2012)
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<td>(Åhman et al., 2016; Philibert, 2017; Wesseling et al., 2017; Bataille et al., 2018)</td>
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<td>(de Coninck and Benson, 2014; Dixon et al., 2015; Bui et al., 2018)</td>
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<td>(Fischedick et al., 2014)</td>
<td>LE</td>
<td>(Åhman et al., 2016; Wesseling et al., 2017)</td>
<td>(Wallquist et al., 2012; Seigo et al., 2014; Ashworth et al., 2015) (Aminu et al., 2017)</td>
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<td>Improved biodiversity</td>
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<td>NE</td>
<td>NE</td>
<td>LE (Koornneef et al., 2012a)</td>
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<td>(Slade et al., 2014) (Beringer et al., 2011; Klein et al., 2014; Creutzig et al., 2015; Kraxner and Nordström, 2015; Searle and Malins, 2015; Smith et al., 2016; Boysen et al., 2017b; Tokimatsu et al., 2017; Heck et al., 2018)</td>
<td>(Philibert, 2017)</td>
<td>(IPCC, 2005; de Coninck and Benson, 2014; Scott et al., 2015)</td>
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<td>(Taibi et al., 2012)</td>
<td>(Fischedick et al., 2014; Wesseling et al., 2017)</td>
<td>(Kuramochi et al., 2012; Mikunda et al., 2014; Bui et al., 2018)</td>
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### Supplementary Material 4.D.2.v Feasibility assessment of carbon dioxide removal mitigation options

**Supplementary Material 4.D.2.v, Table 1**: Feasibility assessment of carbon dioxide removal mitigation options: Bioenergy with carbon dioxide capture and storage (BECCS); and Direct air carbon dioxide capture and storage (DACCS). For methodology, see Supplementary Material 4.D.1.

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<td>(Honegger and Reiner, 2018)</td>
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<td>(Luckow et al., 2010; Koornneef et al., 2012b; Arasto et al., 2014)</td>
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<td>Ethanol – (De Visser et al., 2011; Fabbri et al., 2011; Fornell et al., 2013; Johnson et al., 2014b; Rochedo et al., 2016)</td>
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<td></td>
<td>Combustion – (Kürki et al., 2013; Akşul et al., 2014; Al-Qayim et al., 2015; Onarheim et al., 2015; Sanchez and Callaway, 2016)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Fuss et al., 2018b)</td>
<td></td>
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<tr>
<td></td>
<td>(Bhave et al. 2017)</td>
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</tr>
<tr>
<td>Absence of distributional effects</td>
<td>Bioenergy - (Creutzig et al., 2013, 2015; Hunsberger et al., 2014; Buck, 2016; Robledo-Abad et al., 2017)</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>(Arndt et al., 2011b; German and Schoneveld, 2012; Creutzig et al., 2013; Hunsberger et al., 2014; Buck, 2016;)</td>
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<td>Employment &amp; productivity enhancement potential</td>
<td>2016; Robledo-Abad et al., 2017; Stevanović et al., 2017) (Popp et al., 2014; Persson, 2015; Kline et al., 2017; Searchinger et al., 2017)</td>
<td>(Neal, 2009; Pielke, 2009; Lackner et al., 2012; Nemet and Brandt, 2012; Pritchard et al., 2015) (Nemet et al., 2018)</td>
</tr>
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<td>Technical scalability</td>
<td>(Azar et al., 2010, 2013; Gough and Upham, 2011) (Nemet et al., 2018)</td>
<td>(McLaren, 2012; Boot-Handford et al., 2014; NRC, 2015; Nemet et al., 2018) Demos – (Holmes et al., 2013; Rau et al., 2013; Agee et al., 2016) (Nemet et al., 2018)</td>
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<td>Maturity</td>
<td>(McGlashan et al., 2012; McLaren, 2012; Kemper, 2015; Pang et al., 2017) (Boucher et al., 2014; Fuss et al., 2014; Anderson and Peters, 2016; Vaughan and Gough, 2016; Minx et al., 2017; Streffer et al., 2018c; Vaughan et al., 2018b) (Nemet et al., 2018)</td>
<td>(McLaren, 2012; Boot-Handford et al., 2014; NRC, 2015; Nemet et al., 2018)</td>
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<tr>
<td>Simplicity</td>
<td>Niche markets – (Möllersten et al., 2003; Sanna et al., 2012)</td>
<td>Niche markets – (Lackner et al., 2012; Hou et al., 2017; Ishimoto et al., 2017)</td>
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<td>Political acceptability</td>
<td>BECCS features rarely in policy debates (Fridahl, 2017) (Boysen et al., 2017a)</td>
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<td>Sociocultural</td>
<td>Legal &amp; administrative acceptability</td>
<td>Institutional capacity</td>
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<td></td>
<td>LE</td>
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<tr>
<td></td>
<td>(Honegger and Reiner, 2018) (Kemper, 2015)</td>
<td>(McLaren, 2012) (Frank et al., 2013) (Burns and Nicholson, 2017) (Kemper, 2015)</td>
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<td><strong>Reduction of water use</strong></td>
<td>(Smith and Torn 2013, Smith 2016, Fajardy and MacDowell 2017). (Gerbens-Leenes et al., 2009; Gheewala et al., 2011; Smith and Torn, 2013; Bonsch et al., 2016; Lampert et al., 2016; Mouratiadou et al., 2016; Wei et al., 2016; Mathioudakis et al., 2017) (Hylkema and Rand, 2014) (Koormneef et al., 2012a)</td>
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<tr>
<td><strong>Improved biodiversity</strong></td>
<td>(Lindemayer and Hobbs, 2004; Barlow et al., 2007; Immerzeel et al., 2014; Creutzig et al., 2015) (Holland et al., 2015; Santangeli et al., 2016) (Dale et al., 2015; Kline et al., 2015; Tarr et al., 2017)</td>
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<td><strong>Physical feasibility (physical potentials)</strong></td>
<td>Bioenergy - (Beringer et al., 2011; Klein et al., 2014; Creutzig et al., 2015; Kraxner and Nordström, 2015; Searle and Malins, 2015; Smith et al., 2016; Boysen et al., 2017b; Tokimatsu et al., 2017; Heck et al., 2018) CCS – (Dooley, 2013; Selosse and Ricci, 2017)</td>
<td>CCS – (Dooley, 2013; Selosse and Ricci, 2017) (McLaren, 2012; NRC, 2015; Smith et al., 2016; Fuss et al., 2018a)</td>
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<td><strong>Limited use of land</strong></td>
<td>(Beringer et al., 2011; Creutzig et al., 2015; NRC, 2015; Smith et al., 2016; Heck et al., 2018)</td>
<td>(Keith, 2009; Holmes and Keith, 2012b; Lackner et al., 2012; NRC, 2015)</td>
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<td><strong>Limited use of scarce (geo)physical resources</strong></td>
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<td>NE</td>
</tr>
<tr>
<td>Global spread</td>
<td>(Bright et al., 2015; Robledo-Abad et al., 2017)</td>
<td>(Clarke et al., 2014)</td>
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### Supplementary Material 4.D.2.v, Table 2: Feasibility assessment of carbon dioxide removal mitigation options: Afforestation & reforestation; Soil carbon sequestration & biochar; and Enhanced weathering.

For methodology, see Supplementary Material 4.D.1.

<table>
<thead>
<tr>
<th></th>
<th>Afforestation &amp; reforestation</th>
<th>Soil carbon sequestration &amp; biochar</th>
<th>Enhanced weathering</th>
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<td>Reviews - (Sohngen and Mendelsohn, 2003; Richards and Stokes, 2004; Richards and Stavins, 2005; Nijnik and Halder, 2013; Humpenöder et al., 2014)</td>
<td>Reviews - (McGlashan et al., 2012; McLaren, 2012; Caldecott et al., 2015; Smith et al., 2016; Fuss et al., 2018a)</td>
<td>Reviews - (McLaren, 2012; NRC, 2015)</td>
<td>(Schuiling and Krijgsman, 2006; Hartmann and Kempe, 2008; Köhler et al., 2010; Renforth, 2012; Hartmann et al., 2013; Taylor et al., 2016; Strefler et al., 2018a)</td>
</tr>
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<td>Absence of distributional effects</td>
<td>Locatelli et al 2015, Renner et al 2008 (Lyons and Westoby, 2014)</td>
<td>world poor stand to benefit (Stringer et al., 2012)</td>
<td>NE</td>
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<tr>
<td>Employment &amp; productivity enhancement potential</td>
<td>(Smith et al., 2014b)</td>
<td>(Lal, 2004c; Van Straaten, 2006; Pan et al., 2009; Jeffery et al., 2011) (Jeffery et al., 2011)</td>
<td>NE</td>
</tr>
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<td><strong>Technological</strong></td>
<td></td>
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<td>Technical scalability</td>
<td>(Shvidenko et al., 1997; Polglase et al., 2013; Cunningham et al., 2015; Zhang and Yan, 2015) (Nemet et al., 2018)</td>
<td>(Jiang et al., 2014; Novak et al., 2016; Kammann et al., 2017) (Nemet et al., 2018)</td>
<td>BC – (Roberts et al., 2010; Shackley et al., 2011)</td>
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<td>IPCC SR1.5</td>
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<td>Maturity</td>
<td>(McLaren, 2012; NRC, 2015; Nemet et al., 2018)</td>
<td>(McLaren, 2012; Olson, 2013; Olson et al., 2014; Piccoli et al., 2016; Triberti et al., 2016; Vochozka et al., 2016)</td>
<td>(McLaren, 2012; Hartmann et al., 2013; NRC, 2015)</td>
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<td>Demons – (Gong et al., 2013; Zinda et al., 2017)</td>
<td>(Nemet et al., 2018)</td>
<td>(Nemet et al., 2018)</td>
<td>(Nemet et al., 2018)</td>
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<td>Absence of risk</td>
<td>NE</td>
<td>NE</td>
<td>NE</td>
</tr>
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<td>Simpleity</td>
<td>NE</td>
<td>NE</td>
<td>NE</td>
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<tr>
<td>Absence of political risk</td>
<td>NE</td>
<td>NE</td>
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<td>Institutional capacity</td>
<td>NE</td>
<td>LE</td>
<td>LE</td>
</tr>
<tr>
<td>Transparency &amp; accountability potential</td>
<td>LE</td>
<td>Accounting - (Sanderman and Baldock, 2010; McLaren, 2012; Downie et al., 2014; Nemet et al., 2018)</td>
<td>NE</td>
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<tr>
<td>Social co-benefits (health, education)</td>
<td>(Genesio et al., 2016; Ravi et al., 2016)</td>
<td>NE</td>
<td>NE (Schuiling and Krijgsman, 2006; Taylor et al., 2016)</td>
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<td>Public acceptance</td>
<td>Private landholders – (Nijnik and Halder, 2013; Schirmer and Bull, 2014; Trevisan et al., 2016)</td>
<td>(Glenk and Colombo, 2011; Lomax et al., 2015; Jørgensen and Termansen, 2016)</td>
<td>LE (Wright et al., 2014b)</td>
</tr>
<tr>
<td>Social &amp; regional inclusiveness</td>
<td>(Atela et al., 2014; Sunderlin et al., 2014; Brugnach et al., 2017; Ngendakumana et al., 2017; Turnhout et al., 2017)</td>
<td>NE</td>
<td>NE</td>
</tr>
<tr>
<td>Intergenerational equity</td>
<td>LE</td>
<td>(Smith et al., 2014b)</td>
<td>NE</td>
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<td>Human capabilities</td>
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<td>NE</td>
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<td>Reduction of air pollution</td>
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<td>Reduction of toxic waste</td>
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<tr>
<td>Reduction of water use</td>
<td>NA</td>
<td>(Jackson et al., 2005; Smith and Torn, 2013; Deng et al., 2017)</td>
<td>(Lal, 2004b; Bamminger et al., 2016; Smith, 2016)</td>
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<td>Improved biodiversity</td>
<td>NA</td>
<td>(Diaz et al., 2009; McKinley et al., 2011; Hall et al., 2012; Venter et al., 2012; Greve et al., 2013; Cunningham et al., 2015; Locatelli et al., 2015a; Paul et al., 2016)</td>
<td>NE</td>
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<td>Geophysical</td>
<td>BC</td>
<td>(Sohngen and Mendelsohn, 2003; Canadell and Raupach, 2008; Strengers et al., 2008; Thomson et al., 2008; van Minnen et al., 2008; Houghton et al., 2015; Sonntag et al., 2016; Griscom et al., 2017)</td>
<td>BC – (Lehmann et al., 2006; Laird et al., 2009; Lee et al., 2010; Wolff et al., 2010; Lenton, 2010; Moore et al., 2010; Pratt and Moran, 2010; McLaren, 2012; Powell and Lenton, 2012; Lomax et al., 2015; Smith, 2016; Paustian et al., 2016)</td>
</tr>
</tbody>
</table>

Note: BC refers to ‘biological carbon cycles’ and SCS refers to ‘soil carbon sequestration’.
| Limited use of land | (Smith and Torn, 2013; Houghton et al., 2015) | (Smith, 2016; Fuss et al., 2018a) | (Hartmann et al., 2013; Strefler et al., 2018b) 
Could enhance yields reducing land competition pressure – (Edwards et al., 2017; Kantola et al., 2017) |
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<tr>
<td>Limited use of scarce (geo)physical resources</td>
<td>LE (Smith and Torn, 2013)</td>
<td>NA</td>
<td>LE (NRC, 2015)</td>
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<td>Global spread</td>
<td>(Anderson et al., 2011; Arora and Montenegro, 2011; Wang et al., 2014)</td>
<td>Permanence diff areas – BC - (Zimmermann et al., 2012; Sheng et al., 2016)</td>
<td>(Garcia et al., 2018; Strefler et al., 2018a)</td>
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### Supplementary Material 4.D.3 Feasibility assessment of adaptation options as presented in Section 4.5.3

#### Supplementary Material 4.D.3.i Feasibility assessment of adaptation options in energy system transitions

**Supplementary Material 4.D.3.i, Table 1:** Feasibility assessment of energy system transition adaptation option: Power infrastructure, including water. For methodology, see Supplementary Material 4.D.1.

<table>
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<tr>
<th>Evidence</th>
<th>Agreement</th>
<th>Micro-economic viability</th>
<th>(Kopytko and Perkins, 2011; Inderberg and Løchen, 2012; Brouwer et al., 2015)</th>
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<td>Medium</td>
<td>High</td>
<td>Macro-economic viability</td>
<td>(Koch and Vögele, 2009; Kopytko and Perkins, 2011; Soito and Freitas, 2011; Inderberg and Løchen, 2012; Schaeffer et al., 2012; Jahandideh-Tehrani et al., 2014; Brouwer et al., 2015; Cortekar and Groth, 2015; Panteli and Mancarella, 2015; van Vliet et al., 2016)</td>
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<tr>
<td>Socio-economic vulnerability reduction potential</td>
<td>(Koch and Vögele, 2009; Soito and Freitas, 2011; Cortekar and Groth, 2015; van Vliet et al., 2016)</td>
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<td>Employment &amp; productivity enhancement potential</td>
<td>(Inderberg and Løchen, 2012; Cortekar and Groth, 2015; Panteli and Mancarella, 2015; van Vliet et al., 2016)</td>
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<td>Technical resource availability</td>
<td>(Koch and Vögele, 2009; Soito and Freitas, 2011; Inderberg and Løchen, 2012; Jahandideh-Tehrani et al., 2014; Cortekar and Groth, 2015; Murrant et al., 2015; Panteli and Mancarella, 2015; Parkinson and Djilali, 2015; van Vliet et al., 2016)</td>
<td></td>
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<td>Risks mitigation potential (stranded Assets, unforeseen Impacts)</td>
<td>(Koch and Vögele, 2009; Inderberg and Løchen, 2012; Schaeffer et al., 2012; Jahandideh-Tehrani et al., 2014; Cortekar and Groth, 2015; Murrant et al., 2015; Panteli and Mancarella, 2015; Parkinson and Djilali, 2015; van Vliet et al., 2016)</td>
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<td>Political acceptability</td>
<td>(Soito and Freitas, 2011; Inderberg and Løchen, 2012; Cortekar and Groth, 2015; Murrant et al., 2015)</td>
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<td>Legal &amp; regulatory acceptability</td>
<td>(Soito and Freitas, 2011; Inderberg and Løchen, 2012; Cortekar and Groth, 2015; Benson, 2018)</td>
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<td>Institutional capacity &amp; Administrative feasibility</td>
<td>(Eisenack and Stecker, 2012; Inderberg and Løchen, 2012; Cortekar and Groth, 2015; Murrant et al., 2015)</td>
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<td>Transparency &amp; accountability potential</td>
<td>LE</td>
<td>(Inderberg and Løchen, 2012; Cortekar and Groth, 2015)</td>
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<td>Social-cultural</td>
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<td>Social &amp; regional inclusiveness</td>
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<td>(Koch and Vögele, 2009; Soito and Freitas, 2011; Inderberg and Løchen, 2012; Schaeffer et al., 2012; Jahandideh-Tehrani et al., 2014; Murrant et al., 2015; Parkinson and Djilali, 2015)</td>
<td>(Koch and Vögele, 2009; Soito and Freitas, 2011; Inderberg and Løchen, 2012; Schaeffer et al., 2012; Jahandideh-Tehrani et al., 2014; Cortekar and Groth, 2015; Murrant et al., 2015; Parkinson and Djilali, 2015; van Vliet et al., 2016)</td>
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<th>Geophysical</th>
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<th>Hazard risk reduction potential</th>
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<td>(Schaeffer et al., 2012; Jahandideh-Tehrani et al., 2014; Parkinson and Djilali, 2015)</td>
<td>(Inderberg and Løchen, 2012; Schaeffer et al., 2012; Jahandideh-Tehrani et al., 2014; Brouwer et al., 2015; Cortekar and Groth, 2015; Murrant et al., 2015; Panteli and Mancarella, 2015; Parkinson and Djilali, 2015; van Vliet et al., 2016)</td>
<td>(Inderberg and Løchen, 2012; Schaeffer et al., 2012; Jahandideh-Tehrani et al., 2014; Brouwer et al., 2015; Cortekar and Groth, 2015; Murrant et al., 2015; Panteli and Mancarella, 2015; Parkinson and Djilali, 2015; van Vliet et al., 2016)</td>
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### Supplementary Material 4.D.3.ii Feasibility assessment of adaptation options in land & ecosystem transitions

**Supplementary Material 4.D.3.ii, Table 1:** Feasibility assessment of land and ecosystem transition adaptation options: Conservation agriculture; Efficient irrigation; Efficient livestock; Agroforestry; and Community-based adaptation. For methodology, see Supplementary Material 4.D.1.

<table>
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<tr>
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<td>(Grabowski and Kerr, 2014; Jat et al., 2014; Pittelkow et al., 2014; Thierfelder et al., 2015, 2017; Smith et al., 2017b)</td>
<td>(Olmstead, 2014; Roco et al., 2014; Venot et al., 2014; Varela-Ortega et al., 2016; Bjornlund et al., 2017; Herwehe and Scott, 2017; Mdemu et al., 2017)</td>
<td>(Thornton and Herrero, 2014; Herrero et al., 2015; Weindl et al., 2015; Ghahramani and Bowran, 2018)</td>
<td>(Valdivia et al., 2012; Kumar, 2013; Lasco et al., 2014; Mbow et al., 2014a, 2014b; Brockington et al., 2016; Iiyama et al., 2017; Jacobi et al., 2017; Hernández-Morcillo et al., 2018)</td>
<td>(Mannke, 2011; Archer et al., 2014; Wright et al., 2014a; Fernández-Giménez et al., 2015; Dodman et al., 2017a)</td>
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<td><strong>Macro-economic viability</strong></td>
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<td>(Elliott et al., 2014; Kirby et al., 2014; Olmstead, 2014; Girard et al., 2015; Kahl et al., 2015; Varela-Ortega et al., 2016; Bjornlund et al., 2017; Herwehe and Scott, 2017)</td>
<td>(Herrero et al., 2015; Weindl et al., 2015; García de Jalón et al., 2017)</td>
<td>(Valdivia et al., 2012; Lasco et al., 2014; Jacobi et al., 2017; Hernández-Morcillo et al., 2018)</td>
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<td><strong>Socio-economic vulnerability reduction potential</strong></td>
<td>(Bhan and Behera, 2014; Pittelkow et al., 2014; Stevenson et al., 2014; Prosdociami et al., 2016; Smith et al., 2017b)</td>
<td>(Burney and Naylor, 2012; Levidow et al., 2014; Roco et al., 2014; Venot et al., 2014; Ashofteh et al., 2017; Bjornlund et al., 2017)</td>
<td>(Herrero et al., 2015; García de Jalón et al., 2017; Thornton et al., 2018)</td>
<td>(Valdivia et al., 2012; Brockington et al., 2016; Coq-Huelva et al., 2017; Coulibaly et al., 2017; Iiyama et al., 2017; Jacobi et al., 2017; Quandt et al., 2017)</td>
<td>(Mannke, 2011; Archer et al., 2014; Reid and Huq, 2014; Wright et al., 2014a; Fernández-Giménez et al., 2015; Ensor et al., 2016, 2018; Ford et al., 2018)</td>
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<tr>
<td>Employment &amp; productivity enhancement potential</td>
<td>(Bhan and Behera, 2014; Grabowski and Kerr, 2014; Kirkegaard et al., 2014; Pittelkow et al., 2014; Stevenson et al., 2014)</td>
<td>(Burney and Naylor, 2012; Burney et al., 2014; Kirby et al., 2014; Levidow et al., 2014)</td>
<td>(Briske et al., 2015; García de Jalón et al., 2017)</td>
<td>LE</td>
<td>(Verchot et al., 2007; Buckeridge et al., 2012)</td>
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<td>------------------------------------------------------------------------------------------------</td>
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<td>Technical resource availability</td>
<td>(Palm et al., 2014; Stevenson et al., 2014; Adenle et al., 2015; Smith et al., 2017b)</td>
<td>(Venot et al., 2014; Esteve et al., 2015; Fishman et al., 2015; Azhoni et al., 2017; Mdemu et al., 2017)</td>
<td>(Descheemaeker et al., 2016; Thornton et al., 2018)</td>
<td>(Verchot et al., 2007; Valdivia et al., 2012; Mbow et al., 2014a; Iiyama et al., 2017; Jacobi et al., 2017; Hernández-Morcillo et al., 2018)</td>
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<td>Risks mitigation potential</td>
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<td>(Burney et al., 2014; Fishman et al., 2015; Jägermeyr et al., 2015; Blanc et al., 2017)</td>
<td>(Briske et al., 2015; Thornton and Herrero, 2015; Thornton et al., 2018)</td>
<td>(Verchot et al., 2007; Jacobi et al., 2017; Abdulai et al., 2018; Hernández-Morcillo et al., 2018; Sida et al., 2018)</td>
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<td>(Burney and Naylor, 2012; Esteve et al., 2015)</td>
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<td>(Buckeridge et al., 2012; Mbow et al., 2014b; Jacobi et al., 2017)</td>
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Do Not Cite, Quote or Distribute 4-54 Total pages: 171
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Do Not Cite, Quote or Distribute 4-55  Total pages: 171
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<td>(Bell et al., 2014; Havet et al., 2014; Lemaire et al., 2014; Thornton and Herrero, 2014; Briske et al., 2015; Herrero et al., 2015; Weindl et al., 2015; Ghahramani and Bowran, 2018)</td>
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<td>Physical feasibility</td>
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<td>(Weindl et al., 2015; Thornton et al., 2018)</td>
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<td>Geophysical land use change enhancement potential</td>
<td>(Grabowski and Kerr, 2014; Stevenson et al., 2014; Giller et al., 2015; Prosdocimi et al., 2016; Cui et al., 2018; Pradhan et al., 2018)</td>
<td>(Lasco et al., 2014; Mbow et al., 2014a; Coulibaly et al., 2017; Hernández-Morcillo et al., 2018)</td>
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<td>(Lasco et al., 2014; Mbow et al., 2014a; Coulibaly et al., 2017; Abdulai et al., 2018; Hernández-Morcillo et al., 2018)</td>
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**Do Not Cite, Quote or Distribute** 4-56

Total pages: 171
**Supplementary Material 4.D.3.ii, Table 2: Feasibility assessment of land and ecosystem transition adaptation options:** Ecosystem restoration & avoided deforestation; Biodiversity management; Coastal defense and hardening; and Sustainable aquaculture. For methodology, see Supplementary Material 4.D.1.

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<th>Ecosystem restoration &amp; avoided deforestation</th>
<th>Biodiversity management</th>
<th>Coastal defense and hardening</th>
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<td>(Dang Phan et al., 2014; Ingalls and Dwyer, 2016; Rakatama et al., 2017; Spencer et al., 2017)</td>
<td>(Rodrigues et al., 2009; Alagador et al., 2014; Mantyka-Pringle et al., 2016; Gómez-Aíza et al., 2017; Reside et al., 2017b; Monahan and Theobald, 2018)</td>
<td>(Firth et al., 2014; Barbier, 2015a; Elliott and Wolanski, 2015; Diaz, 2016; Betzold and Mohamed, 2017)</td>
<td>(Boonstra and Hanh, 2015; Joffre et al., 2015; FAO, 2016; FAO et al., 2017; Pérez-Escamilla, 2017)</td>
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<td>(Rodrigues et al., 2009; Berrang-Ford et al., 2012; Pullin et al., 2013; Brockington and Wilkie, 2015; Newbold et al., 2015; Oldekop et al., 2016; Griscom et al., 2017; Milman and Jagannathan, 2017; Terraube et al., 2017; Essl and Mauerhofer, 2018)</td>
<td>(Rabbani et al., 2010b, 2010a; Gutiérrez et al., 2012; Arkema et al., 2013, 2017; Neumann et al., 2015; Sovacool et al., 2015; Sutton-Grier et al., 2015; Betzold and Mohamed, 2017)</td>
<td>(Bell et al., 2011; Smith et al., 2013; Orchard et al., 2015; Béné et al., 2016; Jennings et al., 2016; Mycoo, 2017; Ahmed et al., 2018)</td>
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Do Not Cite, Quote or Distribute 4-57 Total pages: 171
<p>| Technical resource availability | (Ingalls and Dwyer, 2016; Spencer et al., 2017; Turnhout et al., 2017) | (Nadeau et al., 2015; Schmitz et al., 2015; Thomas and Gillingham, 2015; Jones et al., 2016a; Urban et al., 2016; Milman and Jagannathan, 2017; Reside et al., 2017b) | (Arkema et al., 2013; Bosello and De Cian, 2014; Smajgl et al., 2015; Hauer et al., 2016; Betzold and Mohamed, 2017; Williams et al., 2018) | (UNEP, 2013; Ahmed et al., 2014, 2018; Brilant, 2014; Edwards, 2015; Lucas, 2015; Fidelman et al., 2017) |
| Risks mitigation potential | LE | (Spencer et al., 2017; Turnhout et al., 2017) | LE | (Firth et al., 2014; Sovacool et al., 2015; André et al., 2016; Cashman and Nagdee, 2017; Brown et al., 2018; Storlazzi et al., 2018; Williams et al., 2018) | (Boonstra and Hanh, 2015; Blanchard et al., 2017) |
| Political acceptability | (Sunderlin et al., 2014; Ingalls and Dwyer, 2016; Ngendakumana et al., 2017) | LE | (Milman and Jagannathan, 2017; Essl and Mauerhofer, 2018) | (Duvat, 2013; Nordstrom, 2014; Sovacool et al., 2015; Betzold and Mohamed, 2017) | |
| Legal &amp; regulatory acceptability | LE | (Sunderlin et al., 2014; Turnhout et al., 2017) | | | |
| Institutional capacity &amp; Administrative feasibility | (Jagger et al., 2014; Sunderlin et al., 2014; Wallbott, 2014; Atela et al., 2015; Ingalls and Dwyer, 2016; Ngendakumana et al., 2017; Spencer et al., 2017; Turnhout et al., 2017; Well and Carrapatoso, 2017; Wehkamp et al., 2018a) | (Dallimer and Strange, 2015; Jones et al., 2016a; Drielsma et al., 2017; Essl and Mauerhofer, 2018; Monahan and Theobald, 2018; Triviño et al., 2018) | (Dallimer and Strange, 2015; Thomas and Gillingham, 2015; Jones et al., 2016a; Essl and Mauerhofer, 2018; Monahan and Theobald, 2018) | (Hallegatte et al., 2013; Spalding et al., 2014; Mills et al., 2016; Estrada et al., 2017) | LE | (Ahmed et al., 2014; Broitman et al., 2017; Fidelman et al., 2017) |
| Transparency &amp; accountability potential | (Jagger et al., 2014; Sunderlin et al., 2014; Atela et al., 2015; Ingalls and Dwyer, 2016; Ngendakumana et al., 2017; | LE | NE | NE | |
| Social co-benefits (health, education) | (Sunderlin et al., 2014; Jagger et al., 2014; Atela et al., 2015; Elmoqvist et al., 2015; Camps-Calvet et al., 2016; Ingalls and Dwyer, 2016; McPhearson et al., 2016; Turnhout et al., 2017; Collas et al., 2017; Li et al., 2017; Ngendakumana et al., 2017; Spencer et al., 2017) | (Rodrigues et al., 2009; Berrang-Ford et al., 2012; Pullin et al., 2013; Brockington and Wikie, 2015; Oldekop et al., 2016; Clark and Tilman, 2017; Terraube et al., 2017; Essl and Mauerhofer, 2018) | (Sovacool et al., 2015; Sutton-Grier et al., 2015; Arkema et al., 2017; Betzold and Mohamed, 2017) | LE (Weatherdon et al., 2016; Fidelman et al., 2017) |
| Socio-cultural acceptability | (Sunderlin et al., 2014; Wallbott, 2014; Atela et al., 2015; Ingalls and Dwyer, 2016; Ngendakumana et al., 2017; Spencer et al., 2017) | (Pullin et al., 2013; Brockington and Wikie, 2015; Oldekop et al., 2016; Milman and Jagannathan, 2017) | (Sovacool et al., 2015; Gibbs, 2016; Morris et al., 2016; Betzold and Mohamed, 2017; Marengo et al., 2017) | LE (Asiedu et al., 2017a; Fidelman et al., 2017) |
| Social &amp; regional inclusiveness | LE | (Ingalls and Dwyer, 2016; Spencer et al., 2017) | (Pullin et al., 2013; Brockington and Wikie, 2015; Oldekop et al., 2016; Milman and Jagannathan, 2017; Terraube et al., 2017) | NE |
| Intergenerational equity | (Ingalls and Dwyer, 2016; Ngendakumana et al., 2017; Spencer et al., 2017) | NE | NE | NA |
| Ecological capacity | (Sunderlin et al., 2014; Spencer et al., 2017; Turnhout et al., 2017) | (Rodrigues et al., 2009; Virkkala et al., 2014; Thomas and Gillingham, 2015; Gillingham et al., 2015; Nadeau et al., 2015; Schmitz et al., 2015; Feeley and Silman, 2016; Gaüzère et al., 2016; Greenwood et al., 2016; Gómez-Aíza et al., 2017; Mingarro and | (Bilkovic and Mitchell, 2013; Spalding et al., 2014; Joffre et al., 2015; Sutton-Grier et al., 2015) | (David et al., 2015; Joffre et al., 2015; Blanchard et al., 2017; Broitman et al., 2017; Ahmed et al., 2018) |</p>
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<th>Adaptive capacity/resilience</th>
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<th>(Boonstra and Hanh, 2015; Orchard et al., 2015; Blanchard et al., 2017; Fidelman et al., 2017; Cinner et al., 2018)</th>
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<td>(Duvat, 2013; Hinkel et al., 2014; Smith et al., 2015; André et al., 2016; Cooper et al., 2016; Vousdoukas et al., 2016; Arkema et al., 2017)</td>
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<td>Geophysical</td>
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<td>(Schmitz et al., 2015; Reside et al., 2017b, 2017a)</td>
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<td>Land use change enhancement potential</td>
<td>(Dang Phan et al., 2014; Sunderlin et al., 2014; Ingalls and Dwyer, 2016; Ngendakumana et al., 2017; Turnhout et al., 2017; Houghton and Nassikas, 2018; Wehkamp et al., 2018a)</td>
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<td>(Schmitz et al., 2015; Reside et al., 2017b, 2017a)</td>
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<td>(Ingalls and Dwyer, 2016; Spencer et al., 2017)</td>
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### Supplementary Material 4.D.3.iii Table 1: Feasibility assessment of urban and infrastructure transition adaptation options: Sustainable land-use & urban planning; and Sustainable water management. For methodology, see Supplementary Material 4.D.1.

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<th>Economic Category</th>
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<td>(Liu et al., 2014; Lamond et al., 2015; Voskamp and Van de Ven, 2015; Xue et al., 2015; Costa et al., 2016; Mguni et al., 2016; Poff et al., 2016; Ossa-Moreno et al., 2017; Vincent et al., 2017; Xie et al., 2017)</td>
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<td>(Eberhard et al., 2011; Measham et al., 2011; Aerts et al., 2014; Jaglin, 2014; Beccali et al., 2015; Bougedir, 2015; Watkins, 2015; Eberhard et al., 2016; Ziervogel et al., 2016a; Chu et al., 2017; Hess and Kelman, 2017; Ziervogel et al., 2017)</td>
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<td>(Villarroel Walker et al., 2014; Ziervogel and Joubert, 2014; Brown and McGranahan, 2016; Chu et al., 2016; Chant et al., 2017; Dodman et al., 2017b, 2017a; Ossa-Moreno et al., 2017; Gunasekara et al., 2018)</td>
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<td>(Lamond et al., 2015; Leck et al., 2015; Padawangi and Douglass, 2015; Rasul and Sharma, 2016; Soz et al., 2016)</td>
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<td>Hazard risk reduction potential</td>
<td>(Kiunsi, 2013; Aerts et al., 2014; Watkins, 2015; Bougeddir, 2015; Archer, 2016; Woodruff and Stults, 2016; Eisenberg, 2016; Hetz, 2016; King et al., 2016; Mahlkow and Donner, 2017; Movhura et al., 2017; Stults and Woodruff, 2017)</td>
<td>(Liu et al., 2014; Angotti, 2015; Bell et al., 2015; Voskamp and Van de Ven, 2015; Biggs et al., 2015; Gwedla and Shackleton, 2015; Lamond et al., 2015; Lwasa et al., 2015; Mguni et al., 2016; Yang et al., 2016; Chen and Chen, 2016; Costa et al., 2016; Sanesi et al., 2017; Xie et al., 2017; Gunasekara et al., 2018)</td>
</tr>
</tbody>
</table>
**Supplementary Material 4.D.3.iii, Table 2: Feasibility assessment of urban and infrastructure transition adaptation options: Green infrastructure and ecosystem services; and Building codes and standards. For methodology, see Supplementary Material 4.D.1.**

<table>
<thead>
<tr>
<th>Evidence</th>
<th>Green infrastructure and ecosystem services</th>
<th>Building codes and standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agreement</td>
<td>Medium</td>
<td>Limited</td>
</tr>
<tr>
<td><strong>Economic</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micro-economic viability</td>
<td>(Elmqvist et al., 2015; Soderlund and Newman, 2015; McPhearson et al., 2016; Zinia and McShane, 2018)</td>
<td>(Steenhof and Sparling, 2011; Bendito and Barrios, 2016; Ruparathna et al., 2016; Mavhura et al., 2017; Wells et al., 2018)</td>
</tr>
<tr>
<td>Macro-economic viability</td>
<td>LE (Culwick and Bobbins, 2016)</td>
<td>(Steenhof and Sparling, 2011; Aerts et al., 2014; Späth and Rohracher, 2015; Chandel et al., 2016; Shapiro, 2016; Hess and Kelman, 2017; Wells et al., 2018)</td>
</tr>
<tr>
<td>Socio-economic vulnerability reduction potential</td>
<td>(Tallis et al., 2011; Elmqvist et al., 2015; Soderlund and Newman, 2015; Camps-Calvet et al., 2016; McPhearson et al., 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; Li et al., 2017; White et al., 2017b; Zinia and McShane, 2018)</td>
<td>(Steenhof and Sparling, 2011; FEMA, 2014; Bendito and Barrios, 2016; Hess and Kelman, 2017; Reckien et al., 2017)</td>
</tr>
<tr>
<td>Employment &amp; productivity enhancement potential</td>
<td>NE</td>
<td>NE</td>
</tr>
<tr>
<td><strong>Technological</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical resource availability</td>
<td>NA</td>
<td>(Steenhof and Sparling, 2011; Aerts et al., 2014; Bendito and Barrios, 2016; Chandel et al., 2016; Ruparathna et al., 2016; Garsaball and Markov, 2017; Tait and Euston-Brown, 2017; Wells et al., 2018)</td>
</tr>
<tr>
<td>Risks mitigation potential (stranded Assets, unforeseen Impacts)</td>
<td>(Tallis et al., 2011; Elmqvist et al., 2013b; Buckeridge, 2015; Elmqvist et al., 2015; Soderlund and Newman, 2015; Camps-Calvet et al., 2016; McPhearson et al., 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; Li et al., 2017; White et al., 2017b; Zinia and McShane, 2018)</td>
<td>(Aerts et al., 2014; Ruparathna et al., 2016)</td>
</tr>
<tr>
<td><strong>Institutional</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Political acceptability</td>
<td>LE (Brown and McGranahan, 2016; Ziervogel et al., 2016b)</td>
<td>(Aerts et al., 2014; Späth and Rohracher, 2015; Chandel et al., 2016; Eisenberg, 2016; Shapiro, 2016; Tait and Euston-Brown, 2017; Wells et al., 2018)</td>
</tr>
<tr>
<td>Legal &amp; regulatory acceptability</td>
<td>(Brown and McGranahan, 2016; Ziervogel et al., 2016b; Collas et al., 2017; Li et al., 2017; Sirakaya et al., 2018)</td>
<td>(Steenhof and Sparling, 2011; Burch et al., 2014; Späth and Rohracher, 2015; Eisenberg, 2016; Ruparathna et al., 2016; Shapiro, 2016; Hess and Kelman, 2017; Stults and Woodruff, 2017)</td>
</tr>
<tr>
<td>Institutional capacity &amp; Administrative feasibility</td>
<td>(Brown and McGranahan, 2016; Culwick and Bobbins, 2016; Ziervogel et al., 2016b; Collas et al., 2017; Li et al., 2017; Prudencio and Null, 2018)</td>
<td>(Aerts et al., 2014; Chandel et al., 2016; Eisenberg, 2016; Shapiro, 2016; Garsaball and Markov, 2017; Hess and Kelman, 2017; Mavhura et al., 2017; Stults and Woodruff, 2017; Tait and Euston-Brown, 2017)</td>
</tr>
<tr>
<td>Translucency &amp; accountability potential</td>
<td>LE (Li et al., 2017)</td>
<td>(Steenhof and Sparling, 2011; Aerts et al., 2014; Späth and Rohracher, 2015; Chandel et al., 2016; Shapiro, 2016)</td>
</tr>
<tr>
<td>Social co-benefits (health, education)</td>
<td>(Beatley, 2011; Tallis et al., 2011; Elmqvist et al., 2013b; Demuzere et al., 2014; Liu et al., 2014; Buckeridge, 2015; Elmqvist et al., 2015; Lamond et al., 2015; Mullaney et al., 2015; Norton et al., 2015; Skougaard Kaspersen et al., 2015; Soderlund and Newman, 2015; Voskamp and Van de Ven, 2015; Beaudoin and Gosselin, 2016; Brown and McGranahan, 2016; Camps-Calvet et al., 2016; Costa et al., 2016; Culwick and Bobbins, 2016; Green et al., 2016; McPhearson et al., 2016; Mguni et al., 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; Collas et al., 2017; Li et al., 2017; Lin et al., 2017; Xie et al., 2017; Zinia and McShane, 2018)</td>
<td>NE</td>
</tr>
<tr>
<td>Socio-cultural acceptability</td>
<td>(Beatley, 2011; Elmqvist et al., 2015; Beaudoin and Gosselin, 2016; Brown and McGranahan, 2016; Camps-Calvet et al., 2016; McPhearson et al., 2016; Ziervogel et al., 2016b; Collas et al., 2017; Li et al., 2017; Zinia and McShane, 2018)</td>
<td>(Späth and Rohracher, 2015; Bendito and Barrios, 2016; Eisenberg, 2016; Tait and Euston-Brown, 2017)</td>
</tr>
<tr>
<td>Social &amp; regional inclusiveness</td>
<td>(Tallis et al., 2011; Elmqvist et al., 2013b; Buckeridge, 2015; Elmqvist et al., 2015; Beaudoin and Gosselin, 2016; Brown and McGranahan, 2016; Camps-Calvet et al., 2016; Culwick and Bobbins, 2016; McPhearson et al., 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; Ziervogel et al., 2016b; Collas et al., 2017; Li et al., 2017; White et al., 2017b; Prudencio and Null, 2018)</td>
<td>(Parnell, 2015; Shapiro, 2016; Mavhura et al., 2017; Reckien et al., 2017)</td>
</tr>
<tr>
<td>Intergenerational equity</td>
<td>(Elmqvist et al., 2013b; Liu et al., 2014; Elmqvist et al., 2015; Lamond et al., 2015; Skougaard Kaspersen et al., 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; McPhearson et al., 2016; Mguni et al., 2016; Xie et al., 2017)</td>
<td>NE</td>
</tr>
<tr>
<td>Environmental / ecological capacity</td>
<td>(Liu et al., 2014; Lamond et al., 2015; Skougaard Kaspersen et al., 2015; Costa et al., 2016; Mguni et al., 2016; Xie et al., 2017)</td>
<td>NE</td>
</tr>
<tr>
<td>Adaptive capacity/ resilience</td>
<td>(Beatley, 2011; Elmqvist et al., 2013b, 2015; Voskamp and Van de Ven, 2015; Beaudoin and Gosselin, 2016; Brown and</td>
<td>(Steenhof and Sparling, 2011; Aerts et al., 2014; Bendito and Barrios, 2016)</td>
</tr>
<tr>
<td>Geophysical</td>
<td>Physical feasibility</td>
<td>NE</td>
</tr>
<tr>
<td>-----------------------------------------</td>
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</tr>
<tr>
<td></td>
<td>(Liu et al., 2014; Lamond et al., 2015; Skougaard Kaspersen et al., 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; Mguni et al., 2016; Collas et al., 2017; Xie et al., 2017)</td>
<td></td>
</tr>
<tr>
<td>Land use change enhancement potential</td>
<td>(Tallis et al., 2011; Elmqvist et al., 2013b; Buckeridge, 2015; Culwick and Bobbins, 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; Collas et al., 2017; White et al., 2017b)</td>
<td>(Bendito and Barrios, 2016; Reckien et al., 2017)</td>
</tr>
<tr>
<td>Hazard risk reduction potential</td>
<td>(Nowak et al., 2006; Tallis et al., 2011; Elmqvist et al., 2013b; Buckeridge, 2015; Elmqvist et al., 2015; Soderlund and Newman, 2015; Brown and McGranahan, 2016; Camps-Calvet et al., 2016; Culwick and Bobbins, 2016; McPhearson et al., 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; Ziervogel et al., 2016b; Collas et al., 2017; Li et al., 2017; White et al., 2017b; Zinia and McShane, 2018)</td>
<td>(Steenhof and Sparling, 2011; FEMA, 2014; Bendito and Barrios, 2016; Garsaball and Markov, 2017; Reckien et al., 2017)</td>
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### Supplementary Material 4.D.3.iv Feasibility assessment of adaptation options in industrial system transitions

**Supplementary Material 4.D.3.iv, Table 1:** Feasibility assessment of industrial system transition adaptation option: Intensive industry infrastructure resilience and water management. For methodology, see Supplementary Material 4.D.1.

<table>
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<th>Evidence</th>
<th>Intensive industry infrastructure resilience and water management</th>
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<td>Agreement</td>
<td>High</td>
</tr>
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<td>Economic</td>
<td></td>
</tr>
<tr>
<td>Micro-economic viability</td>
<td>NE</td>
</tr>
<tr>
<td>Macro-economic viability</td>
<td>NE</td>
</tr>
<tr>
<td>Socio-economic vulnerability reduction</td>
<td></td>
</tr>
<tr>
<td>potential</td>
<td></td>
</tr>
<tr>
<td>Employment &amp; productivity enhancement</td>
<td>NE</td>
</tr>
<tr>
<td>Technical</td>
<td></td>
</tr>
<tr>
<td>Technical resource availability</td>
<td>(Koch and Vögele, 2009; Jahandideh-Tehrani et al., 2014; Murrant et al., 2015; Parkinson and Djilali, 2015)</td>
</tr>
<tr>
<td>Risks mitigation potential</td>
<td>(Jahandideh-Tehrani et al., 2014; Murrant et al., 2015; Parkinson and Djilali, 2015)</td>
</tr>
<tr>
<td>Institutional</td>
<td></td>
</tr>
<tr>
<td>Political acceptability</td>
<td>LE</td>
</tr>
<tr>
<td>Legal &amp; regulatory acceptibility</td>
<td>NE</td>
</tr>
<tr>
<td>Institutional capacity &amp; Administrative</td>
<td>LE</td>
</tr>
<tr>
<td>feasibility</td>
<td>(Eisenack and Stecker, 2012; Murrant et al., 2015)</td>
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<tr>
<td>Transparency &amp; accountability potential</td>
<td>NE</td>
</tr>
<tr>
<td>Socio-cultural</td>
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</tr>
<tr>
<td>Social co-benefits (health, education)</td>
<td>NA</td>
</tr>
<tr>
<td>Socio-cultural acceptability</td>
<td>NE</td>
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<tr>
<td>Social &amp; regional inclusiveness</td>
<td>NA</td>
</tr>
<tr>
<td>Environmental/ ecological</td>
<td>Intergenerational equity</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Ecological capacity</td>
<td></td>
</tr>
<tr>
<td>Adaptive capacity/resilience</td>
<td></td>
</tr>
<tr>
<td>Physical feasibility</td>
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</tr>
<tr>
<td>Land use change enhancement potential</td>
<td>LE</td>
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<tr>
<td>Hazard risk reduction potential</td>
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</tbody>
</table>
**Supplementary Material 4.D.3.v Feasibility assessment of overarching adaptation options**

**Supplementary Material 4.D.3.v, Table 1:** Feasibility assessment of overarching adaptation options: Disaster risk management; Risk spreading and sharing; Climate services; and Indigenous knowledge. For methodology, see Supplementary Material 4.D.1.

<table>
<thead>
<tr>
<th>Evidence</th>
<th>Micro-economic viability</th>
<th>Macroeconomic viability</th>
<th>Disaster risk management</th>
<th>Risk spreading and sharing</th>
<th>Climate services</th>
<th>Indigenous knowledge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>(IPCC, 2012; Mavhura et al., 2013; Yu and Gillis, 2014; Johnson and Abe, 2015; Mawere and Mubaya, 2015; Archer, 2016; Kull et al., 2016; Rose, 2016; Watanabe et al., 2016)</td>
<td>(IPCC, 2012; Hinkel et al., 2014; Anacona et al., 2015; Bougmedir, 2015; Howes et al., 2015; Johnson and Abe, 2015; Archer, 2016; Diaz, 2016; Haebeli et al., 2016; Kull et al., 2016; Rose, 2016; de Leon and Pittock, 2017; Haebeli et al., 2017; Kelman, 2017)</td>
<td>(Panda et al., 2013; Weinhofer and Busch, 2013; Falco et al., 2014; Thornton and Herrero, 2014; Annan and Schlenker, 2015; Bogale, 2015; García Romero and Molina, 2015; Greatrex et al., 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Nicola, 2015; Akter et al., 2016; Jin et al., 2016; Surminska et al., 2016; Akter et al., 2017; Farzaneh et al., 2017; Glaas et al., 2017; Jensen and Barrett, 2017; Patel et al., 2017; Shively, 2017)</td>
<td>(Cook and Dowlatabadi, 2011; Falco et al., 2014; García Romero and Molina, 2015; Joyette et al., 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Wolfrom and Yokoi-Arai, 2015; Surminska et al., 2016; Glaas et al., 2017; Jenkins et al., 2017)</td>
<td>(Vaughan and Dessai, 2014; Snow et al., 2016; Lechthaler and Vinogradova, 2017; Webber, 2017; Ouédraogo et al., 2018)</td>
<td>(Berkes et al., 2000; Nakashima et al., 2012; Leonard et al., 2013; McNamara and Prasad, 2014; Pearce et al., 2015; Mapfumo et al., 2016; Altei and Nicholls, 2017; Nunn et al., 2017; Ruiz-Mallén et al., 2017; Crane et al., 2017; Ingy, 2017; Kihila, 2017; Magni, 2017)</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
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<td>Medium</td>
<td>Medium</td>
</tr>
</tbody>
</table>

**Evidence Level:** Medium

**Agreement:** High
<table>
<thead>
<tr>
<th>Socio-economic vulnerability reduction potential</th>
<th>Employment &amp; productivity enhancement potential</th>
<th>Technological resource availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>(IPCC, 2012; Mavhura et al., 2013; Boeckmann and Rohn, 2014; McNamara and Prasad, 2014; Anacona et al., 2015; Bougedhir, 2015; Howes et al., 2015; Johnson and Abe, 2015; Kelman et al., 2015; Mawere and Mubaya, 2015; Archer, 2016; Diaz, 2016; Haeberli et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Rose, 2016; Watanabe et al., 2016; de Leon and Pittock, 2017; Granderson, 2017; Haeberli et al., 2017; Wallace, 2017; Brundiers, 2018; Nahayo et al., 2018)</td>
<td>(IPCC, 2012; Mavhura et al., 2013; Yu and Gillis, 2014; Johnson and Abe, 2015; Mawere and Mubaya, 2015; Terrier et al., 2015; Archer, 2016; Haeberli et al., 2016; Kull et al., 2016; Rose, 2016; Haeberli et al., 2017)</td>
<td>(IPCC, 2012; Mavhura et al., 2013; Boeckmann and Rohn, 2014; McNamara and Prasad, 2014; Yu and Gillis, 2014; Anacona et al., 2015; Bougedhir, 2015; Howes et al., 2015; Johnson and Abe, 2015; Kelman et al., 2015; Mawere and Mubaya, 2015; Howes et al., 2015; Johnson and Abe, 2015; Kelman et al., 2015; Mawere and Mubaya, 2015; Archer, 2016; Diaz, 2016; Haeberli et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Rose, 2016; Watanabe et al., 2016; de Leon and Pittock, 2017; Granderson, 2017; Haeberli et al., 2017; Wallace, 2017; Brundiers, 2018; Nahayo et al., 2018)</td>
</tr>
<tr>
<td>(Mills, 2007; Panda et al., 2013; Falco et al., 2014; Thornton and Herrero, 2014; Anan and Schlenker, 2015; Bogale, 2015; García Romero and Molina, 2015; Grearx et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Nicola, 2015; Wolfrom and Yokoi-Arai, 2015; Jin et al., 2016; O’Hare et al., 2016; Surminski et al., 2016; Akter et al., 2017; Farzaneh et al., 2017; Glaas et al., 2017; Hansen et al., 2017; Jensen and Barrett, 2017; Patel et al., 2017; Surminski and Thieken, 2017)</td>
<td>(Panda et al., 2013; Falco et al., 2014; Thornton and Herrero, 2014; Bogale, 2015; Grearx et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Nicola, 2015; Hansen et al., 2017; Jensen and Barrett, 2017)</td>
<td>(Falco et al., 2014; García Romero and Molina, 2015; Joyette et al., 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Dinku et al., 2014; Jancloes et al., 2014; Gebru et al., 2015; Weisse et al., 2015; Brasseur and Gallardo, 2016; Cortekar, 2015;</td>
</tr>
<tr>
<td>Risks mitigation potential</td>
<td>Institutional acceptability</td>
<td></td>
</tr>
<tr>
<td>----------------------------</td>
<td>-----------------------------</td>
<td></td>
</tr>
<tr>
<td>(IPCC, 2012; Mavhura et al., 2013; Yu and Gillis, 2014; Boughedir, 2015; Howes et al., 2015; Johnson and Abe, 2015; Kelman et al., 2015; Mawere and Mubaya, 2015; Archer, 2016; Haeberli et al., 2016; Kaya et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Rose, 2016; Haeberli et al., 2017; Kita, 2017; Wallace, 2017)</td>
<td>(Carey, 2005, 2008; IPCC, 2012; Boughedir, 2015; Johnson and Abe, 2015; Archer, 2016; Haeberli et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Granderson, 2017; Kelman, 2017; Kita, 2017; Ruiz-Rivera and Lucatello, 2017; Rosendo et al., 2018)</td>
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| (Akter et al., 2016; Surmsnki et al., 2016; Adiku et al., 2017; Jensen and Barrett, 2017) | (García Romero and Molina, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Nicola, 2015; Wolf and Yokoi-Arai, 2015; Jin et al., 2016; Surmsnksi et al., 2016; Farzaneh et al., 2017; Hansen et al., 2017; Jensen and Barrett, 2017; Surmsnksi and Eldridge, 2017; Surmsnksi and Thieken, 2017) |
| (Mills, 2007; Cook and Dowlatbadi, 2011; Panda et al., 2013; Weinhofer and Busch, 2013; Falco et al., 2014; Thornton and Herrero, 2014; Anh and Schlenker, 2015; Fabian, 2015; García Romero and Molina, 2015; Greathex et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Nicola, 2015; Wolf and Yokoi-Arai, 2015; Jin et al., 2016; Surmsnksi et al., 2016; Farzaneh et al., 2017; Hansen et al., 2017; Jensen and Barrett, 2017; Surmsnksi and Eldridge, 2017; Surmsnksi and Thieken, 2017) | (Rogers and Tsirkunov, 2010; WMO, 2015) |

<p>| (Nakashima et al., 2012; McNamara and Prasad, 2014; Mapfumo et al., 2016; Kihila, 2017; Magni, 2017) | (Gebru et al., 2015; Vincent et al., 2015; Cortekar et al., 2016; Singh et al., 2016; Snow et al., 2016; Harjanne, 2017; Webber, 2017) |
| (Nakashima et al., 2012; McNamara and Prasad, 2014; Mapfumo et al., 2016; Kihila, 2017; Magni, 2017) | (Nakashima et al., 2012; Leonard et al., 2015; Ford et al., 2015; Hooli, 2016; Mistry and Berardi, 2016; Fernández-Llamazares et al., 2017; Russell-Smith et al., 2017; Russell-Smith et al., 2017; Williams et al., 2017; Ingty, 2017; Kihila, 2017; Magni, 2017; Ruiz-Mallén et al., 2017) |</p>
<table>
<thead>
<tr>
<th>Legal &amp; regulatory acceptability</th>
<th>(IPCC, 2012; Boughedir, 2015; Howes et al., 2015; Johnson and Abe, 2015; Kelman et al., 2015; Haebelri et al., 2016; Kaya et al., 2016; Kull et al., 2016; Muñoz et al., 2016; van der Keur et al., 2016; de Leon and Pittock, 2017; Haebelri et al., 2017; Kelman, 2017; Kita, 2017; Ruiz-Rivera and Lucatello, 2017; Serrao-Neumann et al., 2017; Wallace, 2017; Rosendo et al., 2018)</th>
<th>(Falco et al., 2014; Thornton and Herrero, 2014; García Romero and Molina, 2015; Joyette et al., 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Wolfrom and Yokoi-Arai, 2015; Surminski et al., 2016; Adiku et al., 2017; Glaas et al., 2017; Hansen et al., 2017; Jenkins et al., 2017; Jensen and Barrett, 2017)</th>
<th>(Mantilla et al., 2014; Coulibaly et al., 2015; Lobo et al., 2017)</th>
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</thead>
<tbody>
<tr>
<td>Institutional capacity &amp; Administrative feasibility</td>
<td>(Carey, 2008; IPCC, 2012; Mavhura et al., 2013; McNamara and Prasad, 2014; Boughedir, 2015; Howes et al., 2015; Johnson and Abe, 2015; Kelman et al., 2015; Mawere and Mubaya, 2015; Archer, 2016; Haebelri et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Rose, 2016; van der Keur et al., 2016; Watanabe et al., 2016; Granderson, 2017; Haebelri et al., 2017; Kelman, 2017; Kita, 2017; Ruiz-Rivera and Lucatello, 2017; Serrao-Neumann et al., 2017; Wallace, 2017; Nahayo et al., 2018; Rosendo et al., 2018)</td>
<td>(Cook and Dowlatabadi, 2011; Weinhofer and Busch, 2013; Falco et al., 2014; Thornton and Herrero, 2014; García Romero and Molina, 2015; Greatrex et al., 2015; Joyette et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Wolfrom and Yokoi-Arai, 2015; Akter et al., 2016; Surminski et al., 2016; Adiku et al., 2017; Glaas et al., 2017; Hansen et al., 2017; Jenkins et al., 2017; Jensen and Barrett, 2017; Surminski and Eldridge, 2017)</td>
<td>(Dinku et al., 2014; Jancloes et al., 2014; Vaughan and Dessai, 2014; Wood et al., 2014; Vincent et al., 2015; Brasseur and Gallardo, 2016; Lourenço et al., 2016; Snow et al., 2016; Trenberth et al., 2016; Vaughan et al., 2016; Harjanne, 2017; Räsänen et al., 2017; Singh et al., 2017)</td>
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Do Not Cite, Quote or Distribute 4-72 Total pages: 171
<table>
<thead>
<tr>
<th>Social co-benefits (health, education)</th>
<th>Socio-cultural acceptability</th>
<th>Social &amp; regional inclusiveness</th>
</tr>
</thead>
<tbody>
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<td>(IPCC, 2012; Mavhura et al., 2013; McNamara and Prasad, 2014; Mawere and Mubaya, 2015; Samaddar et al., 2015; Archer, 2016; Haebel et al., 2016; Kull et al., 2016; Rose, 2016; Watanabe et al., 2016; Brundiers, 2018; Nahayo et al., 2018)</td>
<td>(Carey, 2005; IPCC, 2012; Mavhura et al., 2013; McNamara and Prasad, 2014; Anacona et al., 2015; Mawere and Mubaya, 2015; Samaddar et al., 2015; Archer, 2016; Kaya et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Rose, 2016; van der Keur et al., 2016; Watanabe et al., 2016; de Leon and Pittock, 2017; Granderson, 2017; Kita, 2017; Serrao-Neumann et al., 2017)</td>
<td>(Carey, 2005; IPCC, 2012; Mavhura et al., 2013; McNamara and Prasad, 2014; Mawere and Mubaya, 2015; Samaddar et al., 2015; Archer, 2016; Kaya et al., 2016; Kull et al., 2016; Rose, 2016; Watanabe et al., 2016; de Leon and Pittock, 2017; Granderson, 2017; Kita, 2017; Nahayo et al., 2018)</td>
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<td>(Panda et al., 2013; Thornton and Herrero, 2014; Greatrex et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Adiku et al., 2017; Glaas et al., 2017; Hansen et al., 2017; Jensen and Barrett, 2017)</td>
<td>(Bogale, 2015; García Romero and Molina, 2015; Greatrex et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Jin et al., 2016; Adiku et al., 2017; Akter et al., 2017; Farzaneh et al., 2017; Glaas et al., 2017; Hansen et al., 2017; Jensen and Barrett, 2017)</td>
<td>(Sivakumar et al., 2014; Vincent et al., 2015; Brasseur and Gallardo, 2016; Cortekar et al., 2016; Carr and Onzere, 2017; Singh et al., 2017; Webber and Donner, 2017; Guido et al., 2018)</td>
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<td>(Rogers and Tsirkunov, 2010; Kadi et al., 2011; Hunt et al., 2017)</td>
<td>(Natcher et al., 2007; Ford et al., 2010; Cunsolo Willox et al., 2012; Nakashima et al., 2012; Adger et al., 2013; Leonard et al., 2013; Green and Minchin, 2014; MacDonald et al., 2015a; Hiwasaki et al., 2015; Johnson et al., 2015; Mapfumo et al., 2016; Mistry and Berardi, 2016; Hooli, 2016; Magni, 2017; Kihila, 2017)</td>
<td>(Berkes et al., 2000; Nakashima et al., 2012; Adger et al., 2013; Leonard et al., 2013; Green and Minchin, 2014; McNamara and Prasad, 2014; MacDonald et al., 2015a; Mistry and Berardi, 2016; Hooli, 2016; Nunn et al., 2017; Ruiz-Mallén et al., 2017)</td>
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Do Not Cite, Quote or Distribute: 4-73 Total pages: 171

2017; Hansen et al., 2017; Jensen and Barrett, 2017)
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<th>Adaptive capacity/resilience</th>
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<td>(IPCC, 2012; Mavhura et al., 2013; Boeckmann and Rohn, 2014; McNamara and Prasad, 2014; Yu and Gillis, 2014; Anacona et al., 2015; Howes et al., 2015; Johnson and Abe, 2015; Kelman et al., 2015; Mawere and Mubaya, 2015; Archer, 2016; Haeberli et al., 2016; Kaya et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Rose, 2016; Watanabe et al., 2016; de Leon and Pittock, 2017; Granderson, 2017; Haeberli et al., 2017; Kelman, 2017; Wallace, 2017; Brundiers, 2018)</td>
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<td>NA</td>
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<td>(Berkes et al., 2000; Ford et al., 2010; Nakashima et al., 2012; Leonard et al., 2013; McNamara and Prasad, 2014; Hiwasaki et al., 2015; MacDonald et al., 2015a; Tschakert et al., 2017; Kihila, 2017; Magni, 2017; Nunn et al., 2017)</td>
<td>(Berkes et al., 2000; Forbes et al., 2009; Leonard et al., 2013; McNamara and Prasad, 2014; MacDonald et al., 2015b; Altieri and Nicholls, 2017; Russell-Smith et al., 2017; Tschakert et al., 2017; Ingy, 2017; Kihila, 2017; Magni, 2017; Nunn et al., 2017)</td>
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<td>(Panda et al., 2013; Annan and Schlenker, 2015; Greatrex et al., 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Hansen et al., 2017; Jenkins et al., 2017; Jensen and Barrett, 2017)</td>
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<tr>
<td>Geophysical hazard risk reduction potential</td>
<td>(Carey, 2005, 2008; IPCC, 2012; Mavhura et al., 2013; Boeckmann and Rohn, 2014; McNamara and Prasad, 2014; Yu and Gillis, 2014; Anacona et al., 2015; Howes et al., 2015; Johnson and Abe, 2015; Kelman et al., 2015; Mawere and Mubaya, 2015; Boughedir, 2015; Archer, 2016; Kaya et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Rose, 2016; Watanabe et al., 2016; Diaz, 2016; Haeberli et al., 2016, 2017; Kelman, 2017; Kita, 2017; Milner et al., 2017; Wallace, 2017; Brundiers, 2018)</td>
<td>(Mills, 2007; Falco et al., 2014; Annan and Schlenker, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Wolfrom and Yokoi-Arai, 2015; García Romero and Molina, 2015; Greatrex et al., 2015; Lashley and Warner, 2015; Surminski et al., 2016; Jin et al., 2016; Patel et al., 2017; Surminski and Eldridge, 2017; Surminski and Thieken, 2017; Farzaneh et al., 2017; Glaas et al., 2017; Hansen et al., 2017; Jensen and Barrett, 2017)</td>
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</tbody>
</table>
**Supplementary Material 4.D.3.v, Table 2**: Feasibility assessment of overarching adaptation options: Education and learning; Population health and health system adaptation; Social safety nets; and Human Migration. For methodology, see Supplementary Material 4.D.1.

<table>
<thead>
<tr>
<th>Evidence</th>
<th>Education and learning</th>
<th>Population health and health system adaptation</th>
<th>Social safety nets</th>
<th>Human migration</th>
</tr>
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<tr>
<td>Agreements</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
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</table>

<p>| Economic viability            |                        |                                                |                   |                 |
| Micro-economic viability      | (Rumore et al., 2016; Lutz and Muttarak, 2017) | (Toloo et al., 2013; Burton et al., 2014; Hoy et al., 2014; Paterson et al., 2014; Smith et al., 2014a; Confalonieri et al., 2015; Araos et al., 2016a; Hess and Ebi, 2016; Ebi and del Barrio, 2017; Gilfillan et al., 2017; Paavola, 2017) | (Shiferaw et al., 2014; Devereux et al., 2015) | (Birk and Rasmussen, 2014; Betzold, 2015; Ionescu et al., 2016; Musah-Surugu et al., 2018) |
| Macro-economic viability      | (Hoffmann and Muttarak, 2017; Lutz and Muttarak, 2017) | (Ebi et al., 2004; Hess et al., 2012; Hosking and Campbell-Lendrum, 2012; Bowen et al., 2013; Lesnikowski et al., 2013; Toloo et al., 2013; Hoy et al., 2014; Smith et al., 2014a; Austin et al., 2015; Watts et al., 2015; WHO, 2015; Araos et al., 2016a; Hess and Ebi, 2016; Paz et al., 2016; Ebi and del Barrio, 2017; Gilfillan et al., 2017; Nitschke et al., 2017; Paavola, 2017) | (Devereux et al., 2015) | (Grecequet et al., 2017; Hino et al., 2017) |
| Socio-economic vulnerability reduction potential | (Frankenberg et al., 2013; K.C., 2013; Striessnig et al., 2013; van der Land and Hummel, 2013; Muttarak and Lutz, 2014; Rumore et al., 2016; Hoffmann and Muttarak, 2017; Lutz and Muttarak, 2017) | (Ebi et al., 2004; Hess et al., 2012; Hosking and Campbell-Lendrum, 2012; Bowen et al., 2013; Panic and Ford, 2013; Toloo et al., 2013; Boeckmann and Rohn, 2014; Smith et al., 2014a; Austin et al., 2015; Confalonieri et al., 2015; Watts et al., 2015; WHO, 2015; Araos et al., 2016a; Benmarhnia et al., 2016; Ebi et al., 2016; Hess and Ebi, 2016; Paz et al., 2016; Ebi and del Barrio, 2017; Ebi and Hess, 2017; Gilfillan et al., 2017) | (Davies et al., 2013; Weldegebriel and Prowse, 2013; Berhane et al., 2014; Eakin et al., 2014; Leichenko and Silva, 2014; Devereux, 2016; Lemos et al., 2016; Godfrey-Wood and Flower, 2017; Schwand and Yu, 2017) | (Birk and Rasmussen, 2014; Adger et al., 2015; Betzold, 2015; Grecequet et al., 2017; Melde et al., 2017; World Bank, 2017) |
| Employment &amp; productivity enhancement potential | (van der Land and Hummel, 2013; Muttarak and Lutz, 2014; Lutz and Muttarak, 2017) | (Bowen et al., 2013; Toloo et al., 2013; Burton et al., 2014; Hoy et al., 2014; Smith et al., 2014a; Benmarhnia et al., 2016; Paz et al., 2016; Gilfillan et al., 2017; Nitschke et al., 2017) | (Davies et al., 2013; Berhane et al., 2014; Shiferaw et al., 2014) | NA |
| Technical resource availability | (Chaudhury et al., 2013; Baird et al., 2014; Cloutier et al., 2015; Rumore et al., 2016) | (Hess et al., 2012; Bowen et al., 2013; Lesnikowski et al., 2013; Panic and Ford, 2013; Toloo et al., 2013; Burton et al., 2014; Hoy et al., 2014; Paterson et al., 2014; Rumsey et al., 2014; Smith et al., 2014a; Austin et al., 2015; Confalonieri et al., 2015; WHO, 2015; Araos et al., 2016a; Benmarhnia et al., 2016; Ebi et al., 2016; Hess and Ebi, 2016; Paz et al., 2016; Ebi and del Barrio, 2017; Ebi and Hess, 2017; Nitschke et al., 2017; Paavola, 2017; Sheehan et al., 2017) | (Kim and Yoo, 2015) | (Birk and Rasmussen, 2014; Gemenne and Blocher, 2017; Melde et al., 2017) |
| Institutional political acceptability | LE (Butler et al., 2015, 2016b; Cloutier et al., 2015) | (Hess et al., 2012; Bowen et al., 2013; Lesnikowski et al., 2013; Burton et al., 2014; Hoy et al., 2014; Rumsey et al., 2014; Smith et al., 2014a; Austin et al., 2015; Confalonieri et al., 2015; Watts et | (Porter et al., 2014; Rurinda et al., 2014; Wilhite et al., 2014; Brooks, 2015; Kim and Yoo, 2015; Ravi and | (Kothari, 2014; Methmann and Oels, 2015; Brzoska and Fröhlich, 2016; Gemenne and Blocher, 2017; Grecequet et al., 2017; Yamamoto et al., |</p>
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<th>IPCC SR1.5</th>
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<td>Chapter 4 Supplementary Material</td>
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<td>Legal &amp; regulatory</td>
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<td>acceptability</td>
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<td></td>
<td>(Wamsler et al., 2012; Chaudhury</td>
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<td></td>
<td>et al., 2013; Odemerho, 2014;</td>
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<td></td>
<td>Cloutier et al., 2015; Butler et</td>
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<td>al., 2016b, 2016a)</td>
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<td>(Engler, 2015; Schwan and Yu, 2017)</td>
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<td>(Hess et al., 2012; Lesnikowski</td>
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<td>et al., 2013; Burton et al., 2014;</td>
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<td>Austin et al., 2015; Watts et al,</td>
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<td>2015; WHO, 2015; Araos et al.,</td>
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<td>2016a; Ebi et al., 2016; Hess and</td>
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<td>Ebi, 2016; Ebi and del Barrio, 2017; Gilfillan et al., 2017; Green et al., 2017; Sen et al., 2017</td>
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<td>(Rurinda et al., 2014; Devereux et al., 2015)</td>
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<td>Wilhite et al., 2014; Ravi and</td>
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<td>Engler, 2015; Schwan and Yu, 2017)</td>
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<td>(Davies et al., 2013; Rurinda</td>
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<td>et al., 2014; Wilhite et al., 2014;</td>
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<td>Ravi and Engler, 2015; Schwan and</td>
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<td>Institutional</td>
<td>(Chaudhury et al., 2013; Odemerho</td>
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<td>capacity &amp;</td>
<td>(Chaudhury et al., 2013; Odemerho</td>
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<td>Administrative</td>
<td>et al., 2014; Cloutier et al.,</td>
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<td>feasibility</td>
<td>2015; Butler et al., 2016b,</td>
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<td>2016a)</td>
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<td>Transparency &amp;</td>
<td>(Chaudhury et al., 2013; Odemerho</td>
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<td>(Chaudhury et al., 2013; Odemerho</td>
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<td>(Masud-All-Kamal and Saha, 2014; Devereux et al., 2015; Masiero, 2015; Ravi and Engler, 2015; Schwan and Yu, 2017)</td>
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<td>Social co-benefits (health, education)</td>
<td>Social &amp; regional inclusiveness</td>
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<td>Socio-cultural acceptability</td>
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<td>(Chaudhury et al., 2013; Sharma et al., 2013; Demuzere et al., 2014; Odemerho, 2014; Ensor and Harvey, 2015; Butler et al., 2016a; Myers et al., 2017; Flynn et al., 2018)</td>
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<td>(Wamsler et al., 2012; Muttarak and Lutz, 2014; Suarez et al., 2014; Ensor and Harvey, 2015; Ford et al., 2016, 2018)</td>
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<td>LE (Rurinda et al., 2014; Wilhite et al., 2014)</td>
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| (Berhan et al., 2014; Leichenko and Silva, 2014; Rurinda et al., 2014; Shiferaw et al., 2014; Verguet et al., 2015; Devereux, 2016; Lemos et al., 2016) | (Kothari, 2014; Bettini et al., 2016; Gioli et al., 2016; Bhagat, 2017; Melde et al., 2017; Schwan and Yu, 2017; World Bank, 2018) | (Kothari, 2014; Kelman, 2015; Schwan and Yu, 2017; Matthews and Potts, 2018; World Bank, 2018) | (Wilmsen and Webber, 2015) | (Niven and Bardsley, 2013; Birk and Rasmussen, 2014) | (Birk and Rasmussen, 2014; Adger et al., 2015; Grecoquet et al., 2017; Davies et al., 2013; Weldegebriel and Prowse, 2013; Eakin et al.)
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<td>2015; Benmarhnia et al., 2016; Hess and Ebi, 2016; Paz et al., 2016; Ebi and del Barrio, 2017; Nitschke et al., 2017; Paavola, 2017; Sen et al., 2017)</td>
<td>al., 2014; Rurinda et al., 2014; Shiferaw et al., 2014; Lemos et al., 2016; Schwan and Yu, 2017)</td>
<td>Melde et al., 2017; Tadgell et al., 2017; World Bank, 2018)</td>
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<td></td>
<td>(Birk and Rasmussen, 2014; Cattaneo and Peri, 2016; Grecequet et al., 2017; Tadgell et al., 2017; Crnčević and Orlović Lovren, 2018; World Bank, 2018)</td>
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</tbody>
</table>
Supplementary Material 4.E Adaptation and mitigation synergies and trade-offs as discussed in Section 4.5.4

Mitigation options may affect the feasibility of adaptation options, and the other way around. Supplementary Material 4.E.1, Table 1 provides examples of possible positive impacts (synergies) and negative impacts (trade-offs) of mitigation options for adaptation. Supplementary Material 4.E.2, Table 1 lists examples of synergies and trade-offs of adaptation options for mitigation.

Supplementary Material 4.E.1 Mitigation options with adaptation synergies and trade-offs

Supplementary Material 4.E.1, Table 1: Mitigation options with adaptation synergies and trade-offs identified

<table>
<thead>
<tr>
<th>System</th>
<th>Mitigation option</th>
<th>Synergies</th>
<th>Trade-offs</th>
</tr>
</thead>
<tbody>
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<td>Energy system transitions</td>
<td>Wind energy</td>
<td>Resilience can be increased by wind, solar and bioenergy due to distributed grids (Parkinson and Djilali, 2015), given that energy security standards are in place (Almeida Prado et al., 2016). The use of residential batteries can increase resiliency, especially after extreme weather events (Qazi and Young Jr., 2014; Liu et al., 2017).</td>
<td>Renewable energy infrastructure that does not follow security standards can increase vulnerability (Ley, 2017).</td>
</tr>
<tr>
<td></td>
<td>Solar PV</td>
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<tr>
<td></td>
<td>Bioenergy</td>
<td></td>
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<tr>
<td></td>
<td>Electricity storage</td>
<td>A shift from coal-generated to natural gas-generated electricity could decrease water consumption (DeNooyer et al., 2016).</td>
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<td></td>
<td>Power sector CCS</td>
<td>NE</td>
<td>Some renewable energy technologies, carbon dioxide capture and storage (CCS), and concentrating solar power (CSP) technologies have substantial water demand associated with their operation (Fricko et al., 2016). In particular, lower power plant efficiency due to CCS increases the vulnerability to water constraints in most regions (McCullum et al., 2013; van Vliet et al., 2016).</td>
</tr>
<tr>
<td></td>
<td>Nuclear energy</td>
<td>Increased safety and protection standards can improve the climate risk profiles (Schneider et al., 2017).</td>
<td>Increased safety and protection standards will increase costs making some electricity systems less reliable (Jacobson and Delucchi, 2009; Lovins et al., 2018).</td>
</tr>
<tr>
<td>Land &amp; ecosystem transitions</td>
<td>Reduced food</td>
<td>Reducing food loss and waste can decrease pressure of deforestation (FAO, 2013a), pressure on land use for agriculture (Foley et al., 2011; Hiç et al., 2016), and provide long-term food security (Bajželj et al., 2014).</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>wastage &amp; efficient food production</td>
<td></td>
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<td></td>
<td>Dietary shifts</td>
<td>Shift from animal- to plant-related diets can significantly decrease land use and biodiversity loss due to a decrease in pressure on land use by livestock production (Newbold et al., 2015; Ramankutty et al., 2018;</td>
<td>Shift from animal- to plant-related diets will require improvement of mixed crop-livestock systems, which are more difficult to manage well and need higher capital to be</td>
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### Sustainable intensification of agriculture

| Sparovek et al., 2018 along with health benefits (Tilman and Clark, 2014; Westhoek et al., 2014; Hallström et al., 2017; Song et al., 2017). | Sustainable intensification can increase offsite impacts from fertiliser, herbicide and pesticide use (Stevens and Quinton, 2009), increase costs and increase climate risk. No-tillage without pairing with other agronomic practices can reduce crop yields. |
| Agroforestry practices increase soil carbon stocks and above-ground biomass as well as diversify incomes, reducing financial risk, and provide shade for protection from rising temperatures (Harvey et al., 2014). | No till agriculture can reduce GHG emissions but increase pesticide concentrations (Stevens and Quinton, 2009). |
| Agroforestry can sustain or increase food production in some systems, increasing farmers’ resilience to climate change (Jones et al., 2012). | Adaptation gains made through improved irrigation efficiency can be undermined by shifts to water-intensive crops for mitigation (e.g. shifting to bioenergy crops) (Chaturvedi et al., 2015). |
| Mixed agroforestry systems may simultaneously meet the water, food, energy and income needs of densely populated rural and peri-urban areas (van Noordwijk et al., 2016). | Conservation agriculture agricultural reduces yields 3–5 years after adoption, but enhances productivity and carbon sequestration over longer periods (Harvey et al., 2014). |
| | Agroforestry can, in some dry environments, increase competition with crops and pastures decreasing productivity and reduce catchment water yield (Schroebback et al., 2011). |
| | Fast-growing tree monocultures or biofuel crops may enhance carbon stocks but reduce downstream water availability and decrease availability of agricultural land (Harvey et al., 2014). |
| | Agricultural intensification that improves crop productivity can increase incomes but undermine local livelihoods and wellbeing as seen in shifts to intensified sugarcane production in Ethiopia or more intensive land use in Southeast Asia (Liao and Brown, 2018). |

### Ecosystem restoration

| Sustainable water management – restored/healthy ecosystems provide water storage, and filtration services (Jones et al., 2012). | A focus on mitigation, e.g. through REDD+, can result in conservation-priority sites with lower carbon densities to end up without REDD+ protection (Phelps et al., 2012; Murray et al., 2015; Reside et al., 2017a; Turnhout et al., 2017). |
| Restoration of mangroves and coastal wetlands to sequester (blue) carbon increases carbon sinks, reduces coastal erosion, and protects from storm surges and otherwise mitigates impacts of sea level rise and | Potential conflict with biodiversity goals in habitat restoration |
extreme weather along the coastline (Alongi, 2008; Siikamäki et al., 2012; Romañach et al., 2018).

Blue biofuels do not compete for land, water and are not global food staples (posing less of a food security issue). Most farms do not use fertilizer and could even remove excess nutrients, decreasing eutrophication (Turner et al., 2009; Duarte et al., 2013).

Stabilization and support of fisheries can add value to marine biodiversity (Turner et al., 2009).

Carbon offset funds provide opportunities for protection and restoration of native ecosystems, with corresponding gains for biodiversity and reductions in carbon (Reside et al., 2017).

Coupled with biodiversity and conservation interventions, ecosystem restoration and avoided deforestation can complement habitat provision (Felton et al., 2016).

Forests (through REDD+) can support economies dependent on climate-sensitive sectors including agriculture, fisheries, and energy (Somorin et al., 2016; Few et al., 2017).

REDD+ has the potential to promote sustainable development activities through the cash-flow from donors/international funds to local forest stakeholders (West, 2016)

Tropical reforestation for climate change mitigation can help to protect rural economies from impacts of climate variation, reduce impacts of climatic variation on water cycle and associated human uses, reduce local impacts of extreme weather events and reduce climate impacts on biodiversity (Locatelli et al., 2015a).

Breeding animals with lower emissions per unit of dry matter intake can reduce GHG emissions; when integrated within broader breeding programmes, can offer synergies with breeding for improved adaptation to local conditions (Pickering et al., 2015; Nguyen et al., 2016). May have consumer health concerns that need evaluation and addressing (Barrows et al., 2014; Fraser et al., 2016).
<table>
<thead>
<tr>
<th>Land-use &amp; urban planning</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Urban &amp; infrastructure system transitions</strong></td>
<td>Potential for synergies in urban planning at policy, organizational, and practical levels (e.g. urban regeneration, retrofitting, urban greening) (Landauer et al., 2015).</td>
<td>Potential conflicts including urban densification to reduce emissions which can intensify heat island effect and increase surface run-off, and may compete with a desire to expand green space, restore local ecosystems, (Landauer et al., 2015; Di Gregorio et al., 2017b; Endo et al., 2017; Ürge-Vorsatz et al., 2018) though demonstrations of biophilic urbanism show this can be managed (Beatley, 2011; Newman et al., 2017).</td>
</tr>
<tr>
<td>Spatial planning can enhance adaptation, mitigation, and sustainable development (Hurlimann and March, 2012; Davidse et al., 2015; King et al., 2016; Francesch-Huidobro et al., 2017).</td>
<td>Through the use of integrated approaches there is potential synergy in land use planning (e.g. maintenance of urban forests, urban greening) (Newman et al., 2017).</td>
<td>In water-scarce regions, there may be trade-offs between mitigation measures that require water – such as localized cooling – and the population’s water needs (Georgescu et al., 2015).</td>
</tr>
<tr>
<td></td>
<td>Through the use of integrated approaches there is potential synergy in land use planning (e.g. maintenance of urban forests, urban greening) (Newman et al., 2017).</td>
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<tr>
<td></td>
<td>Urban densification to reduce emissions can go along with regenerative qualities for green spaces, reduced urban heat island and flooding impacts by employing biophilic urbanism design (Beatley, 2011; Newman et al., 2017).</td>
<td></td>
</tr>
<tr>
<td><strong>Sustainable and resilient transport systems</strong></td>
<td>Cities can re-urbanise in ways that promote transport sector adaptation and mitigation (Newman et al., 2017; Salvo et al., 2017; Gota et al., 2018).</td>
<td>In middle and low income countries urban density of informal settlements is typically associated with a range of water and vector-borne health risks that undermine benefits of energy efficiency, may provide a notable exception to the adaptive advantages of urban density (Mitlin and Satterthwaite, 2013; Lilford et al., 2017) unless new approaches using leapfrog technology are used to upgrade slums in situ (Teferi and Newman, 2017).</td>
</tr>
<tr>
<td>Cities that reduce the use of private cars, and develop sustainable transport systems can simultaneously benefit from reduced air pollution, congestion and road fatalities while reducing overall energy intensity in the urban transport sector (Goodwin and Van Dender, 2013; Newman and Kenworthy, 2015; Wee, 2015).</td>
<td>Non-motorized transport use is associated with lower emissions and better public health in cities. Urbanisation and improved access to basic services correlate with lower short-term morbidity (STM), such as fever, cough and diarrhea (Ahmad et al., 2017).</td>
<td></td>
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<tr>
<td>Non-motorized transport use is associated with lower emissions and better public health in cities. Urbanisation and improved access to basic services correlate with lower short-term morbidity (STM), such as fever, cough and diarrhea (Ahmad et al., 2017).</td>
<td>Promoting energy-efficient mobility systems, for instance by a 10% increase in bicycling, could lower chronic conditions like diabetes and cardio-vascular diseases for 0.3 million people while also abating emissions. (Ahmad et al., 2017).</td>
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<tr>
<td>Sharing schemes in transportation</td>
<td>Greater use of sharing schemes can make transport out of vulnerable areas more equitable and ordered (Gomez et al., 2015; Ambrosino et al., 2016; Kent and Dowling, 2016).</td>
<td>Highly ICT dependent sharing schemes may not be resilient during disasters, but this can be managed via local shared</td>
</tr>
<tr>
<td>Industrial system transitions</td>
<td>Energy efficiency</td>
<td>Reduced competition for resources (Hennessey et al., 2017)</td>
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<tr>
<td>Bio-based &amp; circularity</td>
<td>Reduced competition for resources (Hennessey et al., 2017)</td>
<td>Biomass production for industry, if well managed, can diversify local livelihoods, enhance incomes and strengthen local institutions (Locatelli et al., 2015a).</td>
</tr>
<tr>
<td>Electrification &amp; hydrogen</td>
<td>NA</td>
<td>Greater reliance on variable and weather-dependent sources of electricity (Philibert, 2017)</td>
</tr>
<tr>
<td>Industrial CCUS</td>
<td>NA</td>
<td>Cooling requirements for CO₂ capture put pressure on adaptation (Magneschi et al., 2017)</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>Bioenergy if well managed can diversify local livelihoods, enhance incomes and strengthen local institutions (Locatelli et al., 2015a).</td>
<td>Bioenergy plantations can decrease food security, compete for land and provide short-term benefits for only a few stakeholders</td>
</tr>
<tr>
<td>Removal (BECCS)</td>
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<tr>
<td>Combining BECCS with soil carbon management, agroforestry and afforestation can remove CO(_2), while limiting adverse impacts on water, food and biodiversity (Burns and Nicholson, 2017; Stoy et al., 2018).</td>
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<tr>
<td>Afforestation &amp; reforestation</td>
<td>Reforestation connecting fragmented forests reduces exposure to forest edge disturbances (Pütz et al., 2014).</td>
<td>Water - increase water demand reducing catchment yield (Berry et al 2014)</td>
</tr>
<tr>
<td></td>
<td>Reforestation and coastal restoration are associated with improved water filtration, ground water recharge and flood control (Ellison et al., 2017; Griscom et al., 2017)</td>
<td>Biodiversity - species and habitat loss due to monocultures, chemical inputs or forest management (Berry et al., 2015)</td>
</tr>
<tr>
<td></td>
<td>Reduce flooding through decreased peak river flow, improved water quality and groundwater recharge (Berry et al., 2015)</td>
<td>Loss of agricultural land (Berry et al., 2015)</td>
</tr>
<tr>
<td></td>
<td>Increase diversity and habitat availability (when properly managed) (Berry et al., 2015)</td>
<td>Forest plantations can decrease food security, compete for land and provide short-term benefits for only a few stakeholders (Locatelli et al., 2015b).</td>
</tr>
<tr>
<td></td>
<td>Tree planting led to more resilient livestock by providing shade and shelter (Hayman et al., 2012)</td>
<td>Local benefits, especially for indigenous communities, will only be accrued if land tenure is respected and legally protected, which is not often the case for Indigenous communities (Brugnach et al., 2017).</td>
</tr>
<tr>
<td></td>
<td>Forestry if well managed can diversify local livelihoods, enhance incomes and strengthen local institutions (Locatelli et al., 2015b)</td>
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<tr>
<td></td>
<td>Afforestation of degraded areas can produce large synergies between mitigation and adaptation through their impact on farmer livelihoods (Rahn et al., 2014).</td>
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<tr>
<td>Soil carbon sequestration &amp; biochar</td>
<td>With agroforestry, CO(_2) is sequestered in trees and soils additionally planted, while tree products provide livelihood to communities (Verchot et al., 2007; Nair et al., 2009; Branca et al., 2013; Lasco et al., 2014; Mbou et al., 2014a; Smith et al., 2014b)</td>
<td>Biochar amendments lead to plant growth and thus, may down-regulate plant defense genes increasing the vulnerability against insects, pathogens, and drought (Viger et al., 2015).</td>
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<td>Soil organic carbon may foster crop resilience to climate change (Aguilera et al., 2013).</td>
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<td>Biochar application to soil sequesters CO(_2) and at the same time increases crop productivity by up to 10% (Jeffery et al., 2011) and can improve the soil’s water balance (Bamminger et al., 2016).</td>
<td></td>
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<tr>
<td>Enhanced weathering</td>
<td>NE</td>
<td>Potential adverse health effects because of air particles (Taylor et al., 2016)</td>
</tr>
</tbody>
</table>
## Supplementary Material 4.E.2 Adaptation options with mitigation synergies and trade-offs

### Supplementary Material 4.E.2, Table 1: Adaptation options with mitigation synergies and trade-offs identified

<table>
<thead>
<tr>
<th>System</th>
<th>Adaptation option</th>
<th>Synergies</th>
<th>Trade-offs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy system transitions</td>
<td>Power infrastructure, including water</td>
<td>Some adaptation options can help improve system efficiency and reliability (Cortekar and Groth, 2015; van Vliet et al., 2016) Synergies with Sustainable Development Goals, poverty, and well being (Dagnachew et al., 2018; Fusco Nerini et al., 2018; Gi et al., 2018).</td>
<td>A shift from open-loop to closed-loop cooling technologies could decrease withdrawals, with the trade-off of increasing water consumption for power generation (DeNooy et al., 2016).</td>
</tr>
<tr>
<td>Land &amp; ecosystem transitions</td>
<td>Conservation agriculture</td>
<td>Agro-ecological practices can reduce farm-scale carbon footprint significantly (Rakotovao et al., 2017). Practices such as improved soil conservation practices in coffee agroforestry systems and improved slash and mulch agroforestry in bean-maize cultivation, have low carbon footprint reduction potential (CFRP) and medium carbon sequestration potential (CSP) (Rahn et al., 2014). Land and water management adaptation measures have mitigation co-benefits through soil/atmospheric carbon sequestration, reduced emissions, soil nitrification and reduced use of inorganic fertilisers (Chandra et al., 2016). Conservation agriculture agricultural reduces yields 3–5 years after adoption, but enhances productivity and carbon sequestration over longer periods (Harvey et al., 2014). For conservation agriculture and efficient irrigation, synergies are regionally differentiated: (Lobell et al., 2013).</td>
<td>Technologies enhancing farm productivity (such as adding fertilizers) might improve adaptive capacity through higher incomes but at the same time drive GHG emissions (Harvey et al., 2014; Thornton et al., 2017). In some cases, conservation agriculture practices can increase emissions (Gupta et al., 2016).</td>
</tr>
<tr>
<td>Efficient irrigation</td>
<td>Improving irrigation efficiency</td>
<td>Improving irrigation efficiency have adaptation and mitigation co-benefits (Zou et al., 2012; Adenle et al., 2015; Suckall et al., 2015; Win et al., 2015). Efficient irrigation practices such as drip-irrigation has, on average, 80% lower N₂O emissions than sprinkler systems. Drip-irrigation combined with optimized fertilization reduces direct N₂O emissions up to 50% (Sanz-Cobena et al., 2017). Solar-powered drip irrigation significantly increases household income and</td>
<td>Micro-irrigation technologies such as drip and sprinkler irrigation increase irrigation efficiency but increase energy demand (Rasul and Sharma, 2016). Biomass production for biofuels may contribute to regional water shortages, salinization and water logging (Beringer et al., 2011).</td>
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<tr>
<td><strong>Efficient livestock</strong></td>
<td>Nutritional intake, enable households to meet daily water needs, and save 0.86 tons of carbon emissions each year against a liquid fuel (e.g. kerosene) alternative (Suckall et al., 2015).</td>
<td>Strong synergies between climate change adaptation and mitigation in the livestock sector (Weindl et al., 2015; Rivera-Ferre et al., 2016) but these are differentiated by region and type of livestock system (Locatelli et al., 2015b; Thornton et al., 2017). For example, shifting from grazing to mixed livestock systems increase productivity while reducing GHG emissions, by gains in feed and forage productivity through more intensive inputs and management (Rivera-Ferre et al., 2016). Shifting towards mixed crop-livestock systems is a resource- and cost-efficient option (Herrero et al., 2015; Weindl et al., 2015; Thornton et al., 2018). Reducing livestock diseases can improve the productivity of livestock systems and increase their resilience to stresses while reducing the emissions intensity of livestock production (Bartley et al., 2016; FAO &amp; NZAGRC, 2017). Adaptation through livestock supplementation and reducing stocking densities can reduce methane emissions (Locatelli et al., 2015b). Improved grassland management and appropriate stocking density can help to increase soil carbon stocks (Rivera-Ferre et al., 2016; Thornton et al., 2017).</td>
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<tr>
<td><strong>Agroforestry</strong></td>
<td>Sequesters carbon through accumulation in woody biomass and soil (Lasco et al., 2014)</td>
<td>Reduce GHG emission through reduced deforestation and fossil fuel consumption (Lasco et al., 2014) Coupling native forest regeneration in concert with sugarcane bioethanol production can significantly increase carbon storage in the bioenergy production system and preserve biodiversity (Rodrigues et al., 2009; Buckeridge et al., 2012). The use of fertilizer trees can improve soil fertility through nitrogen fixation, by increasing supply of nutrients for crop production (Coulibaly et al., 2017). Integrating crop, livestock and forestry systems – like in Brazil (Gil et al., 2014).</td>
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<td>Increased productivity of livestock systems generally increases overall food production and absolute GHG emissions, albeit at lower emissions per unit of food (Gerber et al., 2013; FAO &amp; NZAGRC, 2017). Shifting to rangeland for feed can strongly increase tropical deforestation (Weindl et al., 2015). Shifting to mixed crop-livestock systems is expected to cause additional GHG emissions (Weindl et al., 2015). Providing cooling and ventilation systems for livestock (as an adaptation to higher temperatures) can increase GHG emissions (Locatelli et al., 2015b). Some adaptation options such as inter-regional livestock trading can increase CO₂ emissions through transportation (Rivera-Ferre et al., 2016).</td>
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<td></td>
<td>Lower carbon sequestration potential compared with natural forest and secondary forest (Lasco et al., 2014)</td>
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<td>Topic</td>
<td>Description</td>
<td>Reference(s)</td>
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</tr>
<tr>
<td>Food loss &amp; waste management</td>
<td>Waste materials can be transformed into products with marketable value (Papargyropoulou et al., 2014), improving economic gain and stimulating decrease of food waste and loss.</td>
<td>NA</td>
<td></td>
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<tr>
<td>Community-based adaptation</td>
<td>NE – Most literature addresses synergies with sustainable development, poverty and equity</td>
<td>NE - Most literature addresses trade-offs with sustainable development, poverty and equity</td>
<td></td>
</tr>
<tr>
<td>Ecosystem restoration &amp; avoided deforestation</td>
<td>Tropical reforestation as an adaptation measure can also result in significant carbon storage under climate-smart strategies (Locatelli et al., 2015a).</td>
<td>Failure to consider mitigation in adaptation initiatives may lead to adaptation measures that increase greenhouse gas emissions, which is one type of maladaptation. (Porter and Xie, 2014; Kongsager et al., 2016)</td>
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<tr>
<td>Biodiversity management</td>
<td>Biodiversity has value in terms of ecosystem services as well protection/defence against invading species and disease organisms. Maintaining for high levels of biodiversity also recognises the fact that many species, biological processes and molecules in nature are as yet unexplored yet have potential to provide enormous benefits to human beings (Knowlton et al., 2010; Pereira et al., 2010; Onaindia et al., 2013; Pistorious and Kiff, 2017; Price et al., 2018).</td>
<td>Areas with greatest potential for protecting biodiversity may not overlap with areas with most potential for carbon sequestration (Essi and Mauerhofer 2018; Phelps et al., 2012).</td>
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<tr>
<td>Coastal defense &amp; hardening</td>
<td>NE</td>
<td>An alternative strategy is not to ‘defend’ using harden structures along coastlines, but rather to retreat as sea levels rise and storm surge goes further inland. The strategy of ‘retreat’ tends to make economic sense while at the same time accommodating the transition from terrestrial to marine systems (e.g. migration of salt marsh, mangroves and seagrass towards the land as sea levels rise (Brown et al., 2016a; Mills et al., 2016). There has been an increasing focus on natural barriers to storm surge and erosion, such as mangroves, oyster banks, coral reefs and seagrass meadows. Within these broad options, there are trade-offs that involve direct human intervention (e.g. coastal hardening, seawalls and artificial reefs) (Rinkevich, 2014, 2015; André et al., 2016; Cooper et al., 2016; Narayan et al., 2016), while there are others that exploit the opportunities for increasing coastal protection by involving a naturally occurring oyster banks, coral reefs, mangroves, seagrass, and other ecosystems (UNEP-WCMC, 2006; Scyphers et al., 2006).</td>
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<td>Category</td>
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<tr>
<td>Sustainable aquaculture</td>
<td>NE</td>
<td>Protection using materials such as concrete to provide a barrier against the ocean. These structures can be installed quickly but the trade-off is that they have a range of negative consequences such as being expensive, interrupting natural ecosystems (Mills et al., 2016; Wernberg et al., 2016), being ultimately short-term solutions to the long-term problem of sea level rise and intensifying storm systems (Brooke et al., 1992; Wescott, 2010; Mills et al., 2016).</td>
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<tr>
<td>Fisheries restoration</td>
<td>Development of more sustainable practices also has benefits for ocean ecosystems in general. Fish play a crucial role in everything from maintaining ecological balances through their feeding habits to playing important roles within nutrient cycles in a range of habitats (Holmlund and Hammer, 1999).</td>
<td>Regulating and avoiding next loss of coastal ecosystems such as mangroves and seagrass, while the same time as developing food materials that have much lower impact on the environment (Schlag, 2010; Asiedu et al., 2017b, 2017a).</td>
<td></td>
</tr>
<tr>
<td>Coastal &amp; marine biodiversity management</td>
<td>NE</td>
<td>Planning for multiple objectives (e.g. biodiversity protection and carbon sequestration) increases the complexity of planning processes and data needs, an accompanying increase in technical capacity by planners (Reside et al., 2018).</td>
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</tr>
<tr>
<td>Integrated coastal zone management</td>
<td>Mangroves serve as sinks for carbon, through accumulation of living biomass and through litter and dead wood deposition, including the trapping of sediments delivered from the uplands (Romañach et al., 2018).</td>
<td>NE</td>
<td></td>
</tr>
<tr>
<td>Urban &amp; infrastructure system transitions</td>
<td>Potential for synergies in urban planning at policy, organizational, and practical levels e.g. urban regeneration or retrofitting policies, urban greening (Landauer et al., 2015; Ürge-Vorsatz et al., 2018), including generating a shared sense of risks and promotion of local participation (Archer et al., 2014; Kettle et al., 2014; Campos et al., 2016; Siders, 2017)). Urban planning can enhance adaptation, mitigation, and sustainable development (Hurlimann and March, 2012; Davidse et al., 2015; King et al., 2016; Francesch-Huidobro et al., 2017). Land use management for co-benefits can result in carbon sequestration (Duguma et al., 2014; Woolf et al., 2018).</td>
<td>Promotion of green spaces to reduce flood risk and heat island effects may reduce potential for the promotion of urban densification (Landauer et al., 2015; Di Gregorio et al., 2017b; Endo et al., 2017; Ürge-Vorsatz et al., 2018).</td>
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</table>
| Sustainable land-use & urban planning                                  | Strong co-benefits to the implementation of demand-side management | Increasing water quality is linked to increasing energy use in the...
<table>
<thead>
<tr>
<th>Chapter 4 Supplementary Material</th>
<th>Final Government Draft</th>
<th>IPCC SR1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water management</strong></td>
<td>measures, such as reducing leakages and water loss (Wang et al., 2011; Deng and Zhao, 2015), while minimizing the need to address the environmental and energy implications of supply measures such as desalination (Miller et al., 2015)</td>
<td>water sector (Rothausen and Conway, 2011; Mamais et al., 2015),</td>
</tr>
<tr>
<td><strong>Green infrastructure &amp; ecosystem services</strong></td>
<td>Urban canopy is a cooling mechanism that can help decrease heat and water stress (Hines, 2017)</td>
<td>Not considering the role green cover and vegetation has within the heat-water-vegetation nexus can worsen heat and water stress (Hines, 2017),</td>
</tr>
<tr>
<td><strong>Building codes &amp; standards</strong></td>
<td>Sustainable construction materials, reduced building energy consumption, and construction designed to reduce the urban heat island effect can have adaptation and mitigation benefits (Stehnorf and Sparling, 2011; Aerts et al., 2014; Stewart, 2015; Shapiro, 2016; Ürge-Vorsatz et al., 2018)</td>
<td>NE</td>
</tr>
<tr>
<td><strong>Industrial system transitions</strong></td>
<td>Intensive industry infrastructure resilience and water management</td>
<td>NE</td>
</tr>
<tr>
<td><strong>Overarching adaptation options</strong></td>
<td>Incorporating environmental considerations into recovery decision-making (Amin Hosseini et al., 2016), implementing disaster risk management plans and increasing ex-ante resilience to disasters are important to reduce the extent of rebuilding following disasters, and the emissions associated with recovery. Post-disaster recovery can help rebuild in a more resilient way with less GHG emissions, or to “build back better”, particularly where immediate impact is substantial but not overwhelming (Guarnacci, 2012; Mochizuki and Chang, 2017). Effective disaster risk management may reduce the need for international transport of materials and other forms of aid, which can be emissions-intensive (Abrahams, 2014).</td>
<td>The urgency of recovery and the surge in demand for construction materials have been observed to promote unsustainable behaviours, including deforestation (Nazara and Resosudarmo, 2007; Chang et al., 2010) or uncontrolled extraction of sand and gravel (Abrahams, 2014). ‘Building back better’ requires capacity, time, and mechanisms for balancing competing desires and perspectives that are not necessarily available after severe disasters, and may be challenged by both local and external influences in the rebuilding process (Abrahams, 2014; O’Hare et al., 2016; Paidakaki and Moulaoert, 2017).</td>
</tr>
<tr>
<td><strong>Risk spreading and sharing</strong></td>
<td>In response to the substantial risk posed to the insurance industry by climate change (Bank of England, 2015; Glaaas et al., 2017), insurance companies are mobilizing their role as investment manager to promote climate mitigation; for example, in 2014, insurance companies pledged to invest USD 420 billion over five years in renewable energy, energy efficiency, and sustainable agriculture projects (Fabian, 2015; Webster and Clarke, 2017).</td>
<td>Agricultural insurance may have unintended impacts, promoting the intensification of land use in some cases (Annan and Schlenker, 2015; Müller and Kreuer, 2016; Müller et al., 2017).</td>
</tr>
<tr>
<td><strong>Climate</strong></td>
<td>Climate services aid adaptation decision-making and can help mitigate GHGs</td>
<td>NE</td>
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services

through improving farm practices (e.g. matching fertilizer use with existing weather conditions so that less GHGs are emitted) (Thornton et al., 2017).

Indigenous knowledge

Revitalization of traditional management of agriculture may simultaneously increase resilience, improve biodiversity, and reduce emissions by eliminating agrochemical inputs production to food production (Nyong et al., 2007; Niggli et al., 2009; Altieri and Nicholls, 2017).

Recognizing and supporting Indigenous management of blue carbon habitats (Vierros, 2017) and grasslands (Dong, 2017; Russell-Smith et al., 2017), and utilizing new technologies to revitalize traditional forms of energy provision (Thornton and Comberti, 2017), can provide mitigation and adaptation benefits.

Population health and health system

Forest retention and urban agricultural land are forms of urban green infrastructure that can simultaneously mediate floods, promote healthy lifestyles, and reduce emissions and air pollution. (Nowak et al., 2006; Tallis et al., 2011; Elmqvist et al., 2013a; Buckeridge, 2015; Culwick and Bobbins, 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; White et al., 2017b)

The use of air conditioners to meet health standards could result in increased emissions (Ürge-Vorsatz et al., 2018).

Social safety nets

Public work programmes structured to address climate risks, for instance, Ethiopia’s Productive Safety Net Programme has been used to employ locals suffering from food insecurity to work on water-shed management interventions, sequestering carbon in the soil and reducing greenhouse gas emissions (Jirka et al., 2015).

Where cash transfers to households to build adaptive capacity are not conditional, limited increases in purchasing power can prompt families to invest in additional consumption, transport, or agricultural equipment as part of a general risk reduction strategy (Lemos et al., 2016; Nelson et al., 2016); Aggregated, these individual investments could lead to increased emissions.
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**Chapter 4 Supplementary Material**

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**IPCC SR1.5**

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Chapter 5: Sustainable Development, Poverty Eradication and Reducing Inequalities

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**Date of Draft:** 23 May 2018

**Notes:** TSU Compiled Version
Where reference is made to Table 5.3, this is available as a supplementary pdf (file Chapter 5 – Table 5.3)
Executive Summary ........................................................................................................................................ 4

5.1 Scope and Delineations .......................................................................................................................... 8
  5.1.1 Sustainable Development, SDGs, Poverty Eradication and Reducing Inequalities ......................... 8
  5.1.2 Pathways to 1.5°C ............................................................................................................................ 9
  5.1.3 Types of evidence ............................................................................................................................. 10

5.2 Poverty, Equality, and Equity Implications of a 1.5°C Warmer World ............................................. 10
  5.2.1 Impacts and Risks of a 1.5°C Warmer World: Implications for Poverty and Livelihoods 10
  5.2.2 Avoided Impacts of 1.5°C versus 2°C Warming for Poverty and Inequality ......................... 11
  5.2.3 Risks from 1.5°C versus 2°C Global Warming and the Sustainable Development Goals .12

Cross-Chapter Box 12: Residual risks, limits to adaptation and loss and damage .......... 13

5.3 Climate Adaptation and Sustainable Development .......................................................................... 16
  5.3.1 Sustainable Development in Support of Climate Adaptation ....................................................... 16
  5.3.2 Synergies and Trade-offs between Adaptation Options and Sustainable Development . 17
  5.3.3 Adaptation Pathways toward a 1.5°C Warmer World and Implications for Inequalities 19

Box 5.1: Ecosystem- and Community-based Practices in Drylands ..................................................... 20

5.4 Mitigation and Sustainable Development .......................................................................................... 21
  5.4.1 Synergies and Trade-offs between Mitigation Options and Sustainable Development.... 21
    5.4.1.1 Energy Demand: Mitigation Options to Accelerate Reduction in Energy Use and Fuel Switch .21
    5.4.1.2 Energy Supply: Accelerated Decarbonisation ......................................................................23

Box 5.2: Challenges and Opportunities of Low-Carbon Pathways in Gulf Cooperative Council (GCC) Countries ................................................................. 24
        5.4.1.3 Land-based Agriculture, Forestry and Ocean: Mitigation Response Options and Carbon Dioxide Removal 25

4.2 Sustainable Development Implications of 1.5°C and 2°C Mitigation Pathways ................. 26
  5.4.2.1 Air Pollution and Health ............................................................................................................. 27
  5.4.2.2 Food Security and Hunger ......................................................................................................... 27
  5.4.2.3 Lack of Energy Access/Energy Poverty ....................................................................................... 28
  5.4.2.4 Water Security ........................................................................................................................... 28

5.5 Sustainable Development Pathways to 1.5°C ................................................................................. 31
  5.5.1 Integration of Adaptation, Mitigation, and Sustainable Development ................................. 31
  5.5.2 Pathways for Adaptation, Mitigation, and Sustainable Development ............................... 32
  5.5.3 Climate-Resilient Development Pathways ................................................................................. 33
    5.5.3.1 Transformations, Equity, and Well-being ............................................................................... 34
    5.5.3.2 Development Trajectories, Sharing of Efforts, and Cooperation ............................................ 35
    5.5.3.3 Country and Community Strategies and Experiences ............................................................. 36

Box 5.3: Republic of Vanuatu – National Planning for Development and Climate Resilience . 37

Cross-Chapter Box 13: Cities and Urban Transformation ................................................................. 39

Do Not Cite, Quote or Distribute 5-2 Total pages: 77
5.6 Conditions for Achieving Sustainable Development, Eradicating Poverty and Reducing Inequalities in 1.5°C Warmer Worlds .......................................................... 41
   5.6.1 Finance and Technology Aligned with Local Needs ............................................. 41
   5.6.2 Integration of Institutions .................................................................................. 42
   5.6.3 Inclusive Processes ......................................................................................... 42
   5.6.4 Attention to Issues of Power and Inequality ......................................................... 43
   5.6.5 Reconsidering Values ....................................................................................... 43

5.7 Synthesis and Research Gaps .............................................................................. 43

Frequently Asked Questions ...................................................................................... 45

References .................................................................................................................. 49
Executive Summary

This chapter takes sustainable development as the starting point and focus for analysis. It considers the broad and multifaceted bi-directional interplay between sustainable development, including its focus on eradicating poverty and reducing inequality in their multidimensional aspects, and climate actions in a 1.5°C warmer world. These fundamental connections are embedded in the Sustainable Development Goals (SDGs). The chapter also examines synergies and trade-offs of adaptation and mitigation options with sustainable development and the SDGs and offers insights into possible pathways, especially climate-resilient development pathways toward a 1.5°C warmer world.

Sustainable Development, Poverty, and Inequality in a 1.5°C Warmer World

Limiting global warming to 1.5°C rather than 2°C would make it markedly easier to achieve many aspects of sustainable development, with greater potential to eradicate poverty and reduce inequalities (medium evidence, high agreement). Impacts avoided with the lower temperature limit could reduce the number of people exposed to climate risks and vulnerable to poverty by 62 to 457 million, and lessen the risks of poor people to experience food and water insecurity, adverse health impacts, and economic losses, particularly in regions that already face development challenges (medium evidence, medium agreement) {5.2.2, 5.2.3}. Avoided impacts between 1.5°C and 2°C warming would also make it easier to achieve certain SDGs, such as those that relate to poverty, hunger, health, water and sanitation, cities, and ecosystems (SDGs 1, 2, 3, 6, 12, 14, and 15) (medium evidence, high agreement) {5.2.3, Table 5.3 available as a supplementary pdf}.

Compared to current conditions, 1.5°C of global warming would nonetheless pose heightened risks to eradicating poverty, reducing inequalities and ensuring human and ecosystem well-being (medium evidence, high agreement). Warming of 1.5°C is not considered ‘safe’ for most nations, communities, ecosystems and sectors and poses significant risks to natural and human systems as compared to current warming of 1°C (high confidence) {Cross-Chapter Box 12 in Chapter 5}. The impacts of 1.5°C would disproportionately affect disadvantaged and vulnerable populations through food insecurity, higher food prices, income losses, lost livelihood opportunities, adverse health impacts, and population displacements (medium evidence, high agreement) {5.2.1}. Some of the worst impacts on sustainable development are expected to be felt among agricultural and coastal dependent livelihoods, indigenous people, children and the elderly, poor labourers, poor urban dwellers in African cities, and people and ecosystems in the Arctic and Small Island Developing States (SIDS) (medium evidence, high agreement) {5.2.1 Box 5.3, Chapter 3 Box 3.5, Cross-Chapter Box 9 in Chapter 4}.

Climate Adaptation and Sustainable Development

Prioritisation of sustainable development and meeting the SDGs is consistent with efforts to adapt to climate change (high confidence). Many strategies for sustainable development enable transformational adaptation for a 1.5°C warmer world, provided attention is paid to reducing poverty in all its forms and to promoting equity and participation in decision-making (medium evidence, high agreement). As such, sustainable development has the potential to significantly reduce systemic vulnerability, enhance adaptive capacity, and promote livelihood security for poor and disadvantaged populations (high confidence) {5.3.1}.

Synergies between adaptation strategies and the SDGs are expected to hold true in a 1.5°C warmer world, across sectors and contexts (medium evidence, medium agreement). Synergies between adaptation and sustainable development are significant for agriculture and health, advancing SDGs 1 (extreme poverty), 2 (hunger), 3 (healthy lives and well-being), and 6 (clean water) (robust evidence, medium agreement) {5.3.2}. Ecosystem- and community-based adaptation, along with the incorporation of indigenous and local knowledge, advances synergies with SDGs 5 (gender equality), 10 (reducing inequalities), and 16 (inclusive societies), as exemplified in drylands and the Arctic (high evidence, medium agreement) {5.3.2, Box 5.1, Cross-Chapter Box 10 in Chapter 4}.
Adaptation strategies can result in trade-offs with and among the SDGs (medium evidence, high agreement). Strategies that advance one SDG may create negative consequences for other SDGs, for instance SDGs 3 versus 7 (health and energy consumption) and agricultural adaptation and SDG 2 (food security) versus SDGs 3, 5, 6, 10, 14, and 15 (medium evidence, medium agreement) {5.3.2}.

Pursuing place-specific adaptation pathways toward a 1.5°C warmer world has the potential for significant positive outcomes for well-being, in countries at all levels of development (medium evidence, high agreement). Positive outcomes emerge when adaptation pathways (i) ensure a diversity of adaptation options based on people’s values and trade-offs they consider acceptable, (ii) maximise synergies with sustainable development through inclusive, participatory, and deliberative processes, and (iii) facilitate equitable transformation. Yet, such pathways would be difficult to achieve without redistributive measures to overcome path dependencies, uneven power structures, and entrenched social inequalities (medium evidence, high agreement) {5.3.3}.

Mitigation and Sustainable Development

The deployment of mitigation options consistent with 1.5°C pathways leads to multiple synergies across a range of sustainable development dimensions. At the same time, the rapid pace and magnitude of change that would be required to limit warming to 1.5°C, if not carefully managed, would lead to trade-offs with some sustainable development dimensions (high confidence). The number of synergies between mitigation response options and sustainable development exceeds the number of trade-offs in energy demand and supply sectors, Agriculture, Forestry and Other Land Use (AFOLU) and for oceans (very high confidence) {Figure 5.3, Table 5.3 available as a supplementary pdf}. 1.5°C pathways indicate robust synergies particularly for the SDGs 3 (health), 7 (energy), 12 (responsible consumption and production), and 14 (oceans) (very high confidence) {5.4.2, Figure 5.4}. For SDGs 1 (poverty), 2 (hunger), 6 (water), and 7 (energy), there is a risk of trade-offs or negative side-effects from stringent mitigation actions compatible with 1.5°C (medium evidence, high agreement) {5.4.2}.

Appropriately designed mitigation actions to reduce energy demand can advance multiple SDGs simultaneously. Pathways compatible with 1.5°C that feature low energy demand show the most pronounced synergies and the lowest number of trade-offs with respect to sustainable development and the SDGs (very high confidence). Accelerating energy efficiency in all sectors has synergies with SDG 7, 9, 11, 12, 16, 17 {5.4.1, Figure 5.3, Table 5.2} (robust evidence, high agreement). Low demand pathways, which would reduce or completely avoid the reliance on Bioenergy with Carbon Capture and Storage (BECCS) in 1.5°C pathways, would result in significantly reduced pressure on food security, lower food prices, and fewer people at risk of hunger (medium evidence, high agreement) {5.4.2, Figure 5.4}.

The impacts of Carbon Dioxide Removal (CDR) options on SDGs depend on the type of options and the scale of deployment (high confidence). If poorly implemented, CDR options such as bioenergy, BECCS and AFOLU would lead to trade-offs. Appropriate design and implementation requires considering local people’s needs, biodiversity, and other sustainable development dimensions (very high confidence) {5.4.1.3, Cross-Chapter Box 7 in Chapter 3}.

The design of the mitigation portfolios and policy instruments to limit warming to 1.5°C will largely determine the overall synergies and trade-offs between mitigation and sustainable development (very high confidence). Redistributive policies that shield the poor and vulnerable can resolve trade-offs for a range of SDGs (medium evidence, high agreement). Individual mitigation options are associated with both positive and negative interactions with the SDGs (very high confidence) {5.4.1}. However, appropriate choices across the mitigation portfolio can help to maximize positive side-effects while minimizing negative side-effects (high confidence) {5.4.2, 5.5.2}. Investment needs for complementary policies resolving trade-offs with a range of SDGs are only a small fraction of the overall mitigation investments in 1.5°C pathways (medium evidence, high agreement) {5.4.2, Figure 5.5}. Integration of mitigation with adaptation and sustainable development compatible with 1.5°C requires a systems
Mitigation measures consistent with 1.5°C create high risks for sustainable development in countries with high dependency on fossil fuels for revenue and employment generation (high confidence). These risks are caused by the reduction of global demand affecting mining activity and export revenues and challenges to rapidly decrease high carbon intensity of the domestic economy (robust evidence, high agreement) {5.4.1.2, Box 5.2}. Targeted policies that promote diversification of the economy and the energy sector could ease this transition (medium evidence, high agreement) {5.4.1.2, Box 5.2}.

Sustainable Development Pathways to 1.5°C

Sustainable development broadly supports and often enables the fundamental societal and systems transformations that would be required for limiting warming to 1.5°C (high confidence). Simulated pathways that feature the most sustainable worlds (e.g., Shared Socioeconomic Pathways (SSP)1) are associated with relatively lower mitigation and adaptation challenges and limit warming to 1.5°C at comparatively lower mitigation costs. In contrast, development pathways with high fragmentation, inequality and poverty (e.g., SSP3) are associated with comparatively higher mitigation and adaptation challenges. In such pathways, it is not possible to limit warming to 1.5°C for the vast majority of the integrated assessment models (medium evidence, high agreement) {5.5.2}. In all SSPs, mitigation costs substantially increase in 1.5°C pathways compared to 2°C pathways. No pathway in the literature integrates or achieves all 17 SDGs (high confidence) {5.5.2}. Real-world experiences at the project level show that the actual integration between adaptation, mitigation, and sustainable development is challenging as it requires reconciling trade-offs across sectors and spatial scales (very high confidence) {5.5.1}.

Without societal transformation and rapid implementation of ambitious greenhouse gas reduction measures, pathways to limiting warming to 1.5°C and achieving sustainable development will be exceedingly difficult, if not impossible, to achieve (high confidence). The potential for pursuing such pathways differs between and within nations and regions, due to different development trajectories, opportunities, and challenges (very high confidence) {5.5.3.2, Figure 5.1}. Limiting warming to 1.5°C would require all countries and non-state actors to strengthen their contributions without delay. This could be achieved through sharing of efforts based on bolder and more committed cooperation, with support for those with the least capacity to adapt, mitigate, and transform (medium evidence, high agreement) {5.5.3.1, 5.5.3.2}. Current efforts toward reconciling low-carbon trajectories and reducing inequalities, including those that avoid difficult trade-offs associated with transformation, are partially successful yet demonstrate notable obstacles (medium evidence, medium agreement) {5.5.3.3 Box 5.3, Cross-Chapter Box 13 in this Chapter).

Social justice and equity are core aspects of climate-resilient development pathways for transformational social change. Addressing challenges and widening opportunities between and within countries and communities would be necessary to achieve sustainable development and limit warming to 1.5°C, without making the poor and disadvantaged worse off (high confidence). Identifying and navigating inclusive and socially acceptable pathways toward low-carbon, climate-resilient futures is a challenging yet important endeavour, fraught with moral, practical, and political difficulties and inevitable trade-offs (very high confidence) {5.5.2, 5.5.3.3 Box 5.3}. It entails deliberation and problem-solving processes to negotiate societal values, well-being, risks, and resilience and determine what is desirable and fair, and to whom (medium evidence, high agreement). Pathways that encompass joint, iterative planning and transformative visions, for instance in Pacific SIDS like Vanuatu and in urban contexts, show potential for liveable and sustainable futures (high confidence) {5.5.3.1, 5.5.3.3, Figure 5.6, Box 5.3, Cross-Chapter Box 13 in this Chapter}.

The fundamental societal and systemic changes to achieve sustainable development, eradicate poverty and reduce inequalities while limiting warming to 1.5°C would require a set of institutional, social, cultural, economic and technological conditions to be met (high confidence). The coordination and monitoring of policy actions across sectors and spatial scales is essential to support sustainable development...
in 1.5°C warmer conditions (very high confidence) {5.6.2, Box 5.3}. External funding and technology transfer better support these efforts when they consider recipients’ context-specific needs (medium evidence, high agreement) {5.6.1}. Inclusive processes can facilitate transformations by ensuring participation, transparency, capacity building, and iterative social learning (high confidence) {5.5.3.3, Cross-Chapter Box 13, 5.6.3}. Attention to power asymmetries and unequal opportunities for development, among and within countries is key to adopting 1.5°C-compatible development pathways that benefit all populations (high confidence) {5.5.3, 5.6.4, Box 5.3}. Re-examining individual and collective values could help spur urgent, ambitious, and cooperative change (medium evidence, high agreement) {5.5.3, 5.6.5}. 

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5.1 Scope and Delineations

This chapter takes sustainable development as the starting point and focus for analysis, considering the broader bi-directional interplay and multifaceted interactions between development patterns and climate actions in a 1.5°C warmer world and in the context of eradicating poverty and reducing inequality. It assesses the impacts of keeping temperatures at or below 1.5°C global warming above pre-industrial levels on sustainable development and compares the avoided impacts to 2°C (Section 5.2). It then examines the interactions, synergies and trade-offs of adaptation (Section 5.3) and mitigation (Section 5.4) measures with sustainable development and the Sustainable Development Goals (SDGs). The chapter offers insights into possible pathways toward a 1.5°C warmer world, especially through climate-resilient development pathways providing a comprehensive vision across different contexts (Section 5.5). We also identify the conditions that would be needed to simultaneously achieve sustainable development, poverty eradication, the reduction of inequalities, and the 1.5°C climate objective (Section 5.6).

5.1.1 Sustainable Development, SDGs, Poverty Eradication and Reducing Inequalities

Chapter 1 (see Cross-Chapter Box 4 in Chapter 1) defines sustainable development as ‘development that meets the needs of the present and future generations’ through balancing economic, social and environmental considerations, and then introduces the United Nations (UN) 2030 Agenda for Sustainable Development which sets out 17 ambitious goals for sustainable development for all countries by 2030. These Sustainable Development Goals (SDGs) are: no poverty (SDG 1), zero hunger (SDG 2), good health and well-being (SDG 3), quality education (SDG 4), gender equality (SDG 5), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), industry, innovation and infrastructure (SDG 9), reduced inequalities (SDG 10), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), climate action (SDG 13), life below water (SDG 14), life on land (SDG 15), peace, justice and strong institutions (SDG 16), and partnerships for the goals (SDG 17).

The IPCC Fifth Assessment Report (AR5) included extensive discussion of links between climate and sustainable development, especially in Chapter 13 (Olsson et al., 2014) and Chapter 20 (Denton et al., 2014) in WGII and Chapter 4 (Fleurbaey et al., 2014) in WGIII. However, the AR5 preceded the 2015 adoption of the SDGs and the literature that argues for their fundamental links to climate (Wright et al., 2015; Salleh, 2016; von Stechow et al., 2016; Hammill and Price-Kelly, 2017; ICSU, 2017; Maupin, 2017; Gomez-Echeverri, 2018).

The SDGs build on efforts under the UN Millennium Development Goals to reduce poverty, hunger and other deprivations. According to the UN, the Millennium Development Goals were successful in reducing poverty and hunger and improving water security (UN, 2015a). However, critics argued that they failed to address within-country disparities, human rights, and key environmental concerns, focused only on developing countries, and had numerous measurement and attribution problems (Langford et al., 2013; Fukuda-Parr et al., 2014). While improvements in water security, slums, and health may have reduced some aspects of climate vulnerability, increases in incomes were linked to rising greenhouse gas (GHG) emissions and thus to a trade-off between development and climate change (Janetos et al., 2012; UN, 2015a; Hubacek et al., 2017).

While the SDGs capture many important aspects of sustainable development, including the explicit goals of poverty eradication and reducing inequality, there are direct connections from climate to other measures of sustainable development including multidimensional poverty, equity, ethics, human security, well-being, and climate-resilient development (Bebbington and Larrinaga, 2014; Robertson, 2014; Redlift and Springer, 2015; Barrington-Leigh, 2016; Hellwell et al., 2018; Kirby and O’Mahony, 2018) (see Glossary). The UN proposes sustainable development as ‘eradicating poverty in all its forms and dimensions, combating inequality within and among countries, preserving the planet, creating sustained, inclusive and sustainable economic growth and fostering social inclusion’ (UN, 2015b). There is robust evidence of the links between climate change and poverty (see Chapter 1, Cross-Chapter Box 4). The AR5 concluded with high confidence.
that disruptive levels of climate change would preclude reducing poverty (Denton et al., 2014; Fleurbaey et al., 2014). International organisations have since stated that climate changes ‘undermine the ability of all countries to achieve sustainable development’ (UN, 2015b) and can reverse or erase improvements in living conditions and decades of development (Hallegatte et al., 2016).

Climate warming has unequal impacts on different people and places as a result of differences in regional climate changes, vulnerabilities and impacts, and these differences then result in unequal impacts on sustainable development and poverty (Section 5.2). Responses to climate change also interact in complex ways with goals of poverty reduction. The benefits of adaptation and mitigation projects and funding may accrue to some and not others, responses may be costly and unaffordable to some people and countries, and projects may disadvantage some individuals, groups and development initiatives (Sections 5.3 and 5.4; Cross-Chapter Box 11 in Chapter 4).

5.1.2 Pathways to 1.5°C

Pathways to 1.5°C (see Chapter 1, Cross-Chapter Box 1 in Chapter 1, Glossary) include ambitious reductions in emissions and strategies for adaptation that are transformational, as well as complex interactions with sustainable development, poverty eradication, and reducing inequalities. The AR5 WGII introduced the concept of climate-resilient development pathways (CRDPs) (see Glossary) which combine adaptation and mitigation to reduce climate change and its impacts, and emphasise the importance of addressing structural, intersecting inequalities, marginalisation, and multidimensional poverty to ‘transform […] the development pathways themselves toward greater social and environmental sustainability, equity, resilience, and justice’ (Olsson et al., 2014). This chapter assesses literature on CRDPs relevant to 1.5°C global warming (Section 5.5.3), to understand better the possible societal and systems transformations (see Glossary) that reduce inequality and increase well-being (Figure 5.1). It also summarises the knowledge on conditions to achieve such transformations, including changes in technologies, culture, values, financing, and institutions that support low-carbon and resilient pathways and sustainable development (Section 5.6).

**Figure 5.1:** Climate-resilient development pathways (CRDPs) (green arrows) between a current world in which countries and communities exist at different levels of development (A) and future worlds that range from

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5-9

Total pages: 77
climate-resilient (bottom) to unsustainable (top) (D). CRDPs involve societal transformation rather than business-as-usual approaches, and all pathways involve adaptation and mitigation choices and trade-offs (B). Pathways that achieve the Sustainable Development Goals by 2030 and beyond, strive for net zero emissions around mid-21st century, and stay within the global 1.5°C warming target by the end of the 21st century, while ensuring equity and well-being for all, are best positioned to achieve climate-resilient futures (C). Overshooting on the path to 1.5°C will make achieving CRDPs and other sustainable trajectories more difficult; yet, the limited literature does not allow meaningful estimates.

5.1.3 Types of evidence

We use a variety of sources of evidence to assess the interactions of sustainable development and the SDGs with the causes, impacts, and responses to climate change of 1.5°C warming. We build on Chapter 3 to assess the sustainable development implications of impacts at 1.5°C and 2°C, and Chapter 4 to examine the implications of response measures. We assess scientific and grey literature, with a post-AR5 focus, and data that evaluate, measure, and model sustainable development-climate links from various perspectives, quantitatively and qualitatively, across scales, and through well documented case studies.

Literature that explicitly links 1.5°C global warming to sustainable development across scales remains scarce; yet, we find relevant insights in many recent publications on climate and development that assess impacts across warming levels, the effects of adaptation and mitigation response measures, and interactions with the SDGs. Relevant evidence also stems from emerging literature on possible pathways, overshoot, and enabling conditions (see Glossary) for integrating sustainable development, poverty eradication, and reducing inequalities in the context of 1.5°C.

5.2 Poverty, Equality, and Equity Implications of a 1.5°C Warmer World

Climate change could lead to significant impacts on extreme poverty by 2030 (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017). The AR5 concluded, with very high confidence, that climate change and climate variability worsen existing poverty and exacerbate inequalities, especially for those disadvantaged by gender, age, race, class, caste, indigeneity and (dis)ability (Olsson et al., 2014). New literature on these links is substantial, showing that the poor will continue to experience climate change severely, and climate change will exacerbate poverty (Fankhauser and Stern, 2016; Hallegatte et al., 2016; O’Neill et al., 2017a; Winsemius et al., 2018) (very high confidence). The understanding of regional impacts and risks of 1.5°C global warming and interactions with patterns of societal vulnerability and poverty remains limited. Yet, identifying and addressing poverty and inequality is at the core of staying within a safe and just space for humanity (Raworth, 2017; Bathiany et al., 2018). Building on relevant findings from Chapter 3 (see Section 3.4), this section examines anticipated impacts and risks of 1.5°C and higher warming on sustainable development, poverty, inequality, and equity (see Glossary).

5.2.1 Impacts and Risks of a 1.5°C Warmer World: Implications for Poverty and Livelihoods

Global warming of 1.5°C will have consequences for sustainable development, poverty and inequalities. This includes residual risks, limits to adaptation, and losses and damages (Cross-Chapter Box 12 in this Chapter; see Glossary). Some regions have already experienced a 1.5°C warming with impacts on food and water security, health, and other components of sustainable development (medium evidence, medium agreement) (see Chapter 3, Section 3.4). Climate change is also already affecting poorer subsistence communities through decreases in crop production and quality, increases in crop pests and diseases, and disruption to culture (Savo et al., 2016). It disproportionally affects children and the elderly and can increase gender inequality (Kaijser and Kronsell, 2014; Vinyeta et al., 2015; Carter et al., 2016; Hanna and Oliva, 2016; Li et al., 2016).
At 1.5°C warming, compared to current conditions, further negative consequences are expected for poor people, and inequality and vulnerability (medium evidence, high agreement). Hallegatte and Rozenberg (2017) report that, by 2030 (roughly approximating a 1.5°C warming), 122 million additional people could experience extreme poverty, based on a ‘poverty scenario’ of limited socio-economic progress, comparable to the Shared Socioeconomic Pathway (SSP)4 (inequality), mainly due to higher food prices and declining health, with substantial income losses for the poorest 20% across 92 countries. Pretis et al. (2018) estimate negative impacts on economic growth in lower-income countries at 1.5°C warming, despite uncertainties. Impacts are likely to occur simultaneously across livelihood, food, human, water, and ecosystem security (Byers et al., 2018) (limited evidence, high agreement), but the literature on interacting and cascading effects remains scarce (Hallegatte et al., 2014; O’Neill et al., 2017b; Reyer et al., 2017a, b).

Chapter 3 outlines future impacts and risks for ecosystems and human systems, many of which could also undermine sustainable development and efforts to eradicate poverty and hunger, and protect health and ecosystems. Chapter 3 findings (see Section 3.5.2.1) suggest increasing Reasons for Concern from moderate to high at a warming of 1.1 to 1.6°C, including for indigenous people, their livelihoods, and ecosystems in the Arctic (O’Neill et al., 2017b). In 2050, based on the Hadley Centre Climate Prediction Model 3 (HadCM3) and the Special Report on Emission Scenarios (SRES) A1b scenario (roughly comparable to 1.5°C warming), 450 million more flood-prone people would be exposed to doubling in flood frequency, and global flood risk would increase substantially (Arnell and Gosling, 2016). For droughts, poor people are expected to be more exposed (85% in population terms) in a warming scenario greater >1.5°C for several countries in Asia and Southern and Western Africa (Winsemius et al., 2018). In urban Africa, a 1.5°C warming could expose many households to water poverty and increased flooding (Pelling et al., 2018). At 1.5°C warming, fisheries-dependent and coastal livelihoods, of often disadvantaged populations, would suffer from the loss of coral reefs (see Chapter 3, Box 3.4).

Global heat stress is projected to increase in a 1.5°C warmer world and by 2030, compared to 1961-1990, climate change could be responsible for additional annual deaths of 38,000 people from heat stress, particularly among the elderly, and 48,000 from diarrhoea, 60,000 from malaria, and 95,000 from childhood undernutrition (WHO, 2014). Each 1°C increase could reduce work productivity by 1 to 3% for people working outdoors or without air conditioning, typically the poorer segments of the workforce (Park et al., 2015).

The regional variation in the ‘warming experience at 1.5°C’ (see Chapter 1, Section 1.3.1) is large (see Chapter 3, Section 3.3.2). Declines in crop yields are widely reported for Africa (60% of observations), with serious consequences for subsistence and rain-fed agriculture and food security (Savo et al., 2016). In Bangladesh, by 2050, damages and losses are expected for poor households dependent on freshwater fish stocks due to lack of mobility, limited access to land, and strong reliance on local ecosystems (Dasgupta et al., 2017). Small Island Developing States (SIDS) are expected to experience challenging conditions at 1.5°C warming due to increased risk of internal migration and displacement and limits to adaptation (see Chapter 3, Box 3.5, Cross-Chapter Box 12 in this Chapter). An anticipated decline of marine fisheries of 3 million metric tonnes per degree warming would have serious regional impacts for the Indo-Pacific region and the Arctic (Cheung et al., 2016).

### 5.2.2 Avoided Impacts of 1.5°C versus 2°C Warming for Poverty and Inequality

Avoided impacts between 1.5°C and 2°C warming are expected to have significant positive implications for sustainable development, and reducing poverty and inequality. Using the SSPs (see Chapter 1, Cross-Chapter Box 1 in Chapter 1; Section 5.5.2), Byers et al. (2018) model the number of people exposed to multi-sector climate risks and vulnerable to poverty (income < $10/day), comparing 2°C and 1.5°C; the respective declines are from 86 million to 24 million for SSP1 (sustainability), from 498 million to 286 million for SSP2 (middle of the road), and from 1220 million to 763 million for SSP3 (regional rivalry), which suggests overall 62-457 million less people exposed and vulnerable at 1.5°C warming. Across the SSPs, the largest populations exposed and vulnerable are in South Asia (Byers et al., 2018). The avoided impacts on poverty...
at 1.5°C relative to 2°C are projected to depend at least as much or more on development scenarios than on warming (Wiebe et al., 2015; Hallegratte and Rozenberg, 2017).

Limiting warming to 1.5°C is expected to reduce the people exposed to hunger, water stress, and disease in Africa (Clément, 2009). It is also expected to limit the number of poor people exposed to floods and droughts at higher degrees of warming, especially in African and Asian countries (Winsemius et al., 2018). Challenges for poor populations relating to food and water security, clean energy access, and environmental well-being are projected to be less at 1.5°C, particularly for vulnerable people in Africa and Asia (Byers et al., 2018). The overall projected socio-economic losses compared to present day are less at 1.5°C (8% loss of gross domestic product per capita) compared to 2°C (13%), with lower-income countries projected to experience greater losses, which may increase economic inequality between countries (Pretis et al., 2018).

5.2.3 Risks from 1.5°C versus 2°C Global Warming and the Sustainable Development Goals

The risks that can be avoided by limiting global warming to 1.5°C rather than 2°C have many complex implications for sustainable development (ICSU, 2017; Gomez-Echeverri, 2018). There is high confidence that constraining warming to 1.5°C rather than 2°C would reduce risks for unique and threatened ecosystems, safeguarding the services they provide for livelihoods and sustainable development, and making adaptation much easier (O’Neill et al., 2017b), particularly in Central America, the Amazon, South Africa, and Australia (Schleussner et al., 2016; O’Neill et al., 2017b; Reyers et al., 2017b; Bathiany et al., 2018).

In places that already bear disproportionate economic and social challenges to their sustainable development, people will face lower risks at 1.5°C compared to 2°C. These include North Africa and the Levant (less water scarcity), West Africa (less crop loss), South America and South-East Asia (less intense heat), and many other coastal nations and island states (lower sea-level rise, less coral reef loss) (Schleussner et al., 2016; Betts et al., 2018). The risks for food, water, and ecosystems, particularly in subtropical regions such as Central America, and countries such as South Africa and Australia, are expected to be lower at 1.5°C than at 2°C warming (Schleussner et al., 2016). Less people would be exposed to droughts and heat waves and the associated health impacts in countries such as Australia and India (King et al., 2017; Mishra et al., 2017).

Limiting warming to 1.5°C will make it markedly easier to achieve the SDGs for poverty eradication, water access, safe cities, food security, healthy lives, and inclusive economic growth, and will help to protect terrestrial ecosystems and biodiversity (medium evidence, high agreement) (Table 5.3 (see available as a supplementary pdf)). For example, limiting species loss and expanding climate refugia will make it easier to achieve SDG 15 (see Chapter 3, Section 3.4.3). One indication of how lower temperatures benefit the SDGs is to compare the impacts of Representative Concentration Pathway (RCP)4.5 (lower emissions) and RCP8.5 (higher emissions) on the SDGs (Ansuategi et al., 2015). A low emissions pathway allows for greater success in achieving SDGs for reducing poverty and hunger, providing access to clean energy, reducing inequality, ensuring education for all, and making cities more sustainable. Even at lower emissions, a medium risk of failure exists to meet goals for water and sanitation, and marine and terrestrial ecosystems.

Action on climate change (SDG 13), including slowing the rate of warming, would help reach the goals for water, energy, food, and land (SDGs 6, 7, 2, and 15) (Obersteiner et al., 2016; ICSU, 2017) and contribute to poverty eradication (SDG 1) (Byers et al., 2018). Although the literature that connects 1.5°C to the SDGs is limited, stabilising warming at 1.5°C by the end of the century is expected to increase the chances of achieving the SDGs by 2030, with greater potentials to eradicate poverty, reduce inequality, and foster equity (limited evidence, medium agreement). There are no studies on overshoot and dimensions of sustainable development, although literature on 4°C suggests the impacts would be severe (Reyer et al., 2017b).
Table 5.1: Sustainable development implications of avoided impacts between 1.5°C and 2°C global warming

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Chapter 3 section</th>
<th>1.5°C</th>
<th>2°C</th>
<th>Sustainable development goals (SDGs) more easily achieved when limiting warming to 1.5°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water scarcity</td>
<td>3.4.2.1 Table 3.4</td>
<td>4% more people exposed to water stress with 184-270 million people more exposed</td>
<td>8% more people exposed to water stress with 386-552 million people more exposed</td>
<td>SDG 6 water availability for all</td>
</tr>
<tr>
<td>Ecosystems</td>
<td>3.4.3 Box 3.5</td>
<td>Around 7% of land area experiences biome shifts</td>
<td>Around 13% (range 8-20%) of land area experiences biome shifts</td>
<td>SDG 15 to protect terrestrial ecosystems and halt biodiversity loss</td>
</tr>
<tr>
<td>Coastal cities</td>
<td>3.4.5.1 Box 3.5</td>
<td>31-69 million people exposed to coastal flooding</td>
<td>32-79 million exposed to coastal flooding</td>
<td>SDG 11 to make cities and human settlements safe and resilient</td>
</tr>
<tr>
<td>Food systems</td>
<td>3.4.6 and Box 3.1</td>
<td>Significant declines in crop yields avoided, some yields may increase</td>
<td>SDG 2 to end hunger and achieve food security</td>
<td></td>
</tr>
<tr>
<td>Health</td>
<td>3.4.7 Table 3.4</td>
<td>Lower risk of temperature related morbidity and smaller mosquito range</td>
<td>Higher risks of temperature related morbidity and mortality and larger range of mosquitoes</td>
<td>SDG 3 to ensure healthy lives for all</td>
</tr>
</tbody>
</table>

[INSERT CROSS-CHAPTER BOX 12 HERE]

Cross-Chapter Box 12: Residual risks, limits to adaptation and loss and damage

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Introduction
Residual climate-related risks, limits to adaptation, and loss and damage (see Glossary) are increasingly assessed in the scientific literature (van der Geest and Warner, 2015; Boyd et al., 2017; Mechler et al., 2018). The AR5 (IPCC, 2013; Oppenheimer et al., 2014) documented impacts that have been detected and attributed to climate change, projected increasing climate-related risks with continued global warming, and recognised barriers and limits to adaptation. It recognised that adaptation is constrained by biophysical, institutional, financial, social, and cultural factors, and that the interaction of these factors with climate change can lead to soft adaptation limits (adaptive actions currently not available) and hard adaptation limits (adaptive actions appear infeasible leading to unavoidable impacts) (Klein et al., 2014).

Loss and damage - concepts and perspectives
“Loss and Damage” (L&D) has been discussed in international climate negotiations for three decades (INC,
A work programme on L&D was established as part of the Cancun Adaptation Framework in 2010 supporting developing countries particularly vulnerable to climate change impacts (UNFCCC, 2010). Conference of the Parties (COP) 19 in 2013 established the Warsaw International Mechanism for Loss and Damage (WIM) as a formal part of the United Nations Framework Convention on Climate Change (UNFCCC) architecture (UNFCCC, 2013). It acknowledges that L&D “includes, and in some cases involves more than, that which can be reduced by adaptation” (UNFCCC, 2013). The Paris Agreement recognised “the importance of averting, minimising and addressing loss and damage associated with the adverse effects of climate change” through Article 8 (UNFCCC, 2015).

There is no one definition of L&D in climate policy, and analysis of policy documents and stakeholder views has demonstrated ambiguity (Vanhala and Hestbaek, 2016; Boyd et al., 2017). UNFCCC documents suggest that L&D is associated with adverse impacts of climate change on human and natural systems, including impacts from extreme events and slow-onset processes (UNFCCC, 2011, 2013, 2015). Some documents focus on impacts in developing or particularly vulnerable countries (UNFCCC, 2011, 2013). They refer to economic (loss of assets and crops) and non-economic (biodiversity, culture, health) impacts, the latter also being an action area under the WIM workplan, and irreversible and permanent loss and damage. Lack of clarity of what the term addresses (avoidance through adaptation and mitigation, unavoidable losses, climate risk management, existential risk) was expressed among stakeholders, with further disagreement ensuing about what constitutes anthropogenic climate change versus natural climate variability (Boyd et al., 2017).

**Limits to adaptation and residual risks**

The AR5 described adaptation limits as points beyond which actors’ objectives are compromised by intolerable risks threatening key objectives such as good health or broad levels of well-being, thus requiring transformative adaptation for overcoming soft limits (Dow et al., 2013; Klein et al., 2014) (see Chapter 4, Sections 4.2.2.3 and 4.5.3; Cross-Chapter Box 9 in Chapter 4; Section 5.3.1). The AR5 WGII risk tables, based on expert judgment, depicted the potential for, and the limits of, additional adaptation to reduce risk. Near-term (2030-2040) risks can be used as a proxy for 1.5°C warming by the end of the century, and compared to longer-term (2080-2100) risks associated with an approximate 2°C warming. Building on the AR5 risk approach, Figure 5.2 provides a stylised application example to poverty and inequality.

![Stylised reduced risk levels due to avoided impacts between 2°C and 1.5°C warming (in solid red-orange), additional avoided impacts with adaptation under 2°C (striped orange) and under 1.5°C (striped yellow), and unavoidable impacts (losses) with no or very limited potential for adaptation (grey), extracted from the AR5 WGII risk tables (Field et al., 2014), and underlying chapters by Adger et al. (2014) and Olsson et al. (2014). For some systems and sectors (A), achieving 1.5°C could reduce risks to low (with adaptation) from very high (without adaptation) and high (with adaptation) under 2°C. For other areas (C), no or very limited adaptation potential is anticipated, suggesting limits, with the same risks for 1.5°C and 2°C. Other risks are projected to be medium under 2°C with further potential for reduction, especially with adaptation, to very low levels (B).](image-url)

**Figure 5.2:** Stylised reduced risk levels due to avoided impacts between 2°C and 1.5°C warming (in solid red-orange), additional avoided impacts with adaptation under 2°C (striped orange) and under 1.5°C (striped yellow), and unavoidable impacts (losses) with no or very limited potential for adaptation (grey), extracted from the AR5 WGII risk tables (Field et al., 2014), and underlying chapters by Adger et al. (2014) and Olsson et al. (2014). For some systems and sectors (A), achieving 1.5°C could reduce risks to low (with adaptation) from very high (without adaptation) and high (with adaptation) under 2°C. For other areas (C), no or very limited adaptation potential is anticipated, suggesting limits, with the same risks for 1.5°C and 2°C. Other risks are projected to be medium under 2°C with further potential for reduction, especially with adaptation, to very low levels (B).
Limits to adaptation, residual risks, and losses in a 1.5°C warmer world

The literature on risks at 1.5°C (versus 2°C and more) and potentials for adaptation remains limited, particularly for specific regions, sectors, and vulnerable and disadvantaged populations. Adaptation potential at 1.5°C and 2°C is rarely assessed explicitly, making an assessment of residual risk challenging. Substantial progress has been made since the AR5 to assess which climate change impacts on natural and human systems can be attributed to anthropogenic emissions (Hansen and Stone, 2016) and to examine the influence of anthropogenic emissions on extreme weather events (NASEM, 2016), and on consequent impacts on human life (Mitchell et al., 2016), but less so on monetary losses and risks (Schaller et al., 2016). There has also been some limited research to examine local-level limits to adaptation (Warner and Geest, 2013; Filho and Nalau, 2018). What constitutes losses and damages is context-dependent and often requires place-based research into what people value and consider worth protecting (Barnett et al., 2016; Tschakert et al., 2017). Yet, assessments of non-material and intangible losses are particularly challenging, such as loss of sense of place, belonging, identity, and damages to emotional and mental wellbeing (Serdeczny et al., 2017; Wewerinke-Singh, 2018a). Warming of 1.5°C is not considered ‘safe’ for most nations, communities, ecosystems, and sectors and poses significant risks to natural and human systems as compared to current warming of 1°C (high confidence) (see Chapter 3, Section 3.4, Box 3.4, Box 3.5, Cross-Chapter Box 6 in Chapter 3). Table 5.2, drawing on findings from Chapters 3, 4 and 5, presents examples of soft and hard limits in natural and human systems in the context of 1.5°C and 2°C of warming.

Table 5.2: Soft and hard adaptation limits in the context of 1.5°C and 2°C of global warming

<table>
<thead>
<tr>
<th>System/Region</th>
<th>Example</th>
<th>Soft Limit</th>
<th>Hard Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coral reefs</td>
<td>Loss of 70-90% of tropical coral reefs by mid-century under 1.5°C scenario (total loss under 2°C scenario) (see Chapter 3, Sections 3.4.4 and 3.5.2.1, Box 3.4)</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Biodiversity</td>
<td>6% of insects, 8% of plants and 4% of vertebrates lose over 50% of the climatically determined geographic range at 1.5°C (18% of insects, 16% of plants, 8% of vertebrates at 2°C) (see Chapter 3, Section 3.4.3.3)</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Poverty</td>
<td>24-357 million people exposed to multi-sector climate risks and vulnerable to poverty at 1.5°C (86-1,220 million at 2°C) (see Section 5.2.2)</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Human health</td>
<td>Twice as many megacities exposed to heat stress at 1.5°C compared to present, potentially exposing 350 million additional people to deadly heat wave conditions by 2050 (see Chapter 3, Section 3.4.8)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Coastal livelihoods</td>
<td>Large-scale changes in oceanic systems (temperature, acidification) inflict damage and losses to livelihoods, income, cultural identity and health for coastal-dependent communities at 1.5°C (potential higher losses at 2°C) (see Chapter 3, Sections 3.4.4, 3.4.5, 3.4.6.3, Box 3.4, Box 3.5, Cross-Chapter Box 6; Chapter 4, Section 4.3.5; Section 5.2.3)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Small Island Developing States</td>
<td>Sea level rise and increased wave run up combined with increased aridity and decreased freshwater availability at 1.5°C warming potentially leaving several atoll islands uninhabitable (see Chapter 3, Sections 3.4.3, 3.4.5, Box 3.5; Chapter 4, Cross-Chapter Box 9)</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

Approaches and policy options to address residual risk and loss and damage

Conceptual and applied work since the AR5 has highlighted the synergies and differences with adaptation and disaster risk reduction policies (van der Geest and Warner, 2015; Thomas and Benjamin, 2017), suggesting more integration of existing mechanisms, yet careful consideration is advised for slow-onset and potentially irreversible impacts and risk (Mechler and Schinko, 2016). Scholarship on justice and equity has
provided insight on compensatory, distributive, and procedural equity considerations for policy and practice to address loss and damage (Rosser et al., 2015; Wallimann-Helmer, 2015; Huggel et al., 2016). A growing body of legal literature considers the role of litigation in preventing and addressing loss and damage and finds that litigation risks for governments and business are bound to increase with improved understanding of impacts and risks as climate science evolves (high confidence) (Mayer, 2016; Banda and Fulton, 2017; Marjanac and Patton, 2018; Wewerinke-Singh, 2018b). Policy proposals include international support for experienced losses and damages (Crosland et al., 2016; Page and Heyward, 2017), addressing climate displacement, donor-supported implementation of regional public insurance systems (Surminski et al., 2016) and new global governance systems under the UNFCCC (Biermann and Boas, 2017).

[END CROSS-CHAPTER BOX 12]

5.3 Climate Adaptation and Sustainable Development

Adaptation will be extremely important in a 1.5°C warmer world since substantial impacts will be felt in every region (high confidence) (Chapter 3, Section 3.3), even if adaptation needs will be lower than in a 2°C warmer world (see Chapter 4, Sections 4.3.1 to 4.3.5, 4.5.3, Cross-Chapter Box 10 in Chapter 4). Climate adaptation options comprise structural, physical, institutional, and social responses, with their effectiveness depending largely on governance (see Glossary), political will, adaptive capacities, and availability of finance (Betzold and Weiler, 2017; Sonwa et al., 2017; Sovacool et al., 2017) (see Chapter 4, Sections 4.4.1 to 4.4.5). Even though the literature is scarce on the expected impacts of future adaptation measures on sustainable development specific to warming experiences of 1.5°C, this section assesses available literature on how (i) prioritising sustainable development enhances or impedes climate adaptation efforts (Section 5.3.1); (ii) climate adaptation measures impact sustainable development and the Sustainable Development Goals (SDGs) in positive (synergies) or negative (trade-offs) ways (Section 5.3.2); and (iii) adaptation pathways towards a 1.5°C warmer world affect sustainable development, poverty, and inequalities (Section 5.3.3). The section builds on Chapter 4 (see Section 4.3.5) regarding available adaptation options to reduce climate vulnerability and build resilience (see Glossary) in the context of 1.5°C-compatible trajectories, here with emphasis on sustainable development implications.

5.3.1 Sustainable Development in Support of Climate Adaptation

Making sustainable development a priority, and meeting the SDGs, is consistent with efforts to adapt to climate change (very high confidence). Sustainable development is effective in building adaptive capacity if it addresses poverty and inequalities, social and economic exclusion, and inadequate institutional capacities (Noble et al., 2014; Abel et al., 2016; Colloff et al., 2017). Four ways in which sustainable development leads to effective adaptation are described below.

Firstly, sustainable development enables transformational adaptation (see Chapter 4, Section 4.2.2.2) when an integrated approach is adopted, with inclusive, transparent decision making, rather than addressing current vulnerabilities as stand-alone climate problems (Mathur et al., 2014; Arthurson and Baum, 2015; Shackleton et al., 2015; Lemos et al., 2016; Antwi-Agyei et al., 2017b). Ending poverty in its multiple dimensions (SDG 1) is often a highly effective form of climate adaptation (Fankhauser and McDermott, 2014; Leichenko and Silva, 2014; Hallegratte and Rozenberg, 2017). However, ending poverty is not sufficient, and the positive outcome as an adaptation strategy depends on whether increased household wealth is actually directed towards risk reduction and management strategies (Nelson et al., 2016), as shown in urban municipalities (Colenbrander et al., 2017; Rasch, 2017) and agrarian communities (Hashemi et al., 2017), and whether finance for adaptation is made available (Section 5.6.1).

Secondly, local participation is effective when wider socio-economic barriers are addressed via multi-scale planning (McCubbin et al., 2015; Nyantakyi-Frimpong and Bezner-Kerr, 2015; Toole et al., 2016). This is the case, for instance, when national education efforts (SDG 4) (Muturak and Lutz, 2014; Striessnig and
Loichinger, 2015) and indigenous knowledge (Nkomwa et al., 2014; Pandey and Kumar, 2018) enhance information sharing, which also builds resilience (Santos et al., 2016; Martinez-Baron et al., 2018) and reduces risks for maladaptation (Antwi-Agyei et al., 2018; Gajjar et al., 2018).

Thirdly, development promotes transformational adaptation when addressing social inequalities (Section 5.5.3, 5.6.4), as in SDGs 4, 5, 16, and 17 (O’Brien et al., 2015; K. O’Brien, 2016). For example, SDG 5 supports measures that reduce women’s vulnerabilities and allow women to benefit from adaptation (Antwi-Agyei et al., 2015; Van Aelst and Holvoet, 2016; Cohen, 2017). Mobilisation of climate finance, carbon taxation, and environmentally-motivated subsidies can reduce inequalities (SDG 10), advance climate mitigation and adaptation (Chancel and Picketty, 2015), and be conducive to strengthening and enabling environments for resilience building (Nhamo, 2016; Halonen et al., 2017).

Fourthly, when sustainable development promotes livelihood security, it enhances the adaptive capacities of vulnerable communities and households. Examples include SDG 11 supporting adaptation in cities to reduce harm from disasters (Kelman, 2017; Parnell, 2017); access to water and sanitation (SDG 6) with strong institutions (SDG 16) (Rasul and Sharma, 2016); SDG 2 and its targets that promote adaptation in agricultural and food systems (Lipper et al., 2014); and targets for SDG 3 such as reducing infectious diseases and providing health cover are consistent with health-related adaptation (ICSU, 2017; Gomez-Echeverri, 2018).

Sustainable development has the potential to significantly reduce systemic vulnerability, enhance adaptive capacity, and promote livelihood security for poor and disadvantaged populations (high confidence). Transformational adaptation (see Chapter 4, Sections 4.2.2.2 and 4.5.3) would require development that takes into consideration multidimensional poverty and entrenched inequalities, local cultural specificities, and local knowledge in decision-making, thereby making it easier to achieve the SDGs in a 1.5°C warmer world (medium evidence, high agreement).

5.3.2 Synergies and Trade-offs between Adaptation Options and Sustainable Development

There are short-, medium-, and long-term positive impacts (synergies) and negative impacts (trade-offs) between the dual goal of keeping temperatures below 1.5°C global warming and achieving sustainable development. The extent of synergies between development and adaptation goals will vary by the development process adopted for a particular SDG and underlying vulnerability contexts (medium evidence, high agreement). Overall, the impacts of adaptation on sustainable development, poverty eradication, and reducing inequalities in general, and the SDGs specifically, are expected to be largely positive, given that the inherent purpose of adaptation is to lower risks. Building on Chapter 4 (see Section 4.3.5), this section examines synergies and trade-offs between adaptation and sustainable development for some key sectors and approaches, also.

**Agricultural adaptation:** The most direct synergy is between SDG 2 (zero hunger) and adaptation in cropping, livestock, and food systems, designed to maintain or increase production (Lipper et al., 2014; Rockström et al., 2017). Farmers with effective adaptation strategies tend to enjoy higher food security and experience lower levels of poverty (FAO, 2015; Douxchamps et al., 2016; Ali and Erenstein, 2017). Vermeulen et al. (2016) report strong positive returns on investment across the world from agricultural adaptation with side benefits for environment and economic well-being. Well-adapted agricultural systems contribute to safe drinking water, health, biodiversity, and equity goals (DeClerck et al., 2016; Myers et al., 2017). Climate-smart agriculture has synergies with food security, though it can be biased towards technological solutions, may not be gender sensitive, and can create specific challenges for institutional and distributional aspects (Lipper et al., 2014; Arakelyan et al., 2017; Taylor, 2017).

At the same time, adaptation options increase risk for human health, oceans, and access to water if fertiliser and pesticides are used without regulation or when irrigation reduces water availability for other purposes (Shackleton et al., 2015; Campbell et al., 2016). When agricultural insurance and climate services overlook
the poor, inequality may rise (Dinku et al., 2014; Carr and Owusu-Daaku, 2015; Carr and Onzere, 2017; Georgeson et al., 2017a). Agricultural adaptation measures may increase workloads, especially for women, while changes in crop mix can result in loss of income or culturally inappropriate food (Carr and Thompson, 2014; Thompson-Hall et al., 2016; Bryan et al., 2017), and they may benefit farmers with more land to the detriment of land-poor farmers, as seen in the Mekong River Basin (see Chapter 3, Cross-Chapter Box 6 in Chapter 3).

**Adaptation to protect human health:** Adaptation options in the health sector are expected to reduce morbidity and mortality (Arbuthnott et al., 2016; Ebi and Del Barrio, 2017). Heat-early-warning systems help lower injuries, illnesses, and deaths (Hess and Ebi, 2016), with positive impacts for SDG 3. Institutions better equipped to share information, indicators for detecting climate-sensitive diseases, improved provision of basic health care services, and coordination with other sectors also improve risk management, thus reducing adverse health outcomes (Dasgupta et al., 2016; Dovie et al., 2017). Effective adaptation creates synergies via basic public health measures (K.R. Smith et al., 2014; Dasgupta, 2016) and health infrastructure protected from extreme weather events (Watts et al., 2015). Yet, trade-offs can occur when adaptation in one sector leads to negative impacts in another sector. Examples include the creation of urban wetlands through flood control measures which can breed mosquitoes, and migration eroding physical and mental well-being, hence adversely affecting SDG 3 (K.R. Smith et al., 2014; Watts et al., 2015). Similarly, increased use of air conditioning enhances resilience to heat stress (Petkova et al., 2017); yet it can result in higher energy consumption, undermining SDG 13.

**Coastal adaptation:** Adaptation to sea-level rise remains essential in coastal areas even under a climate stabilisation scenario of 1.5°C (Nicholls et al., 2018). Coastal adaptation to restore ecosystems (for instance by planting mangrove forests) support SDGs for enhancing life and livelihoods on land and oceans (see Chapter 4, Sections 4.3.2.3). Synergistic outcomes between development and relocation of coastal communities are enhanced by participatory decision-making and settlement designs that promote equity and sustainability (Voorn et al., 2017). Limits to coastal adaptation may rise, for instance in low-lying islands in the Pacific, Caribbean, and Indian Ocean, with attendant implications for loss and damage (see Chapter 3 Box 3.5, Chapter 4, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter 12 in Chapter 5, Box 5.3).

**Migration as adaptation:** Migration has been used in various contexts to protect livelihoods from challenges related to climate change (Marsh, 2015; Jha et al., 2017), including through remittances (Betzold and Weiler, 2017). Synergies between migration and the achievement of sustainable development depend on adaptive measures and conditions in both sending and receiving regions (Fatima et al., 2014; McNamara, 2015; Entzinger and Scholten, 2016; Ober and Sakdapmongk, 2017; Schwan and Yu, 2017). Adverse developmental impacts arise when vulnerable women or the elderly are left behind or if migration is culturally disruptive (Wilkinson et al., 2016; Albert et al., 2017; Islam and Shamsuddoha, 2017).

**Ecosystem-based adaptation (EBA):** EBA can offer synergies with sustainable development (Morita and Matsumoto, 2015; Ojea, 2015; Szabo et al., 2015; Brink et al., 2016; Butt et al., 2016; Conservation International, 2016; Hug et al., 2017), although assessments remain difficult (Doswald et al., 2014) (see Chapter 4, Section 4.3.2.2). Examples include mangrove restoration reducing coastal vulnerability, protecting marine and terrestrial ecosystems, and increasing local food security; as well as watershed management reducing flood risks and improving water quality (Chong, 2014). In drylands, EBA practices, combined with community-based adaptation, have shown how to link adaptation with mitigation to improve livelihood conditions of poor farmers (Box 5.1). Synergistic developmental outcomes arise where EBA is cost effective, inclusive of indigenous and local knowledge, and easily accessible by the poor (Ojea, 2015; Daigneault et al., 2016; Estrella et al., 2016). Payment for ecosystem services can provide incentives to land owners and natural resource managers to preserve environmental services with synergies with SDGs 1 and 13 (Arriagada et al., 2015), when implementation challenges are overcome (Calvet-Mir et al., 2015; Wegner, 2016; Chan et al., 2017). Trade-offs include loss of other economic land use types, tension between biodiversity and adaptation priorities, and conflicts over governance (Wamsler et al., 2014; Ojea, 2015).

**Community-based adaptation (CBA):** CBA (see Chapter 4, Sections 4.3.3.2) enhances resilience and
sustainability of adaptation plans (Ford et al., 2016; Fernandes-Jesus et al., 2017; Grantham and Rudd, 2017; Gustafson et al., 2017). Yet, negative impacts occur if it fails to fairly represent vulnerable populations and to foster long-term social resilience (Ensor, 2016; Taylor Aiken et al., 2017). Mainstreaming CBA into planning and decision-making enables the attainment of SDG 5, 10, and 16 (Archer et al., 2014; Reid and Huq, 2014; Vardakoulias and Nicholles, 2014; Cutter, 2016; Kim et al., 2017). Incorporating multiple forms of indigenous and local knowledge (ILK) is an important element of CBA, as shown for instance in the Arctic region (Apgar et al., 2015; Armitage, 2015; Pearce et al., 2015; Chief et al., 2016; Cobbina and Anane, 2016; Ford et al., 2016) (see Chapter 4, Cross-Chapter Box 9, Box 4.3, Section 4.3.5.5). ILK can be synergistic with achieving SDGs 2, 6, and 10 (Ayers et al., 2014; Lasage et al., 2015; Regmi and Star, 2015; Berner et al., 2016; Chief et al., 2016; Murtinho, 2016; Reid, 2016).

There are clear synergies between adaptation options and several SDGs, such as poverty eradication, elimination of hunger, clean water, and health (robust evidence, high agreement) as well-integrated adaptation supports sustainable development (Eakin et al., 2014; Weisser et al., 2014; Adam, 2015; Smucker et al., 2015). Substantial synergies are observed in the agricultural and health sectors, and in ecosystem-based adaptations. However, particular adaptation strategies can lead to adverse consequences for developmental outcomes (medium evidence, high agreement). Adaptation strategies that advance one SDG can result in trade-offs with other SDGs, for instance, agricultural adaptation to enhance food security (SDG 2) causing negative impacts for health, equality, and healthy ecosystems (SDGs 3, 5, 6, 10, 14 and 15), and resilience to heat stress increasing energy consumption (SDGs 3 and 7), and high-cost adaptation in resource-constrained contexts (medium evidence, medium agreement).

5.3.3 Adaptation Pathways toward a 1.5°C Warmer World and Implications for Inequalities

In a 1.5°C warmer world, adaptation measures and options would need to be intensified, accelerated, and scaled up. This entails not only the right ‘mix’ of options (asking ‘right for whom and for what?’) but also a forward-looking understanding of dynamic trajectories, that is adaptation pathways (see Chapter 1, Cross-Chapter Box 1 in Chapter 1), best understood as decision-making processes over sets of potential action sequenced over time (Câmpeneau and Fazey, 2014; Wise et al., 2014). Given the scarcity of literature on adaptation pathways that navigate place-specific warming experiences at 1.5°C, this section presents insights into current local decision making for adaptation futures. This grounded evidence shows that choices between possible pathways, at different scales and for different groups of people, are shaped by uneven power structures and historical legacies that create their own, often unforeseen change (Fazey et al., 2016; Bosomworth et al., 2017; Lin et al., 2017; Murphy et al., 2017; Pelling et al., 2018).

Pursuing a place-specific adaptation pathway approach toward a 1.5°C warmer world harbours the potential for significant positive outcomes, with synergies for well-being possibilities to ‘leap-frog the SDGs’ (J.R.A. Butler et al., 2016), in countries at all levels of development (medium evidence, high agreement). It allows for identifying local, socially-salient tipping points before they are crossed, based on what people value and trade-offs that are acceptable to them (Barnett et al., 2014, 2016; Gorddard et al., 2016; Tschakert et al., 2017). Yet, evidence also reveals adverse impacts that reinforce rather than reduce existing social inequalities and hence may lead to poverty traps (Nagoda, 2015; Warner et al., 2015; Barnett et al., 2016; J.R.A. Butler et al., 2016; Godfrey-Wood and Naess, 2016; Pelling et al., 2016; Albert et al., 2017; Murphy et al., 2017) (medium evidence, high agreement).

Past development trajectories as well as transformational adaptation plans can constrain adaptation futures by reinforcing dominant political-economic structures and processes, and narrowing option spaces; this leads to maladaptive pathways that preclude alternative, locally-relevant, and sustainable development initiatives and increase vulnerabilities (Warner and Kuzdas, 2017; Gajjar et al., 2018). Such dominant pathways tend to validate the practices, visions, and values of existing governance regimes and powerful members of a community while devaluing those of less privileged stakeholders. Examples from Romania, the Solomon Islands, and Australia illustrate such pathway dynamics in which individual economic gains and prosperity matter more than community cohesion and solidarity; this discourages innovation, exacerbates inequalities,
and further erodes adaptive capacities of the most vulnerable (Davies et al., 2014; Fazey et al., 2016; Bosomworth et al., 2017). In the city of London, United Kingdom, the dominant adaptation and disaster risk management pathway promotes resilience that emphasises self-reliance; yet, it intensifies the burden on low-income citizens, the elderly, migrants, and others unable to afford flood insurance or protect themselves against heat waves (Pelling et al., 2016). Adaptation pathways in the Bolivian Altiplano have transformed subsistence farmers into world-leading quinoa producers, but loss of social cohesion and traditional values, dispossession, and loss of ecosystem services now constitute undesirable trade-offs (Chelleri et al., 2016).

A narrow view of adaptation decision making, for example focused on technical solutions, tends to crowd out more participatory processes (Lawrence and Haasnoot, 2017; Lin et al., 2017), obscures contested values, and reinforces power asymmetries (Bosomworth et al., 2017; Singh, 2018). A situated and context-specific understanding of adaptation pathways that galvanises diverse knowledge, values, and joint initiatives, helps to overcome dominant path dependencies, avoid trade-offs that intensify inequities, and challenge policies detached from place (Fincher et al., 2014; Wyborn et al., 2015; Murphy et al., 2017; Gajjar et al., 2018). These insights suggest that adaptation pathway approaches to prepare for 1.5°C warmer futures would be difficult to achieve without considerations for inclusiveness, place-specific trade-off deliberations, redistributive measures, and procedural justice mechanisms to facilitate equitable transformation (medium evidence, high agreement).

[INSERT BOX 5.1 HERE]

**Box 5.1:** Ecosystem- and Community-based Practices in Drylands

Drylands face severe challenges in building climate resilience (Fuller and Lain, 2017), yet, small-scale farmers can play a crucial role as agents of change through ecosystem- and community-based practices that combine adaptation, mitigation, and sustainable development.

Farmer Managed Natural Regeneration (FMNR) of trees in cropland is practised in 18 countries across Sub-Saharan Africa, Southeast Asia, Timor-Leste, India, and Haiti and has, for example, permitted the restoration of over five million hectares of land in the Sahel (Niang et al., 2014; Bado et al., 2016). In Ethiopia, the Managing Environmental Resources to Enable Transitions (MERET) programme, which entails community-based watershed rehabilitation in rural landscapes, supported around 648,000 people, resulting in the rehabilitation of 25,400,000 hectares of land in 72 severely food-insecure districts across Ethiopia during 2012–2015 (Gebrehaweria et al., 2016). In India, local farmers have benefitted from watershed programmes across different agro-ecological regions (Singh et al., 2014; Datta, 2015).

These low-cost, flexible community-based practices represent low-regrets adaptation and mitigation strategies. These strategies often contribute to strengthened ecosystem resilience and biodiversity, increased agricultural productivity and food security, reduced household poverty and drudgery for women, and enhanced agency and social capital (Niang et al., 2014; Francis et al., 2015; Kassie et al., 2015; Mbow et al., 2015; Reij and Winterbottom, 2015; Weston et al., 2015; Bado et al., 2016; Dumont et al., 2017). Small check dams in dryland areas and conservation agriculture can significantly increase agricultural output (Kumar et al., 2014; Agoramoorthy and Hsu, 2016; Pradhan et al., 2018). Mitigation benefits have also been quantified (Weston et al., 2015); for example, FMNR over five million hectares in Niger has sequestered 25–30 Mtonnes of carbon over 30 years (Stevens et al., 2014).

However, several constraints hinder scaling-up efforts: inadequate attention to the socio-technical processes of innovation (Grist et al., 2017; Scoones et al., 2017), difficulties in measuring the benefits of an innovation (Coe et al., 2017), farmers’ inability to deal with long-term climate risk (Singh et al., 2017), and difficulties for matching practices with agro-ecological conditions and complementary modern inputs (Kassie et al., 2015). Key conditions to overcome these challenges include: developing agroforestry value chains and markets (Reij and Winterbottom, 2015) and adaptive planning and management (Gray et al., 2016). Others include inclusive processes giving greater voice to women and marginalised groups (MRFCI, 2015a; UN Women and MRFCJ, 2016; Dumont et al., 2017), strengthening of community land and forest rights.
5.4 Mitigation and Sustainable Development

The AR5 WGIII examined the potential of various mitigation options for specific sectors (energy supply, industry, buildings, transport, and Agriculture, Forestry, and Other Land Use (AFOLU); it provided a narrative of dimensions of sustainable development and equity as a framing for evaluating climate responses and policies, respectively, in Chapters 4, 7, 8, 9, 10, and 11 (IPCC, 2014a). This section builds on analysis of Chapters 2 and 4 of this report to re-assess mitigation and sustainable development in the context of 1.5°C global warming as well as the Sustainable Development Goals (SDGs).

5.4.1 Synergies and Trade-offs between Mitigation Options and Sustainable Development

Adopting stringent climate mitigation options can generate multiple positive non-climate benefits that have the potential to reduce the costs of achieving sustainable development (IPCC, 2014b; Ürge-Vorsatz et al., 2014, 2016; Schaeffer et al., 2015; von Stechow et al., 2015). Understanding the positive impacts (synergies) but also the negative impacts (trade-offs) is key for selecting mitigation options and policy choices that maximise the synergies between mitigation and developmental actions (Hildingsson and Johansson, 2015; Nilsson et al., 2016; Delponte et al., 2017; van Vuuren et al., 2017b; McCollum et al., 2018).

Aligning mitigation response options to sustainable development objectives can ensure public acceptance (IPCC, 2014a), encourage faster action (Lechtenboehmer and Knoop, 2017), and support the design of equitable mitigation (Holz et al., 2017; Winkler et al., 2018) that protect human rights (MRFCJ, 2015b) (Section 5.5.3).

This sub-section assesses available literature on the interactions of individual mitigation options (see Chapter 2, Sections 2.3.1.2, Chapter 4, Sections 4.2 and 4.3) with sustainable development and the SDGs and underlying targets. Table 5.3 (available as a supplementary pdf) presents an assessment of these synergies and trade-offs and the strength of the interaction using an SDG-interaction score (see Glossary) (McCollum et al., 2018), with evidence and agreements levels. Figure 5.3 presents the information of Table 5.3 (available as a supplementary pdf), showing gross (not net) interactions with the SDGs. This detailed assessment of synergies and trade-offs of individual mitigation options with the SDGs (Table 5.3 a–d (available as a supplementary pdf), Figure 5.3) reveals that the number of synergies exceeds that of trade-offs. Mitigation response options in the energy demand sector, AFOLU, and oceans have more positive interactions with a larger number of SDGs compared to those on the energy supply side (robust evidence, high agreement).

5.4.1.1 Energy Demand: Mitigation Options to Accelerate Reduction in Energy Use and Fuel Switch

For mitigation options in the energy demand sectors, the number of synergies with all sixteen SDGs exceeds the number of trade-off (Figure 5.3, also Table 5.3 (available as a supplementary pdf)) (robust evidence, high agreement). Most of the interactions are of reinforcing nature, hence facilitating the achievement of the goals.

Accelerating energy efficiency in all sectors, which is a necessary condition for a 1.5°C warmer world (see Chapters 2 and 4), has synergies with a large number of SDGs (Figure 5.3, Table 5.3 (available as a supplementary pdf)) (robust evidence, high agreement). The diffusion of efficient equipment and appliances...
across end use sectors has synergies with international partnership (SDG 17) and participatory and transparent institutions (SDG 16) because innovations and deployment of new technologies require transnational capacity building and knowledge sharing. Resource and energy savings support sustainable production and consumption (SDG 12), energy access (SDG 7), innovation and infrastructure development (SDG 9), and sustainable city development (SDG 11). Energy efficiency supports the creation of decent jobs by new service companies providing services for energy efficiency, but the net employment effect of efficiency improvement remains uncertain due to macro-economic feedback (SDG 8) (McCollum et al., 2018).

In the buildings sector, accelerating energy efficiency by way of, for example, enhancing the use of efficient appliances, refrigerator transition, insulation, retrofitting, and low- or zero-energy buildings generates benefits across multiple SDG targets. For example, improved cook stoves make fuel endowments last longer and hence reduce deforestation (SDG 15), support equal opportunity by reducing school absences due to asthma among children (SDGs 3 and 4), and empower rural and indigenous women by reducing drudgery (SDG 5) (Derbez et al., 2014; Lucon et al., 2014; Maidment et al., 2014; Scott et al., 2014; Cameron et al., 2015; Fay et al., 2015; Liddell and Guiney, 2015; Shah et al., 2015; Sharpe et al., 2015; Wells et al., 2015; Willand et al., 2015; Hallegatte et al., 2016; Kusumaningtyas and Aldrian, 2016; Berrueta et al., 2017; McCollum et al., 2017) (robust evidence, high agreement).

In energy-intensive processing industries, 1.5°C-compatible trajectories require radical technology innovation through maximum electrification, shift to other low-emission energy carriers such as hydrogen or biomass, integration of Carbon Capture and Storage (CCS) and innovations for Carbon Capture and Utilisation (CCU) (see Chapter 4, Section 4.3.4.5). These transformations have strong synergies with innovation and sustainable industrialisation (SDG 9), supranational partnerships (SDGs 16 and 17) and sustainable production (SDG 12). However, possible trade-offs due to risks of CCS-based carbon leakage, increased electricity demands, and associated price impacts affecting energy access and poverty (SDGs 7 and 1) would need careful regulatory attention (Wesseling et al., 2017). In the mining industry, energy efficiency can be synergetic or face trade-offs with sustainable management (SDG 6), depending on the option retained for water management (Nguyen et al., 2014). Substitution and recycling are also an important driver of 1.5°C-compatible trajectories in industrial systems (see Chapter 4, Section 4.3.4.2). Structural changes and reorganisation of economic activities in industrial park/clusters following the principles of industrial symbiosis (circular economy) improves the overall sustainability by reducing energy and waste (Fan et al., 2017; Preston and Lehne, 2017) and reinforce responsible production and consumption (SDG 12) through recycling, water use efficiency (SDG 6), energy access (SDG 7), and ecosystem service value enhancement (SDG 15) (Karner et al., 2015; Zeng et al., 2017).

In the transport sector, deep electrification may trigger increases of electricity prices and adversely affect poor populations (SDG 1), unless pro-poor redistributive policies are in place (Klausbruckner et al., 2016). In cities, governments can lay the foundations for compact, connected low-carbon cities, which are an important component of 1.5°C-compatible transformations (see Chapter 4, Section 4.3.3) and show synergies with sustainable cities (SDG 11) (Colenbrander et al., 2016).

Behavioural responses are important determinants of the ultimate outcome of energy efficiency on emission reductions and energy access (SDG 7) and their management requires a detailed understanding of the drivers of consumption and the potential for and barriers to absolute reductions (Fuchs et al., 2016). Notably, the rebound effect tends to offset the benefits of efficiency for emission reductions through growing demand for energy services (Sorrell, 2015; Suffolk and Poortinga, 2016). However, high rebound can help in providing faster access to affordable energy (SDG 7.1) where the goal is to reduce energy poverty and unmet energy demand (Chakravarty et al., 2013) (see Chapter 2, Section 2.4.3). Comprehensive policy design, including rebound supressing policies such as carbon price and policies that encourage awareness building and promotional material design, are needed to tap the full potential of energy savings, as applicable to 1.5°C warming context (Chakravarty and Tavoni, 2013; IPCC, 2014b; Karner et al., 2015; Zhang et al., 2015; Altieri et al., 2016; Santarius et al., 2016) and to address policy-related trade-offs and welfare-enhancing benefits (Chakravarty et al., 2013; Chakravarty and Roy, 2016; Gillingham et al., 2016) (robust evidence, high agreement)
high agreement).

Other behavioural responses will affect the interplay between energy efficiency and sustainable development. Building occupants reluctant to change their habits may miss out on welfare-enhancing energy efficiency opportunities (Zhao et al., 2017). Preferences for new products and premature obsolescence for appliances is expected to affect sustainable consumption and production adversely (SDG 12) with ramifications for resource use efficiency (Echegaray, 2016). User behaviour change towards increased physical activity, less reliance on motorised travel over short distances, and the use of public transport would help to decarbonise the transport sector in a synergetic manner with SDGs 3, 11, and 12 (Shaw et al., 2014; Ajanovic, 2015; Chakrabarti and Shin, 2017) while reducing inequality in access to basic facilities (SDG 10) (Lucas and Pangbourne, 2014; Kagawa et al., 2015). However, infrastructure design and regulations would need to ensure road safety and address risks of road accidents for pedestrians (Hwang et al., 2017; Khreis et al., 2017) to ensure sustainable infrastructure growth in human settlements (SDGs 9 and 11) (Lin et al., 2015; SLoCaT, 2017).  

5.4.1.2 Energy Supply: Accelerated Decarbonisation

Decreasing the share of coal in energy supply in line with 1.5°C-compatible scenarios (see Chapter 2, Section 2.4.2) reduces adverse impacts of upstream supply-chain activities, in particular air and water pollution, and coal mining accidents, and enhances health by reducing air pollution, notably in cities, showing synergies with SDGs 3, 11 and 12 (Yang et al., 2016; UNEP, 2017).

Fast deployment of renewables like solar and wind, hydro, modern biomass, together with the decrease of fossil fuels in energy supply (see Chapter 2, Section 2.4.2.1), is aligned with the doubling of renewables in the global energy mix (SDG 7.2). Renewables could also support progress on SDGs 1, 10, 11, and 12 and supplement new technology (Chaturvedi and Shukla, 2014; Rose et al., 2014; Smith and Sagar, 2014; Riahi et al., 2015; IEA, 2016; McCollum et al., 2017; van Vuuren et al., 2017a) (robust evidence, high agreement). However, some trade-offs with the SDGs can emerge from offshore installations, particularly SDG 14 in local contexts (McCollum et al., 2017). Moreover, trade-offs between renewable energy production and affordability (SDG 7) (Labordena et al., 2017) and other environmental objectives would need to be scrutinised for potential negative social outcomes. Policy interventions through regional cooperation building (SDG 17) and institutional capacity (SDG 16) can enhance affordability (SDG 7) (Labordena et al., 2017). The deployment of small-scale renewables, or off-grid solutions for people in remote areas (Sánchez and Izzo, 2017), has strong potential for synergies with access to energy (SDG 7), but the actualisation of these potentials requires measures to overcome technology and reliability risks associated with large-scale deployment of renewables (Giwa et al., 2017; Heard et al., 2017). Bundling energy-efficient appliances and lighting with off-grid renewables can lead to substantial cost reduction while increasing reliability (IEA, 2017). Low-income populations in industrialised countries are often left out of renewable energy generation schemes, either because of high start-up costs or lack of home ownership (UNRISD, 2016).

Nuclear energy, the share of which increases in most of the 1.5°C-compatible pathways (see Chapter 2, Section 2.4.2.1), can increase the risks of proliferation (SDG 16), have negative environmental effects (e.g., for water use, SDG 6), and have mixed effects for human health when replacing fossil fuels (SDGs 7 and 3) (see Table 5.2). The use of fossil CCS, which plays an important role in deep mitigation pathways (see Chapter 2, Section 2.4.2.3), implies continued adverse impacts of upstream supply-chain activities in the coal sector, and because of lower efficiency of CCS coal power plants (SDG 12), upstream impacts and local air pollution are likely to be exacerbated (SDG 3). Furthermore, there is a non-negligible risk of carbon dioxide leakage from geological storage and the carbon dioxide transport infrastructure (SDG 3) (Table 5.3 (available as a supplementary pdf)).

Economies dependent upon fossil fuel-based energy generation and/or export revenue are expected to be disproportionately affected by future restrictions on the use of fossil fuels, under stringent climate goals and higher carbon prices; this includes impacts on employment, stranded assets, resources left underground,
lower capacity use, and early phasing out of large infrastructure already under construction (Johnson et al., 2015; McGlade and Ekins, 2015; UNEP, 2017; Spencer et al., 2018) (Box 5.2) (robust evidence, high agreement). Investment in coal continues to be attractive in many countries as it is a mature technology, provides cheap energy supply, large-scale employment, and energy security (Jakob and Steckel, 2016; Vogt-Schilb and Hallegatte, 2017; Spencer et al., 2018). Hence, accompanying policies and measures would be required to ease job losses and correct for relatively higher prices of alternative energy (Oosterhuis and Ten Brink, 2014; Oei and Mendeleivitch, 2016; Garg et al., 2017; HLCCP, 2017; Jordaan et al., 2017; OECD, 2017; UNEP, 2017; Blondeel and van de Graaf, 2018; Green, 2018). Research on historical transitions shows that managing the impacts on workers through retraining programs is essential in order to align the phase down of mining industries with meeting ambitious climate targets, and the objectives of a ‘just transition’ (Galgóczi, 2014; Caldecott et al., 2017; Healy and Barry, 2017). This aspect is even more important in developing countries where the mining workforce is largely semi- or un-skilled (Altieri et al., 2016; Tung, 2016). Ambitious emission reduction targets can unlock very strong decoupling potentials in industrialised fossil exporting economies (Hatfield-Dodds et al., 2015).

[START BOX 5.2 HERE]

**Box 5.2:** Challenges and Opportunities of Low-Carbon Pathways in Gulf Cooperative Council (GCC) Countries

The Gulf Cooperative Council (GCC) region (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and United Arab Emirates) is characterised by high dependency on hydrocarbon resources (natural oil and gas), with high risks of socio-economic impacts of policies and response measures to address climate change. The region is also vulnerable to the decrease of the global demand and price of hydrocarbons as a result of climate change response measures. The projected declining use of oil and gas under low emissions pathways creates risks of significant economic losses for the GCC region (e.g., Waisman et al., 2013; Van de Graaf and Verbruggen, 2015; Al-Maamary et al., 2016; Bauer et al., 2016), given that natural gas and oil revenues contributed to ~70% of government budgets and > 35% of the gross domestic product in 2010 (Callen et al., 2014).

The current high energy intensity of the domestic economies (Al-Maamary et al., 2017), triggered mainly by low domestic energy prices (Alshehry and Belloumi, 2015), suggests specific challenges for aligning mitigation towards 1.5°C-consistent trajectories, which would require strong energy efficiency and economic development for the region.

Economies of the region are highly reliant on fossil fuel for their domestic activities. Yet, the renewables deployment potentials are large, deployment is already happening (Cugurullo, 2013; IRENA, 2016), and positive economic benefits can be envisaged (Sgouridis et al., 2016). Nonetheless, the use of renewables is currently limited by economics and structural challenges (Lilliestam and Patt, 2015; Griffiths, 2017a). Carbon Capture and Storage (CCS) is also envisaged with concrete steps towards implementation (Alsheyab, 2017; Ustadi et al., 2017); yet, the real potential of this technology in terms of scale and economic dimensions is still uncertain.

Beyond the above mitigation-related challenges, human societies and fragile ecosystems of the region are highly vulnerable to the impacts of climate change, such as water stress (Evans et al., 2004; Shaffrey et al., 2009), desertification (Bayram and Öztürk, 2014), sea level rise affecting vast low costal lands, and high temperature and humidity with future levels potentially beyond adaptive capacities (Pal and Eltahir, 2016). A low-carbon pathway that manages climate-related risks within the context of sustainable development requires an approach that jointly addresses both types of vulnerabilities (Al Ansari, 2013; Lilliestam and Patt, 2015; Babiker, 2016; Griffiths, 2017b).

The Nationally Determined Contributions (NDCs) for GCC countries identified energy efficiency, deployment of renewables, and technology transfer to enhance agriculture, food security, protection of marine, and management of water and costal zones (Babiker, 2016). Strategic vision documents, such as Saudi Arabia’s “Vision 2030”, identify emergent opportunities for energy price reforms, energy efficiency,
turning emissions in valuable products, and deployment of renewables and other clean technologies, if accompanied with appropriate policies to manage the transition and in the context of economic diversification (Luomi, 2014; Atalay et al., 2016; Griffiths, 2017b; Howarth et al., 2017).

[END BOX 5.2 HERE]

5.4.1.3 Land-based Agriculture, Forestry and Ocean: Mitigation Response Options and Carbon Dioxide Removal

In the AFOLU sector, dietary change towards global healthy diets, that is, a shift from over-consumption of animal-related to plant-related diets, and food waste reduction (see Chapter 4, Section 4.3.2.1) are in synergy with SDGs 2 and 6, and SDG 3 through lower consumption of animal products and reduced losses and waste throughout the food system, contributing to achieving SDGs 12 and 15 (Bajželj et al., 2014; Bustamante et al., 2014; Tilman and Clark, 2014; Hiç et al., 2016).

Power dynamics plays an important role in achieving behavioural change and sustainable consumption (Fuchs et al., 2016). In forest management (see Chapter 4, Section 4.3.2.2), encouraging responsible sourcing of forest products and securing indigenous land tenure has the potential to increase economic benefits by creating decent jobs (SDG 8), maintaining biodiversity (SDG 15), facilitating innovation and upgrading technology (SDG 9), and responsible and just decision making (SDG 16) (Ding et al., 2016; WWF, 2017) (medium evidence, high agreement).

Emerging evidence indicates that future mitigation efforts that would be required to reach stringent climate targets, particularly those associated with Carbon Dioxide Removal (CDR) (e.g., Bioenergy with Carbon Capture and Storage (BECCS) and afforestation and reforestation), may also impose significant constraints upon poor and vulnerable communities (SDG 1) via increased food prices and competition for arable land, land appropriation, and dispossession (Cavanagh and Benjamin, 2014; Hunsberger et al., 2014; Work, 2015; Muratori et al., 2016; Smith et al., 2016; Burns and Nicholson, 2017; Corbera et al., 2017) with disproportionate negative impacts upon rural poor and indigenous populations (SDG 1) (Grubert et al., 2014; Grill et al., 2015; Zhang and Chen, 2015; Fricko et al., 2016; Johansson et al., 2016; Aha and Ayitey, 2017; De Stefano et al., 2017; Shi et al., 2017) (Section 5.4.2.2, Table 5.3 (available as a supplementary pdf), Figure 5.3) (robust evidence, high agreement). Crops for bioenergy may increase irrigation needs and exacerbate water stress with negative associated impacts on SDGs 6 and 10 (Boysen et al., 2017).

Ocean Iron Fertilisation (OIF) and enhanced weathering have two-way interactions with life under water and on land and food security (SDGs 2, 14, and 15) (Table 5.3 (available as a supplementary pdf)). Development of blue carbon resources through coastal (mangrove) and marine (seaweed) vegetative ecosystems encourages integrated water resource management (SDG 6) (Vierros, 2017), promotes life on land (SDG 15) (Potouroglou et al., 2017), poverty reduction (SDG 1) (Schirmer and Bull, 2014; Lamb et al., 2016) and food security (SDG 2) (Ahmed et al., 2017a, b; Duarte et al., 2017; Sondak et al., 2017; Vierros, 2017; Zhang et al., 2017).

[INSERT FIGURE 5.3 HERE]
Figure 5.3: **Synergies and trade-offs and gross Sustainable Development Goal (SDG)-interaction with individual mitigation options.** The top three wheels represent synergies and the bottom three wheels show trade-offs. The colours on the border of the wheels correspond to the SDGs listed above, starting at the 9 o'clock position, with reading guidance in the top-left corner with the quarter circle (Note 1). Mitigation (climate action, SDG 13) is at the centre of the circle. The coloured segments inside the circles can be counted to arrive at the number of synergies (green) and trade-offs (red). The length of the coloured segments shows the strength of the synergies or trade-offs (Note 3) and the shading indicates confidence (Note 2). Various mitigation options within the energy demand sector, energy supply sector, and land and ocean sector, and how to read them within a segment are shown in grey (Note 4). See also Table 5.3 (available as a supplementary pdf).

### 5.4.2 Sustainable Development Implications of 1.5°C and 2°C Mitigation Pathways

While previous sections have focused on individual mitigation options and their interaction with sustainable development and the SDGs, this section takes a systems perspective. Emphasis is on quantitative pathways depicting path-dependent evolutions of human and natural systems over time. Specifically, the focus is on fundamental transformations and thus stringent mitigation policies consistent with 1.5°C or 2°C, and the differential synergies and trade-offs with respect to the various sustainable development dimensions.

Both 1.5°C and 2°C pathways would require deep cuts in greenhouse gas (GHG) emissions and large-scale changes of energy supply and demand, as well as in agriculture and forestry systems (see Chapter 2, Section 2.4). For the assessment of the sustainable development implications of these pathways, we draw upon studies that show the aggregated impact of mitigation for multiple sustainable development dimensions (Grubler et al., 2018; McCollum et al., 2018; Rogelj et al., 2018) and across multiple Integrated Assessment.
Modelling (IAM) frameworks. Often these tools are linked to disciplinary models covering specific SDGs in more detail (Cameron et al., 2016; Rao et al., 2017; Grubler et al., 2018; McCollum et al., 2018). Using multiple IAMs and disciplinary models is important for a robust assessment of the sustainable development implications of different pathways. Emphasis is on multi-regional studies, which can be aggregated to the global scale. The recent literature on 1.5°C mitigation pathways has begun to provide quantifications for a range of sustainable development dimensions, including air pollution and health, food security and hunger, energy access, water security, and multidimensional poverty and equity.

5.4.2.1 Air Pollution and Health

Greenhouse gases and air pollutants are typically emitted by the same sources. Hence, mitigation strategies that reduce GHGs or the use of fossil fuels typically also reduce emissions of pollutants, such as particulate matter (e.g., PM2.5 and PM10), black carbon (BC), sulphur dioxide (SO2), nitrogen oxides (NOx), and other harmful species (Clarke et al., 2014) (Figure 5.4), causing adverse health and ecosystem effects at various scales (Kusumaningtyas and Aldrian, 2016).

Mitigation pathways typically show that there are significant synergies for air pollution, and that the synergies increase with the stringency of the mitigation policies (Amann et al., 2011; Rao et al., 2016; Klimont et al., 2017; Shindell et al., 2017; Markandya et al., 2018). Recent multi-model comparisons indicate that mitigation pathways consistent with 1.5°C would result in higher synergies with air pollution compared to pathways that are consistent with 2°C (Figures 5.4 and 5.5). Shindell et al. (2018) indicate that health benefits worldwide over the century of 1.5°C pathways could be in the range of 110 to 190 million fewer premature deaths compared to 2°C pathways. The synergies for air pollution are highest in the developing world, particularly in Asia. In addition to significant health benefits, there are also economic benefits from mitigation, reducing the investment needs in air pollution control technologies by about 35% globally (or about 100 billion US$2015 per year to 2030 in 1.5°C pathways) (McCollum et al., 2018) (Figure 5.5).

5.4.2.2 Food Security and Hunger

Stringent climate mitigation pathways in line with ‘well below 2°C’ or ‘1.5°C’ goals often rely on the deployment of large-scale land-related measures, like afforestation and/or bioenergy supply (Popp et al., 2014; Rose et al., 2014; Creutzig et al., 2015). These land-related measures can compete with food production and hence raise food security concerns (Section 5.4.1.3) (P. Smith et al., 2014). Mitigation studies indicate that so-called ‘single-minded’ climate policy, aiming solely at limiting warming to 1.5°C or 2°C without concurrent measures in the food sector, can have negative impacts for global food security (Hasegawa et al., 2015; McCollum et al., 2018). Impacts of 1.5°C mitigation pathways can be significantly higher than those of 2°C pathways (Figures 5.4 and 5.5). An important driver of the food security impacts in these scenarios is the increase of food prices and the effect of mitigation on disposable income and wealth due to GHG pricing. A recent study indicates that, on aggregate, the price and income effects on food may be bigger than the effect due to competition over land between food and bioenergy (Hasegawa et al., 2015).

In order to address the issue of trade-offs with food security, mitigation policies would need to be designed in a way that shields the population at risk of hunger, including through the adoption of different complementary measures, such as food price support. The investment needs of complementary food price policies are found to be globally relatively much smaller than the associated mitigation investments of 1.5°C pathways (Figure 5.4) (McCollum et al., 2018). Besides food support price, other measures include improving productivity and efficiency of agricultural production systems (FAO and NZAGRC, 2017a, b; Frank et al., 2017) and programs focusing on forest land-use change (Havlík et al., 2014). All these lead to additional benefits of mitigation, improving resilience and livelihoods.

van Vuuren et al. (2018) and Grubler et al. (2018) show that 1.5°C pathways without reliance on BECCS can
be achieved through a fundamental transformation of the service sectors which would significantly reduce energy and food demand (see Chapter 2, Sections 2.1.1, 2.3.1, and 2.4.3). Such low energy demand (LED) pathways would result in significantly reduced pressure on food security, lower food prices, and put fewer people at risk of hunger. Importantly, the trade-offs with food security would be reduced by the avoided impacts in the agricultural sector due to the reduced warming associated with the 1.5°C pathways (see Chapter 3, Section 3.5). However, such feedbacks are not comprehensively captured in the studies on mitigation.

5.4.2.3 Lack of Energy Access/Energy Poverty

A lack of access to clean and affordable energy (especially for cooking) is a major policy concern in many countries, especially in those in South Asia and Africa where major parts of the population still rely primarily on solid fuels for cooking (IEA and World Bank, 2017). Scenario studies which quantify the interactions between climate mitigation and energy access indicate that stringent climate policy which would affect energy prices could significantly slow down the transition to clean cooking fuels, such as liquefied petroleum gas (LPG) or electricity (Cameron et al., 2016).

Estimates across six different IAMs (McCollum et al., 2018) indicate that, in the absence of compensatory measures, the number of people without access to clean cooking fuels may increase. Re-distributional measures, such as subsidies on cleaner fuels and stoves, could compensate for the negative effects of mitigation on energy access. Investment costs of the re-distributional measures in 1.5°C pathways (on average around 120 billion per year to 2030; Figure 5.5) are much smaller than the mitigation investments of 1.5°C pathways (McCollum et al., 2018). The recycling of revenues from climate policy might act as a means to help finance the costs of providing energy access to the poor (Cameron et al., 2016).

5.4.2.4 Water Security

Transformations towards low-emissions energy and agricultural systems can have major implications for freshwater demand as well as water pollution. The scaling up of renewables and energy efficiency as depicted by low emissions pathways would, in most instances, lower water demands for thermal energy supply facilities (‘water-for-energy’) compared to fossil energy technologies, and thus reinforce targets related to water access and scarcity (see Chapter 4, Section 4.2.1). However, some low-carbon options such as bioenergy, centralised solar power, nuclear, and hydropower technologies could, if not managed properly, have countering effects that compound existing water-related problems in a given locale (Byers et al., 2014; Fricko et al., 2016; IEA, 2016; Fujimori et al., 2017a; McCollum et al., 2017; Wang, 2017).

Under stringent mitigation efforts, the demand for bioenergy can result in a substantial increase of water demand for irrigation, thereby potentially contributing to water scarcity in water-stressed regions (Berger et al., 2015; Bonsch et al., 2016; Jägermeyr et al., 2017). However, this risk can be reduced by prioritising rain-fed production of bioenergy (Hayashi et al., 2015, 2018; Bonsch et al., 2016), but might have adverse effects for food security (Boysen et al., 2017).

Reducing food and energy demand without compromising the needs of the poor emerges as a robust strategy for both water conservation and GHG emissions reductions (von Stechow et al., 2015; IEA, 2016; Parkinson et al., 2016; Grubler et al., 2018). The results underscore the importance of an integrated approach when developing water, energy, and climate policy (IEA, 2016).

Estimates across different models for the impacts of stringent mitigation pathways on energy-related water uses seem ambiguous. Some pathways show synergies (Mouratiadou et al., 2018) while others indicate trade-offs and thus increases of water use due to mitigation (Fricko et al., 2016). The signal depends on the adopted policy implementation or mitigation strategies and technology portfolio. A number of adaptation options exist (e.g., dry cooling), which can effectively reduce electricity-related water trade-offs (Fricko et al., 2016).
al., 2016; IEA, 2016). Similarly, irrigation water use will depend on the regions where crops are produced, the sources of bioenergy (e.g., agriculture vs. forestry) and dietary change induced by climate policy. Overall, and also considering other water-related SDGs, including access to safe drinking water and sanitation as well as waste-water treatment, investments into the water sector seem to be only modestly affected by stringent climate policy compatible with 1.5°C (Figure 5.5) (McCollum et al., 2018).

**[INSERT FIGURE 5.4 HERE]**

**a) Scenario ranges for selected sustainable development dimensions (2050)**

**b) Synergies and trade-offs of 1.5°C pathways**

(compared to baseline, 2050)
Figure 5.4: Sustainable development implications of mitigation actions in 1.5°C pathways. Panel (a) shows ranges for 1.5°C pathways for selected sustainable development dimensions compared to the ranges of 2°C pathways and baseline pathways. The panel (a) depicts interquartile and the full range across the scenarios for Sustainable Development Goal (SDG) 2 (hunger), SDG 3 (health), SDG 6 (water), SDG 7 (energy), SDG 13 (climate), and SDG 15 (land). Progress towards achieving the SDGs is denoted by arrow symbols (increase or decrease of indicator). Black horizontal lines show 2015 values for comparison. Note that sustainable development effects are estimated for the effect of mitigation and do not include benefits from avoided impacts (see Chapter 3, Section 3.5). Low energy demand (LED) denotes estimates from a pathway with extremely low energy demand reaching 1.5°C without Bioenergy with Carbon Capture and Storage (BECCS). Panel (b) presents the resulting full range for synergies and trade-offs of 1.5°C pathways compared to the corresponding baseline scenarios. The y-axis in panel (b) indicates the factor change in the 1.5°C pathway compared to the baseline. Note that the figure shows gross impacts of mitigation and does not include feedbacks due to avoided impacts. The realisation of the side-effects will critically depend on local circumstances and implementation practice. Trade-offs across many sustainable development dimensions can be reduced through complementary/re-distributional measures. The figure is not comprehensive and focuses on those sustainable development dimensions for which quantifications across models are available. Sources: 1.5°C pathways database of Chapter 2 (Grubler et al., 2018; McCollum et al., 2018).

Figure 5.5: Investment into mitigation up until 2030 and implications for investments for four sustainable development dimensions. Cross-hatched bars show the median investment in 1.5°C pathways across results from different models, and solid bars for 2°C pathways, respectively. Whiskers on bars represent minima and maxima across estimates from six models. Clean water and air pollution investments are available only from one model. Mitigation investments show the change in investments across mitigation options compared to the baseline. Negative mitigation investments (grey bars) denote disinvestment (reduced investment needs) into fossil fuel sectors compared to the baseline. Investments for different
sustainable development dimensions denote the investment needs for complementary measures in order to avoid trade-offs (negative impacts) of mitigation. Negative sustainable development investments for air pollution indicate cost savings, and thus synergies of mitigation for air pollution control costs. The values compare to about US$(2010) 2 trillion (range of 1.4 to 3 trillion) of total energy-related investments in the 1.5°C pathways. Source: estimates from CD-LINKS scenarios summarised by McCollum et al. (2018).

In summary, the assessment of mitigation pathways shows that, to meet the 1.5°C target, a wide range of mitigation options would need to be deployed (see Chapter 2, Sections 2.3 and 2.4). While pathways aiming at 1.5°C are associated with high synergies for some sustainable development dimensions (such as human health and air pollution, forest preservation), the rapid pace and magnitude of the required changes would also lead to increased risks for trade-offs for other sustainable development dimensions (particularly food security) (Figures 5.4 and 5.5). Synergies and trade-offs are expected to be unevenly distributed between regions and nations (Box 5.2), though little literature has formally examined such distributions under 1.5°C consistent mitigation scenarios. Reducing these risks requires smart policy designs and mechanisms that shield the poor and redistribute the burden so that the most vulnerable are not affected. Recent scenario analyses show that associated investments for reducing the trade-offs for, for example, food, water and energy access to be significantly lower than the required mitigation investments (McCollum et al., 2018). Fundamental transformation of demand, including efficiency and behavioural changes, can help to significantly reduce the reliance on risky technologies, such as BECCS, and thus reduce the risk of potential trade-offs between mitigation and other sustainable development dimensions (von Stechow et al., 2015; Grubler et al., 2018; van Vuuren et al., 2018). Reliance on demand-side measures only, however, would not be sufficient for meeting stringent targets, such as 1.5°C and 2°C (Clarke et al., 2014).

5.5 Sustainable Development Pathways to 1.5°C

This section assesses what is known in the literature on development pathways that are sustainable and climate-resilient and relevant to a 1.5°C warmer world. Pathways, transitions from today’s world to achieving a set of future goals (see Chapter 1, Section 1.2.3, Cross-Chapter Box 1), follow broadly two main traditions: first, as integrated pathways describing the required societal and systems transformations, combining quantitative modelling and qualitative narratives at multiple spatial scales (global to sub-national); and second, as country- and community-level, solution-oriented trajectories and decision-making processes about context- and place-specific opportunities, challenges, and trade-offs. These two notions of pathways offer different, though complementary, insights into the nature of 1.5°C-relevant trajectories and the short-term actions that enable long-term goals. Both highlight to varying degrees the urgency, ethics, and equity dimensions of possible trajectories and society- and system-wide transformations, yet at different scales, building on Chapter 2 (see Section 2.4) and Chapter 4 (see Section 4.5).

5.5.1 Integration of Adaptation, Mitigation, and Sustainable Development

Insights into climate-compatible development (see Glossary) illustrate how integration between adaptation, mitigation, and sustainable development works in context-specific projects, how synergies are achieved, and what challenges are encountered during implementation (Stringer et al., 2014; Suckall et al., 2014; Antwi-Agyei et al., 2017a; Bickersteth et al., 2017; Kalafatis, 2017; Nunan, 2017). The operationalisation of climate-compatible development, including climate-smart agriculture and carbon-forestry projects (Lipper et al., 2014; Campbell et al., 2016; Quan et al., 2017), shows multi-level and multi-sector trade-offs involving ‘winners’ and ‘losers’ across governance levels (Kongsager and Corbera, 2015; Naess et al., 2015; Ficklin et al., 2017; Karlsson et al., 2017; Tanner et al., 2017; Taylor, 2017; Wood, 2017) (high confidence). Issues of power, participation, values, equity, inequality, and justice transcend case study examples of attempted integrated approaches (Nunan, 2017; Phillips et al., 2017; Stringer et al., 2017; Wood, 2017), also reflected in policy frameworks for integrated outcomes (Stringer et al., 2014; Di Gregorio et al., 2017; Few et al., 2017; Tanner et al., 2017).
Ultimately, reconciling trade-offs between development needs and emission reductions towards a 1.5°C warmer world requires a dynamic view of the interlinkages between adaptation, mitigation, and sustainable development (Nunan, 2017). This entails recognition of the ways in which development contexts shape the choice and effectiveness of interventions, limit the range of responses afforded to communities and governments, and potentially impose injustices upon vulnerable groups (UNRISD, 2016; Thornton and Comberti, 2017). A variety of approaches, both quantitative and qualitative, exist to examine possible sustainable development pathways under which climate and sustainable development goals can be achieved, and synergies and trade-offs for transformation identified (Sections 5.3 and 5.4).

### 5.5.2 Pathways for Adaptation, Mitigation, and Sustainable Development

This section focuses on the growing body of pathways literature describing the dynamic and systemic integration of mitigation and adaptation with sustainable development in the context of a 1.5°C warmer world. These studies are critically important for the identification of ‘enabling’ conditions under which climate and the SDGs can be achieved, and thus help the design of transformation strategies that maximise synergies and avoid potential trade-offs (Sections 5.3 and 5.4). Full integration of sustainable development dimensions is, however, challenging, given their diversity and the need for high temporal, spatial, and social resolution to address local effects, including heterogeneity related to poverty and equity (von Stechow et al., 2015). Research on long-term climate change mitigation and adaptation pathways has covered individual SDGs to different degrees. Interactions between climate and other SDGs have been explored for SDGs 2, 3, 4, 6, 7, 8, 12, 14, and 15 (Clarke et al., 2014; Abel et al., 2016; von Stechow et al., 2016; Rao et al., 2017) while interactions with SDGs 1, 5, 11, and 16 remain largely underexplored in integrated long-term scenarios (Zimm et al., 2018).

Quantitative pathways studies now better represent ‘nexus’ approaches to assess sustainable development dimensions. In such approaches (see Chapter 4, Section 4.3.3.8), a sub-set of sustainable development dimensions are investigated together because of their close relationships (Welsch et al., 2014; Conway et al., 2015; Keairns et al., 2016; Parkinson et al., 2016; Rasul and Sharma, 2016; Howarth and Monasterolo, 2017). Compared to single objective climate-SDG assessments (Section 5.4.2), nexus solutions attempt to integrate complex interdependencies across diverse sectors in a systems approach for consistent analysis. Recent pathways studies show how water, energy, and climate (SDGs 6, 7, and 13) interact (Parkinson et al., 2016; McCollum et al., 2018), calling for integrated water-energy investment decisions to manage systemic risks. For instance, the provision of bioenergy, important in many 1.5°C-consistent pathways, can help resolve ‘nexus challenges’ by alleviating energy security concerns, but can also have adverse ‘nexus impacts’ on food security, water use, and biodiversity (Lotze-Campen et al., 2014; Bonsch et al., 2016). Policies that improve the resource use efficiency across sectors can maximise synergies for sustainable development (Bartos and Chester, 2014; McCollum et al., 2018; van Vuuren et al., 2018). Mitigation compatible with 1.5°C can significantly reduce impacts and adaptation needs in the nexus sectors compared to 2°C (Byers et al., 2018). In order to avoid trade-offs due to high carbon pricing of 1.5°C pathways, regulation in specific areas may complement price-based instruments. Such combined policies generally lead also to more early action maximizing synergies and avoiding some of the adverse climate effects for sustainable development (Bertram et al., 2018).

The comprehensive analysis of climate change in the context of sustainable development requires suitable reference scenarios that lend themselves to broader sustainable development analyses. The Shared Socioeconomic Pathways (SSPs) (O’Neill et al., 2017a; Riahi et al., 2017) (Chapter 1, Cross-Chapter Box 1 in Chapter 1) constitute an important first step in providing a framework for the integrated assessment of adaptation and mitigation and their climate-development linkages (Ebi et al., 2014). The five underlying SSP narratives (O’Neill et al., 2017a) map well into some of the key SDG dimensions, with one of the pathways (SSP1) explicitly depicting sustainability as the main theme (van Vuuren et al., 2017b).

To date, no pathway in the literature proves to achieve all 17 SDGs because several targets are not met or not sufficiently covered in the analysis, hence resulting in a sustainability gap (Zimm et al., 2018). The SSPs
facilitate the systematic exploration of different sustainable dimensions under ambitious climate objectives. SSP1 proves to be in line with eight SDGs (3, 7, 8, 9, 10, 11, 13, and 15) and several of their targets in a 2°C warmer world (van Vuuren et al., 2017b; Zimm et al., 2018). But, important targets for SDGs 1, 2, and 4 (i.e., people living in extreme poverty, people living at the risk of hunger, and gender gap in years of schooling) are not met in this scenario.

The SSPs show that sustainable socio-economic conditions will play a key role in reaching stringent climate targets (Riahi et al., 2017; Rogelj et al., 2018). Recent modelling work has examined 1.5°C-consistent, stringent mitigation scenarios for 2100 applied to the SSPs, using six different Integrated Assessment Models (IAMs). Despite limitations of these models which are coarse approximations of reality, robust trends can be identified (Rogelj et al., 2018). SSP1 - which depicts broader “sustainability” as well as enhancing equity and poverty reductions - is the only pathway where all models could reach 1.5°C and is associated with the lowest mitigation costs across all SSPs. A decreasing number of models was successful for SSP2, SSP4, and SSP5, respectively, indicating distinctly higher risks of failure due to high growth and energy intensity as well as geographical and social inequalities and uneven regional development. And reaching 1.5°C has even been found infeasible in the less sustainable SSP3 - “regional rivalry” (Fujimori et al., 2017b; Riahi et al., 2017). All these conclusions hold true if a 2°C objective is considered (Calvin et al., 2017; Fujimori et al., 2017b; Popp et al., 2017; Riahi et al., 2017). Rogelj et al. (2018) also show that fewer scenarios are, however, feasible across different SSPs in case of 1.5°C, and mitigation costs substantially increase in 1.5°C pathways compared to 2°C pathways.

There is a wide range of SSP-based studies focusing on the connections between adaptation/impacts and different sustainable development dimensions (Hasegawa et al., 2014; Ishida et al., 2014; Arnell et al., 2015; Bowyer et al., 2015; Burke et al., 2015; Lemoine and Kapnick, 2016; Rozenberg and Hallegatte, 2016; Blanco et al., 2017; Hallegatte and Rozenberg, 2017; O'Neill et al., 2017a; Rutledge et al., 2017; Byers et al., 2018).

New methods for projecting inequality and poverty (downscaled to sub-national rural and urban levels as well as spatially-explicit levels) have enabled advanced SSP-based assessments of locally sustainable development implications of avoided impacts and related adaptation needs. For instance, Byers et al. (2018) find that, in a 1.5°C warmer world, a focus on sustainable development can reduce the climate risk exposure of populations vulnerable to poverty by more than an order of magnitude (Section 5.2.2). Moreover, aggressive reductions in between-country inequality may decrease the emissions intensity of global economic growth (Rao and Min, 2018). This is due to the higher potential for decoupling of energy from income growth in lower-income countries, due to high potential for technological advancements that reduce the energy intensity of growth of poor countries - critical also for reaching 1.5°C in a socially and economically equitable way. Participatory downscaling of SSPs in several European Union countries and in Central Asia shows numerous possible pathways of solutions to the 2-1.5°C goal, depending on differential visions (Tábara et al., 2018). Other participatory applications of the SSPs, for example in West Africa (Palazzo et al., 2017) and the south-eastern United States (Absar and Preston, 2015), illustrate the potentially large differences in adaptive capacity within regions and between sectors.

Harnessing the full potential of the SSP framework to inform sustainable development requires (1) further elaboration and extension of the current SSPs to cover sustainable development objectives explicitly; (2) the development of new or variants of current narratives that would facilitate more SDG-focused analyses with climate as one objective (among other SDGs) (Riahi et al., 2017); (3) scenarios with high regional resolution (Fujimori et al., 2017b); (4) a more explicit representation of institutional and governance change associated with the SSPs (Zimm et al., 2018); and (5) a scale-up of localised and spatially-explicit vulnerability, poverty and inequality estimates, which have emerged in recent publications based on the SSPs (Byers et al., 2018) and are essential to investigate equity dimensions (Klinsky and Winkler, 2018).

5.5.3 Climate-Resilient Development Pathways

This section assesses the literature on pathways as solution-oriented trajectories and decision-making
processes for attaining transformative visions for a 1.5°C warmer world. It builds on climate-resilient development pathways (CRDPs) introduced in the AR5 (Olsson et al., 2014) (Section 5.1.2) as well as growing, literature (e.g., Eriksen et al., 2017; Johnson, 2017; Orindi et al., 2017; Kirby and O'Mahony, 2018; Solecki et al., 2018) that uses CRDPs as a conceptual and aspirational idea for steering societies towards low-carbon, prosperous, and ecologically safe futures. Such a notion of pathways foregrounds decision-making processes at local to national levels to situate transformation, resilience, equity, and well-being in the complex reality of specific places, nations, and communities (Harris et al., 2017; Ziervogel et al., 2017; Fazey et al., 2018; Gajjar et al., 2018; Klinsky and Winkler, 2018; Patterson et al., 2018; Tâbara et al., 2018).

Pathways compatible with 1.5°C warming are not merely scenarios to envision possible futures but processes of deliberation and implementation that address societal values, local priorities, and inevitable trade-offs. This includes attention to politics and power that perpetuate business-as-usual trajectories (K. O’Brien, 2016; Harris et al., 2017), the politics that shape sustainability and capabilities of everyday life (Agyeman et al., 2016; Schlosberg et al., 2017), and ingredients for community resilience and transformative change (Fazey et al., 2018). Charting CRDPs encourages locally-situated and problem-solving processes to negotiate and operationalise resilience ‘on the ground’ (Beilin and Wilkinson, 2015; Harris et al., 2017; Ziervogel et al., 2017). This entails contestation, inclusive governance, and iterative engagement of diverse populations with varied needs, aspirations, agency, and rights claims, including those most affected, to deliberate trade-offs in a multiplicity of possible pathways (see Figure 5.6) (Stirling, 2014; Vale, 2014; Walsh-Dilley and Wolford, 2015; Biermann et al., 2016; J.R.A. Butler et al., 2016; K.L. O’Brien, 2016; Harris et al., 2017; Jones and Tanner, 2017; Mapfumo et al., 2017; Rosenbloom, 2017; Gajjar et al., 2018; Klinsky and Winkler, 2018; Lyon, 2018; O’Brien, 2018; Tâbara et al., 2018) (high confidence).

![Figure 5.6: Pathways into the future, with path dependencies and iterative problem-solving and decision-making (after Fazey et al. (2016)).](image)

**Figure 5.6:** Pathways into the future, with path dependencies and iterative problem-solving and decision-making (after Fazey et al. (2016)).

5.5.3.1 **Transformations, Equity, and Well-being**

Most literature related to CRDPs invokes the concept of transformation, underscoring the need for urgent and far-reaching changes in practices, institutions, and social relations in society. Transformations toward a 1.5°C warmer world would need to address considerations for equity and well-being, including in trade-off decisions (see Figure 5.1).
To attain the anticipated transformations, all countries as well as non-state actors would need to strengthen their contributions, through bolder and more committed cooperation and equitable effort-sharing (Rao, 2014; Frumhoff et al., 2015; Ekwurzel et al., 2017; Holz et al., 2017; Millar et al., 2017; Shue, 2017; Robinson and Shine, 2018) (medium evidence, high agreement). Sustaining decarbonisation rates at a 1.5°C-compatible level would be unprecedented and not possible without rapid transformations to a net-zero-emissions global economy by mid-century or the later half of the century (see Chapters 2 and 4). Such efforts would entail overcoming technical, infrastructural, institutional, and behavioural barriers across all sectors and levels of society (Pfeiffer et al., 2016; Seto et al., 2016) and defeating path dependencies, including poverty traps (Boonstra et al., 2016; Enqvist et al., 2016; Haider et al., 2017; Lade et al., 2017). Transformation also entails ensuring that 1.5°C-compatible pathways are inclusive and desirable, build solidarity and alliances, and protect vulnerable groups, including against disruptions of transformation (Patterson et al., 2018).

There is growing emphasis on the role of equity, fairness, and justice (see Glossary) regarding context-specific transformations and pathways to a 1.5°C warmer world (Shue, 2014; Thorp, 2014; Dennig et al., 2015; Moellendorf, 2015; Klinsky et al., 2017b; Roser and Seidel, 2017; Sealey-Huggins, 2017; Klinsky and Winkler, 2018; Robinson and Shine, 2018) (medium evidence, high agreement). Consideration for what is equitable and fair suggests the need for stringent decarbonisation and up-scaled adaptation that do not exacerbate social injustices, locally and at national levels (Okereke and Coventry, 2016), uphold human rights (Robinson and Shine, 2018), are socially desirable and acceptable (von Stechow et al., 2016; Rosenbloom, 2017), address values and beliefs (O’Brien, 2018), and overcome vested interests (Normann, 2015; Patterson et al., 2016). Attention is often drawn to huge disparities in the cost, benefits, opportunities, and challenges involved in transformation within and between countries, and the fact that the suffering of already poor, vulnerable, and disadvantaged populations may be worsened, if care to protect them is not taken (Holden et al., 2017; Klinsky and Winkler, 2018; Patterson et al., 2018).

Well-being for all (Dearing et al., 2014; Raworth, 2017) is at the core of an ecologically safe and socially just space for humanity, including health and housing to peace and justice, social equity, gender equality, and political voices (Raworth, 2017). It is in alignment with transformative social development (UNRISD, 2016) and the 2030 Agenda of ‘leaving no one behind’. The social conditions to enable well-being for all are to reduce entrenched inequalities within and between countries (Klinsky and Winkler, 2018), rethink prevailing values, ethics and behaviours (Holden et al., 2017), allow people to live a life in dignity while avoiding actions that undermine capabilities (Klinsky and Golub, 2016), transform economies (Popescu and Ciurlau, 2016; Tábara et al., 2018), overcome uneven consumption and production patterns (Dearing et al., 2014; Häyhä et al., 2016; Raworth, 2017) and conceptualise development as well-being rather than mere economic growth (Gupta and Pouw, 2017) (medium evidence, high agreement).

### 5.5.3.2 Development Trajectories, Sharing of Efforts, and Cooperation

The potential for pursuing sustainable and climate-resilient development pathways toward a 1.5°C warmer world differs between and within nations, due to differential development achievements and trajectories, and opportunities and challenges (Figure 5.1) (very high confidence). There are clear differences between high-income countries where social achievements are high, albeit often with negative effects on the environment, and most developing nations where vulnerabilities to climate change are high and social support and life satisfaction are low, especially in the Least Developed Countries (Sachs et al., 2017; O’Neill et al., 2018). Differential starting points for CRDPs between and within countries, including path dependencies (Figure 5.6), call for sensitivity to context (Klinsky and Winkler, 2018). For the developing world, limiting warming to 1.5°C also means potentially severely curtailed development prospects (Okereke and Coventry, 2016) and risks to human rights from both climate action and inaction to achieve this goal (Robinson and Shine, 2018) (Section 5.2). Within-country development differences remain, despite efforts to ensure inclusive societies (Gupta and Arts, 2017; Gupta and Pouw, 2017). Cole et al. (2017), for instance, show how differences between provinces in South Africa constitute barriers to sustainable development trajectories and for operationalising nation-level SDGs, across various dimensions of social deprivation and environmental
Moreover, various equity and effort- or burden-sharing approaches to climate stabilisation in the literature allow to sketch national potentials for a 1.5°C warmer world (e.g., CSO Review, 2015; Meinshausen et al., 2015; Okereke and Coventry, 2016; Anand, 2017; Bexell and Jönsson, 2017; Holz et al., 2017; Otto et al., 2017; Pan et al., 2017; Robiou du Pont et al., 2017; Kartha et al., 2018; Winkler et al., 2018). Many approaches build on the AR5 ‘responsibility-capacity-need’ assessment (Clarke et al., 2014), complement other proposed national-level metrics for capabilities, equity, and fairness (Heyward and Roser, 2016; Klinsky et al., 2017a), or fall under the wider umbrella of fair share debates on responsibility, capability, and right to development in climate policy (Fuglestvedt and Kallbekken, 2016). Importantly, different principles and methodologies generate different calculated contributions, responsibilities, and capacities (Skeie et al., 2017).

The notion of nation-level fair shares is now also discussed in the context of limiting global warming to 1.5°C, and the Nationally Determined Contributions (NDCs) (see Chapter 4, Cross-Chapter Box 11 in Chapter 4) (CSO Review, 2015; Mace, 2016; Holz et al., 2017; Pan et al., 2017; Robiou du Pont et al., 2017; Kartha et al., 2018; Winkler et al., 2018). A study by Pan et al. (2017) concluded that all countries would need to contribute to ambitious emission reduction and that current pledges for 2030 by seven out of eight high-emitting countries would be insufficient to meet 1.5°C. Emerging literature on justice-centred pathways to 1.5°C points toward ambitious emission reductions domestically and committed cooperation internationally whereby wealthier countries support poorer ones, technologically, financially, and otherwise to enhance capacities (Okereke and Coventry, 2016; Holz et al., 2017; Robinson and Shine, 2018; Shue, 2018). These findings suggest that equitable and 1.5°C-compatible pathways would require fast action across all countries at all levels of development rather than late accession of developing countries (as assumed under SSP3, see Chapter 2), with external support for prompt mitigation and resilience-building efforts in the latter (medium evidence, medium agreement).

Scientific advances since the AR5 now also allow to determine contributions to climate change for non-state actors (see Chapter 4, Section 4.4.1) and their potential to contribute to CRDPs (medium evidence, medium agreement). This includes cities (Bulkeley et al., 2013, 2014; Byrne et al., 2016), businesses (Heede, 2014; Frumhoff et al., 2015; Shue, 2017), transnational initiatives (Castro, 2016; Andonova et al., 2017), and industries. Recent work demonstrates the contributions of 90 industrial carbon producers to global temperature and sea level rise, and their responsibilities to contribute to investments in and support for mitigation and adaptation (Heede, 2014; Ekwurzel et al., 2017; Shue, 2017) (Sections 5.6.1 and 5.6.2).

At the level of groups and individuals, equity in pursuing climate resilience for a 1.5°C warmer world means addressing disadvantage, inequities, and empowerment that shape transformative processes and pathways (Fazey et al., 2018), and deliberate efforts to strengthen the capabilities, capacities, and well-being of poor, marginalised, and vulnerable people (Byrnes, 2014; Tokar, 2014; Harris et al., 2017; Klinsky et al., 2017a; Klinsky and Winkler, 2018). Community-driven CRDPs can flag potential negative impacts of national trajectories on disadvantaged groups, such as low-income families and communities of colour (Rao, 2014). They emphasise social equity, participatory governance, social inclusion, and human rights, as well as innovation, experimentation, and social learning (see Glossary) (medium evidence, high agreement) (Sections 5.5.3.3 and 5.6).

5.5.3.3 Country and Community Strategies and Experiences

There are many possible pathways toward climate-resilient futures (O’Brien, 2018; Tábara et al., 2018). Literature depicting different sustainable development trajectories in line with CRDPs is growing with some specific to 1.5°C global warming. Most experiences to date are at local and sub-national levels (Cross-Chapter Box 13 in this Chapter) while state-level efforts align largely with green economy trajectories or planning for climate resilience (Box 5.3). Due to the fact that these strategies are context-specific, the literature is scarce on comparisons, efforts to scale up, and systematic monitoring.
States can play an enabling or hindering role in transitions to 1.5°C warmer worlds (Patterson et al., 2018). The literature on strategies to reconcile low-carbon trajectories with sustainable development and ecological sustainability through green growth, inclusive growth, de-growth, post-growth, and development as well-being shows low agreement (see Chapter 4, Section 4.5). Efforts that align best with CRDPs are described as ‘transformational’ and ‘strong’ (Ferguson, 2015). Some view ‘thick green’ perspectives as enabling equity, democracy, and agency building (Lorek and Spangenberg, 2014; Stirling, 2014; Ehresman and Okereke, 2015; Buch-Hansen, 2018), others show how green economy and sustainable development pathways can align (Brown et al., 2014; Georgeson et al., 2017b), and how a green economy can help link the SDGs with NDCs, for instance in Mongolia, Kenya, and Sweden (Shine, 2017). Others still critique the continuous reliance on market mechanisms (Wanner, 2014; Brockington and Ponte, 2015), and disregard for equity and distributional and procedural justice (Stirling, 2014; Bell, 2015).

Country-level pathways and achievements vary significantly (robust evidence, medium agreement). For instance, the Scandinavian countries rank top in the Global Green Economy Index (Dual Citizen LLC, 2016), although they also tend to show high spill-over effects (Holz et al., 2017) and transgress their biophysical boundaries (O’Neill et al., 2018). State-driven efforts in non-member countries of the Organisation for Economic Co-operation and Development include Ethiopia’s ‘Climate-resilient Green Economy Strategy’, Mozambique’s ‘Green Economy Action Plan’, and Costa Rica’s ecosystem- and conservation-driven green transition paths. China and India have adopted technology and renewables pathways (Brown et al., 2014; Death, 2014, 2015, 2016; Khanna et al., 2014; Chen et al., 2015; Kim and Thurbon, 2015; Wang et al., 2015; Weng et al., 2015). Brazil promotes low per-capita GHG emissions, clean energy sources, green jobs, renewables, and sustainable transportation while slowing rates of deforestation (Brown et al., 2014; La Rovere, 2017) (see Chapter 4, Box 4.7). Yet, concerns remain regarding persistent inequalities, ecosystem monetisation, lack of participation in green-style projects (Brown et al., 2014), and labour conditions and risk of displacement in the sugarcane ethanol sector (McKay et al., 2016). Experiences with low-carbon development pathways in Least Developed Countries (LDCs) highlight the crucial role of identifying synergies across scale, removing institutional barriers, and ensuring equity and fairness in distributing benefits as part of the right to development (Rai and Fisher, 2017).

In small islands states, for many of which climate change hazards and impacts at 1.5°C pose significant risks to sustainable development (see Chapter 3 Box 3.5, Chapter 4 Box 4.3, Box 5.3), examples of CRDPs have emerged since the AR5. This includes the SAMOA Pathway: SIDS Accelerated Modalities of Action (see Chapter 4, Box 4.3) (UN, 2014a; Government of Kiribati, 2016; Steering Committee on Partnerships for SIDS and UNDESA, 2016; Lefale et al., 2017) and the Framework for Resilient Development in the Pacific, a leading example of integrated regional climate change adaptation planning for mitigation and sustainable development, disaster risk management and low carbon economies (FRDP, 2016). Small islands of the Pacific vary significantly in their capacity and resources to support effective integrated planning (McCubbin et al., 2015; Barnett and Walters, 2016; Cvitanovic et al., 2016; Hemstock, 2017; Robinson and Dorman, 2017). Vanuatu (Box 5.3) has developed a significant coordinated national adaptation plan to advance the 2030 Agenda for Sustainable Development, respond to the Paris Agreement, and reduce the risk of disasters in line with the Sendai targets (UNDP, 2016; Republic of Vanuatu, 2017).

Box 5.3: Republic of Vanuatu – National Planning for Development and Climate Resilience

The Republic of Vanuatu is leading Pacific Small Island Developing States (SIDS) to develop a nationally coordinated plan for climate-resilient development in the context of high exposure to hazard risk (MCCA, 2016; UNU-EHS, 2016). The majority of the population depends on subsistence, rain-fed agriculture and coastal fisheries for food security (Sovacool et al., 2017). Sea level rise, increased prolonged drought, water shortages, intense storms, cyclone events, and degraded coral reef environments threaten human security in a 1.5°C warmer world (see Chapter 3, Box 3.5) (SPC, 2015; Aipira et al., 2017). Given Vanuatu’s long history of disasters, local adaptive capacity is relatively high, despite barriers to the use of local knowledge and...
technology, and low rates of literacy and women’s participation (McNamara and Prasad, 2014; Aipira et al., 2017; Granderson, 2017). However, the adaptive capacity of Vanuatu and other SIDS is increasingly constrained due to more frequent severe weather events (see Chapter 3 Box 3.5, Chapter 4, Cross-Chapter Box 9 in Chapter 4) (Gero et al., 2013; Kuruppu and Willie, 2015; SPC, 2015; Sovacool et al., 2017).

Vanuatu has developed a national sustainable development plan for 2016-2030: the People’s Plan (Republic of Vanuatu, 2016). This coordinated, inclusive plan of action on economy, environment, and society aims to strengthen adaptive capacity and resilience to climate change and disasters. It emphasises rights of all Ni-Vanuatu, including women, youth, the elderly, and vulnerable groups (Nalau et al., 2016). Vanuatu has also developed a Coastal Adaptation Plan (Republic of Vanuatu, 2016), an integrated Climate Change and Disaster Risk Reduction Policy (2016–2030) (SPC, 2015), and the first South Pacific National Advisory Board on Climate Change & Disaster Risk Reduction (SPC, 2015; UNDP, 2016).

Vanuatu aims to integrate planning at multiple scales, and increase climate resilience by supporting local coping capacities and iterative processes of planning for sustainable development and integrated risk assessment (Aipira et al., 2017; Eriksson et al., 2017; Granderson, 2017). Climate-resilient development is also supported by non-state partnerships, for example, the ‘Yumi stap reki long climate change’– or the Vanuatu non-governmental organisation Climate Change Adaptation Program (Maclellan, 2015). This programme focuses on equitable governance, with particular attention to supporting women’s voices in decision making through allied programs addressing domestic violence, and rights-based education to reduce social marginalisation; alongside institutional reforms for greater transparency, accountability, and community participation in decision-making (Davies, 2015; Maclellan, 2015; Starrett, 2015; Ensor, 2016; UN Women, 2016).

Power imbalances embedded in the political economy of development (Nunn et al., 2014), gender discrimination (Aipira et al., 2017), and the priorities of climate finance (Cabezon et al., 2016) may marginalise the priorities of local communities and influence how local risks are understood, prioritised, and managed (Kuruppu and Willie, 2015; Baldacchino, 2017; Sovacool et al., 2017). However, the experience of the low death toll after Cyclone Pam suggests effective use of local knowledge in planning and early warning may support resilience at least in the absence of storm surge flooding (Handmer and Iveson, 2017; Nalau et al., 2017). Nevertheless, the very severe infrastructure damage of Cyclone Pam 2015 highlights the limits of individual Pacific SIDS efforts and the need for global and regional responses to a 1.5°C warmer world (Dilling et al., 2015; Ensor, 2016; Shultz et al., 2016; Rey et al., 2017) (see Chapter 3 Box 3.5, Chapter 4 Box 4.3).

Communities, towns, and cities also contribute to low-carbon pathways, sustainable development and fair and equitable climate resilience, often focused on processes of power, learning, and contestation as entry points to more localised CRDPs (medium evidence, high agreement) (Cross-Chapter Box 13 in this Chapter, Box 5.2). In the Scottish Borders Climate Resilient Communities Project (United Kingdom), local flood management is linked with national policies to foster cross-scalar and inclusive governance, with attention to systemic disadvantages, shocks and stressors, capacity building, learning for change, and climate narratives to inspire hope and action, all of which are essential for community resilience in a 1.5°C warmer world (Fazey et al., 2018). Narratives and storytelling are vital for realising place-based 1.5°C futures as they create space for agency, deliberation, co-constructing meaning, imagination, and desirable and dignified pathways (Veland et al., 2018). Engagement with possible futures, identity, and self-reliance is also documented for Alaska where 1.5°C warming has already been exceeded and indigenous communities invest in renewable energy, greenhouses for food security, and new fishing practices to overcome loss of sea ice, flooding, and erosion (Chapin et al., 2016; Fazey et al., 2018). The Asian Cities Climate Change Resilience Network (ACCRN) facilitates shared learning dialogues, risk-to-resilience workshops, and iterative, consultative planning in flood-prone cities in India; vulnerable communities, municipal government agencies, entrepreneurs, and technical experts negotiate different visions, trade-offs, and local politics to identify desirable pathways (Harris et al., 2017).
Transforming our societies and systems to limit global warming to 1.5°C and ensuring equity and well-being for human populations and ecosystems in a 1.5°C warmer world would require ambitious and well-integrated adaptation-mitigation-development pathways that deviate fundamentally from high-carbon, business-as-usual futures (Okereke and Coventry, 2016; Arts, 2017; Gupta and Arts, 2017; Sealey-Huggins, 2017). Identifying and negotiating socially acceptable, inclusive, and equitable pathways toward climate-resilient futures is a challenging, yet important, endeavour, fraught with complex moral, practical, and political difficulties and inevitable trade-offs (very high confidence). The ultimate questions are: what futures do we want (Bai et al., 2016; Tábara et al., 2017; Klinsky and Winkler, 2018; O’Brien, 2018; Veland et al., 2018), whose resilience matters, for what, where, when and why (Meerow and Newell, 2016), and ‘whose vision … is being pursued and along which pathways’ (Gillard et al., 2016).

[START CROSS-CHAPTER BOX 13 HERE]

Cross-Chapter Box 13: Cities and Urban Transformation

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Global Urbanisation in a 1.5°C Warmer World

The concentration of economic activity, dense social networks, human resource capacity, investment in infrastructure and buildings, relatively nimble local governments, close connection to surrounding rural and natural environments, and a tradition of innovation provide urban areas with transformational potential (Castán Broto, 2017) (see Chapter 4, Section 4.3.3). In this sense, the urbanisation mega-trend that will take place over the next three decades, and add approximately 2 billion people to the global urban population (UN, 2014b), offers opportunities for efforts to limit warming to 1.5°C.

Cities can also, however, concentrate the risks of flooding, landslides, fire, and infectious and parasitic disease that are expected to heighten in a 1.5°C warmer world (Chapter 3). In African and Asian countries where urbanisation rates are high, these risks could expose and amplify pre-existing stresses related to poverty, exclusion, and governance (Gore, 2015; Dodman et al., 2017; Jiang and O’Neill, 2017; Pelling et al., 2018; Solecki et al., 2018). Through its impact on economic development and investment, urbanisation often leads to increased consumption and environmental degradation and enhanced vulnerability, risk, and impacts (Rosenzweig et al., 2018). In the absence of innovation, the combination of urbanisation and urban economic development could contribute 226 GtCO₂ in emissions by 2050 (Bai et al., 2018). At the same time, some new urban developments are demonstrating combined carbon and Sustainable Development Goals (SDG) benefits (Wiktorowicz et al., 2018), and it is in towns and cities that building renovation rates can be most easily accelerated to support the transition to 1.5°C pathways (Kuramochi et al., 2018), including through voluntary programs (Van der Heijden, 2018).

Urban Transformations and Emerging Climate-Resilient Development Pathways

1.5°C pathways require action in all cities and urban contexts. Recent literature emphasises the need to deliberate and negotiate how resilience and climate-resilient pathways can be fostered in the context of people’s daily lives, including the failings of everyday development such as unemployment, inadequate housing, and growing informality, in order to acknowledge local priorities and foster transformative learning (Vale, 2014; Shi et al., 2016; Harris et al., 2017; Ziervogel et al., 2017; Fazey et al., 2018; Macintyre et al., 2018). Enhancing deliberate transformative capacities in urban contexts also entails new and relational forms of envisioning agency, equity, resilience, social cohesion, and well-being (Gillard et al., 2016; Ziervogel et al., 2016) (Section 5.5.3). Two examples of urban transformation are explored here.
The built environment, spatial planning, infrastructure, energy services, mobility, and urban-rural linkages necessary in rapidly growing cities in South Asia and Africa in the next three decades present mitigation, adaptation and development opportunities that are crucial for a 1.5°C world (Newman et al., 2017; Lwasa et al., 2018; Teferi and Newman, 2018). Realising these opportunities would require the structural challenges of poverty, weak and contested local governance, and low levels of local government investment to be addressed on an unprecedented scale (Wachsmuth et al., 2016; Chu et al., 2017; van Noorloos and Kloosterboer, 2017; Pelling et al., 2018).

Urban governance is critical to ensuring that the necessary urban transitions deliver economic growth and equity (Hughes et al., 2018). The proximity of local governments to citizens and their needs can make them powerful agents of climate action (Melica et al., 2018), but urban governance is enhanced when it involves multiple actors (Ziervogel et al., 2016; Pelling et al., 2018), supportive national governments (Tait and Euston-Brown, 2017) and sub-national climate networks (see Chapter 4, Section 4.4.1). Governance is complicated for the urban population currently living in what is termed ‘informality’. This population is expected to triple, to three billion, by 2050 (Satterthwaite et al., 2018), placing a significant portion of the world’s population beyond the direct reach of formal climate mitigation and adaptation policies (Revi et al., 2014). How to address the co-evolved and structural conditions that lead to urban informality and associated vulnerability to 1.5°C of warming is a central question for this report. Brown and McGranahan (2016) cite evidence that the informal urban "green economy” that has emerged out of necessity in the absence of formal service provisions is frequently low-carbon and resource-efficient.

Realising the potential for low carbon transitions in informal urban settlements would require an express recognition of the unpaid-for contributions of women in the informal economy, and new partnerships between the state and communities (Ziervogel et al., 2017; Pelling et al., 2018; Satterthwaite et al., 2018). There is no guarantee that these partnerships will evolve or cohere into the type of service delivery and climate governance system that could steer the change on a scale required to limit to warming to 1.5°C (Jaglin, 2014). However, transnational networks such as Shack/Slum Dwellers International, C40, the Global Covenant of Mayors, and International Council for Local Environmental Initiatives (ICLEI), as well as efforts to combine in-country planning for Nationally Determined Contributions (NDCs) (Andonova et al., 2017; Fuhr et al., 2018) with those taking place to support the New Urban Agenda and National Urban Policies, represent one step towards realising the potential (Tait and Euston-Brown, 2017). So too do “old urban agendas” such as slum upgrading and universal water and sanitation provision (McGranahan et al., 2016; Satterthwaite, 2016; Satterthwaite et al., 2018).

**Transition Towns (TTs)** is a type of urban transformation mainly in high-income countries. The grassroots TT movement (origin in the United Kingdom) combines adaptation, mitigation, and just transitions, mainly at the level of communities and small towns. It now has >1,300 registered local initiatives in >40 countries (Grossmann and Creamer, 2017), many of them in the United Kingdom, the United States, and other high-income countries. TTs are described as ‘progressive localism’ (Cretney et al., 2016), aiming to foster a ‘communitarian ecological citizenship’ that goes beyond changes in consumption and lifestyle (Kenis, 2016). They aspire to promote equitable communities resilient to the impacts of climate change, peak oil, and unstable global markets; re-localisation of production and consumption; and transition pathways to a post-carbon future (Feola and Nunes, 2014; Evans and Phelan, 2016; Grossmann and Creamer, 2017).

TT initiatives typically pursue lifestyle-related low-carbon living and economies, food self-sufficiency, energy efficiency through renewables, construction with locally-sourced material, and cottage industries (Barnes, 2015; Staggenborg and Ogrodnik, 2015; Taylor Aiken, 2016). Social and iterative learning through the collective involves dialogue, deliberation, capacity building, citizen science engagements, technical re-skilling to increase self-reliance, for example canning and preserving food and permaculture, future visioning, and emotional training to share difficulties and loss (Feola and Nunes, 2014; Barnes, 2015; Boke, 2015; Taylor Aiken, 2015; Kenis, 2016; Mehmood, 2016; Grossmann and Creamer, 2017).

Important conditions for successful transition groups include flexibility, participatory democracy, care ethics,
inclusiveness, and consensus-building, assuming bridging or brokering roles, and community alliances and partnerships (Feola and Nunes, 2014; Mehmood, 2016; Taylor Aiken, 2016; Grossmann and Creamer, 2017). Smaller scale rural initiatives allow for more experimentation (Cretney et al., 2016) while those in urban centres benefit from stronger networks and proximity to power structures (North and Longhurst, 2013; Nicolosi and Feola, 2016). Increasingly, TTs recognise the need to participate in policy making (Kenis and Mathijs, 2014; Barnes, 2015).

Despite high self-ratings of success, some TT initiatives are too inwardly focused and geographically isolated (Feola and Nunes, 2014) while others have difficulties in engaging marginalised, non-white, non-middle-class community members (Evans and Phelan, 2016; Nicolosi and Feola, 2016; Grossmann and Creamer, 2017). In the United Kingdom, expectations of innovations growing in scale (Taylor Aiken, 2015) and carbon accounting methods required by funding bodies (Taylor Aiken, 2016) undermine local resilience building. Tension between explicit engagements with climate change action and efforts to appeal to more people have resulted in difficult trade-offs and strained member relations (Grossmann and Creamer, 2017) though the contribution to changing an urban culture that prioritises climate change can be underestimated (Wiktorowicz et al., 2018).

Urban actions that can highlight the 1.5°C agenda include individual actions within homes (Werfel, 2017; Buntaine and Prather, 2018), demonstration zero carbon developments (Wiktorowicz et al., 2018), new partnerships between communities, government and business to build mass transit and electrify transport (Glazebrook and Newman, 2018), city plans to include climate outcomes (Millard-Ball, 2013), and support for transformative change across political, professional, and sectoral divides (Bai et al., 2018).

[END CROSS-CHAPTER BOX 13 HERE]

5.6 Conditions for Achieving Sustainable Development, Eradicating Poverty and Reducing Inequalities in 1.5°C Warmer Worlds

This chapter has described the fundamental, urgent, and systemic transformations that would be needed to achieve sustainable development, eradicate poverty, and reduce inequalities in a 1.5°C warmer world, in various contexts and across scales. In particular, it has highlighted the societal dimensions, putting at the centre people’s needs and aspirations in their specific contexts. Here, we synthesise some of the most pertinent enabling conditions (see Glossary) to support these profound transformations. These conditions are closely interlinked and connected by the overarching concept of governance, which broadly includes institutional, socioeconomic, cultural, and technological elements (see Chapter 1, Cross-Chapter Box 4 in Chapter 1).

5.6.1 Finance and Technology Aligned with Local Needs

Significant gaps in green investment constrain transitions to a low-carbon economy aligned with development objectives (Volz et al., 2015; Campiglio, 2016). Hence, unlocking new forms of public, private, and public–private financing is essential to support environmental sustainability of the economic system (Croce et al., 2011; Blyth et al., 2015; Falcone et al., 2018) (see Chapter 4, Section 4.4.5). To avoid risks of undesirable trade-offs with the SDGs caused by national budget constraints, improved access to international climate finance is essential for supporting adaptation, mitigation, and sustainable development, especially for Least Developed Countries (LDCs) and Small Island Developing States (SIDS) (Shine and Campillo, 2016; Wood, 2017) (medium evidence, high agreement). Care needs to be taken when international donors or partnership arrangements influence project financing structures (Kongsager and Corbera, 2015; Purdon, 2015; Ficklin et al., 2017; Phillips et al., 2017). Conventional climate funding schemes, especially the Clean Development Mechanism (CDM), have shown positive effects on sustainable development but also adverse consequences, for example on adaptive capacities of rural households and uneven distribution of costs and
benefits, often exacerbating inequalities (Aggarwal, 2014; Brohé, 2014; He et al., 2014; Schade and Obergassel, 2014; Smits and Middleton, 2014; Wood et al., 2016a; Horstmann and Hein, 2017; Kreibich et al., 2017) (robust evidence, high agreement). Close consideration of recipients’ context-specific needs when designing financial support helps to overcome these limitations as it better aligns community needs, national policy objectives, and donors’ priorities, puts the emphasis on the increase of transparency and predictability of support, and fosters local capacity building (Barrett, 2013; Boyle et al., 2013; Shine and Campillo, 2016; Ley, 2017; Sánchez and Izzo, 2017) (medium evidence, high agreement).

The development and transfer of technologies is another enabler for developing countries to contribute to the requirements of the 1.5°C objective while achieving climate resilience and their socioeconomic development goals (see Chapter 4, Section 4.4.4). International-level governance would be needed to boost domestic innovation and the deployment of new technologies such as Negative Emission Technologies toward the 1.5°C objective (see Chapter 4, Section 4.3.7), but the alignment with local needs depends on close consideration of the specificities of the domestic context in countries at all levels of development (de Coninck and Sagar, 2015; IEA, 2015; Parikh et al., 2018). Technology transfer supporting development in developing countries would require an understanding of local and national actors and institutions (de Coninck and Puig, 2015; de Coninck and Sagar, 2017; Michaelowa et al., 2018), careful attention to the capacities in the entire innovation chain (Khosla et al., 2017; Olawuyi, 2017), and transfer of not only equipment but also knowledge (Murphy et al., 2015) (medium evidence, high agreement).

5.6.2 Integration of Institutions

Multi-level governance in climate change has emerged as a key enabler for systemic transformation and effective governance (see Chapter 4, Section 4.4.1). On the one hand, low-carbon and climate-resilient development actions are often well aligned at the lowest scale possible (Suckall et al., 2015; Sánchez and Izzo, 2017), and informal, local institutions are critical in enhancing the adaptive capacity of countries and marginalised communities (Yaro et al., 2015). On the other hand, international and national institutions can provide incentives for projects to harness synergies and avoid trade-offs (Kongsager et al., 2016).

Governance approaches that coordinate and monitor multi-scale policy actions and trade-offs across sectoral, local, national, regional, and international levels are therefore best suited to implement goals toward 1.5°C warmer conditions and sustainable development (Ayers et al., 2014; Stringer et al., 2014; von Stechow et al., 2016; Gwimi, 2017; Hayward, 2017; Maor et al., 2017; Roger et al., 2017; Michaelowa et al., 2018). Vertical and horizontal policy integration and coordination is essential to take into account the interplay and trade-offs between sectors and spatial scales (Duguma et al., 2014; Naess et al., 2015; von Stechow et al., 2015; Antwi-Agyei et al., 2017a; Di Gregorio et al., 2017; Runhaar et al., 2018), enable the dialogue between local communities and institutional bodies (Colenbrander et al., 2016), and involve non-state actors such as business, local governments, and civil society operating across different scales (Hajer et al., 2015; Labriet et al., 2015; Hale, 2016; Pelling et al., 2016; Kalafatis, 2017; Lyon, 2018) (robust evidence, high agreement).

5.6.3 Inclusive Processes

Inclusive governance processes are critical for preparing for a 1.5°C warmer world (Fazey et al., 2018; O’Brien, 2018; Patterson et al., 2018). These processes have been shown to serve the interests of diverse groups of people and enhance empowerment of often excluded stakeholders, notably women and youth, (MRFCJ, 2015a; Dumont et al., 2017). They also enhance social and co-learning which, in turn, facilitates accelerated and adaptive management and the scaling up of capacities for resilience building (Ensor and Harvey, 2015; Reij and Winterbottom, 2015; Tschakert et al., 2016; Binam et al., 2017; Dumont et al., 2017; Fazey et al., 2018; Lyon, 2018; O’Brien, 2018), and provides opportunities to blend indigenous, local, and scientific knowledge (Antwi-Agyei et al., 2017a; Coe et al., 2017; Thornton and Comberti, 2017) (see Chapter 4, Section 4.3.5.5, Box 4.3; Section 5.3) (robust evidence, high agreement). Such co-learning has...
been effective in improving deliberative decision-making processes that incorporate different values and world views (Cundill et al., 2014; C. Butler et al., 2016; Ensor, 2016; Fazey et al., 2016; Gorddard et al., 2016; Aipira et al., 2017; Fook, 2017; Maor et al., 2017), and create space for negotiating diverse interests and preferences (O’Brien et al., 2015; Gillard et al., 2016; DeCaro et al., 2017; Harris et al., 2017; Lahn, 2017) (robust evidence, high agreement).

5.6.4 Attention to Issues of Power and Inequality

Societal transformations to limit global warming to 1.5°C and strive for equity and well-being for all are not power neutral (Section 5.5.3). Development preferences are often shaped by powerful interests that determine the direction and pace of change, anticipated benefits and beneficiaries, and acceptable and unacceptable trade-offs (Newell et al., 2014; Fazey et al., 2016; Tschanert et al., 2016; Winkler and Dubash, 2016; Wood et al., 2016b; Karlsson et al., 2017; Quan et al., 2017; Tanner et al., 2017). Each development pathway, including legacies and path dependencies, creates its own set of opportunities and challenges and winners and losers, both within and across countries (Figure 5.6) (Mathur et al., 2014; Ficklin et al., 2017; Phillips et al., 2017; Stringer et al., 2017; Wood, 2017; Gajjar et al., 2018) (robust evidence, high agreement).

Addressing the uneven distribution of power is critical to ensure that societal transformation toward a 1.5°C warmer world does not exacerbate poverty and vulnerability or create new injustices but rather encourages equitable transformational change (Patterson et al., 2018). Equitable outcomes are enhanced when they pay attention to just outcomes for those negatively affected by change (Newell et al., 2014; Dilling et al., 2015; Naess et al., 2015; Sovacool et al., 2015; Cervigni and Morris, 2016; Keohane and Victor, 2016) and promote human rights, increase equality, and reduce power asymmetries within societies (UNRISD, 2016; Robinson and Shine, 2018) (robust evidence, high agreement).

5.6.5 Reconsidering Values

The profound transformations that would be needed to integrate sustainable development and 1.5°C-compatible pathways call for examining the values, ethics, attitudes, and behaviours that underpin societies (Hartzell-Nichols, 2017; O’Brien, 2018; Patterson et al., 2018). Infusing values that promote sustainable development (Holden et al., 2017), overcome individual economic interests and go beyond economic growth (Hackmann, 2016), encourage desirable and transformative visions (Tâbara et al., 2018), and care for the less fortunate (Howell and Allen, 2017) is part and parcel of climate-resilient and sustainable development pathways. This entails helping societies and individuals to strive for sufficiency in resource consumption within planetary boundaries alongside sustainable and equitable well-being (O’Neill et al., 2018). Navigating 1.5°C societal transformations, characterised by action from local to global, stresses the core commitment to social justice, solidarity, and cooperation, particularly regarding the distribution of responsibilities, rights, and mutual obligations between nations (Patterson et al., 2018; Robinson and Shine, 2018) (medium evidence, high agreement).

5.7 Synthesis and Research Gaps

The assessment in Chapter 5 illustrates that limiting global warming to 1.5°C is fundamentally connected with achieving sustainable development, poverty eradication, and reducing inequalities. It shows that avoided impacts between 1.5°C and 2°C temperature stabilisation would make it easier to achieve many aspects of sustainable development, although important risks would remain at 1.5°C (Section 5.2). Synergies between adaptation and mitigation response measures with sustainable development and the Sustainable Development Goals (SDGs) can often be enhanced when attention is paid to well-being and equity while, when unaddressed, poverty and inequalities may be exacerbated (Section 5.3 and 5.4). Climate-resilient
Development pathways (CRDPs) open up routes toward socially desirable futures that are sustainable and liveable, but concrete evidence reveals complex trade-offs along a continuum of different pathways, highlighting the role of societal values, internal contestations, and political dynamics (Section 5.5). The transformations towards sustainable development in a 1.5°C warmer world, in all contexts, involve fundamental societal and systemic changes over time and across scale, and a set of enabling conditions without which the dual goal is difficult if not impossible to achieve (Sections 5.5 and 5.6).

This assessment is supported by growing knowledge on the linkages between a 1.5°C warmer world and different dimensions of sustainable development. However, several gaps in the literature remain:

Limited evidence exists that explicitly examines the real-world implications of a 1.5°C warmer world (and overshoots) as well as avoided impacts between 1.5°C versus 2°C for the SDGs and sustainable development more broadly. Few projections are available for households, livelihoods, and communities. And literature on differential localised impacts and their cross-sector interacting and cascading effects with multidimensional patterns of societal vulnerability, poverty, and inequalities remains scarce. Hence, caution is needed when global-level conclusions about adaptation and mitigation measures in a 1.5°C warmer world are applied to sustainable development in local, national, and regional settings.

Limited literature has systematically evaluated context-specific synergies and trade-offs between and across adaptation and mitigation response measures in 1.5°C-compatible pathways and the SDGs. This hampers the ability to inform decision-making and fair and robust policy packages adapted to different local, regional, or national circumstances. More research is required to understand how trade-offs and synergies will intensify or decrease, differentially across geographic regions and time, in a 1.5°C warmer world and as compared to higher temperatures.

Limited availability of interdisciplinary studies also poses a challenge for connecting the socio-economic transformations and the governance aspects of low-emission, climate-resilient transformations. For example, it remains unclear how governance structures enable or hinder different groups of people and countries to negotiate pathway options, values, and priorities.

The literature does not demonstrate the existence of 1.5°C-compatible pathways achieving the "universal and indivisible" agenda of the 17 SDGs, and hence does not show whether and how the nature and pace of changes that would be required to meet 1.5°C climate stabilisation could be fully synergetic with all the SDGs.

The literature on low-emission and climate-resilient development pathways in local, regional, and national contexts is growing. Yet, the lack of standard indicators to monitor such pathways makes it difficult to compare evidence grounded in specific contexts with differential circumstances and therefore to derive generic lessons on the outcome of decisions on specific indicators. This knowledge gap poses a challenge for connecting local-level visions with global-level trajectories to better understand key conditions for societal and systems transformations that reconcile urgent climate action with well-being for all.
Frequently Asked Questions

FAQ 5.1: What are the connections between sustainable development and limiting global warming to 1.5°C?

Summary: Sustainable development seeks to meet the needs of people living today without compromising the needs of future generations, while balancing social, economic and environmental considerations. The 17 UN Sustainable Development Goals (SDGs) include targets for eradicating poverty; ensuring health, energy and food security; reducing inequality; protecting ecosystems; pursuing sustainable cities and economies; and a goal for climate action (SDG13). Climate change affects the ability to achieve sustainable development goals and limiting warming to 1.5°C will help meet some sustainable development targets. Pursuing sustainable development will influence emissions, impacts and vulnerabilities. Responses to climate change in the form of adaptation and mitigation will also interact with sustainable development with positive effects, known as synergies, or negative effects, known as trade-offs. Responses to climate change can be planned to maximize synergies and limit trade-offs with sustainable development.

For more than 25 years, the United Nations (UN) and other international organizations have embraced the concept of sustainable development to promote wellbeing and meet the needs of today’s population without compromising the needs of future generations. This concept spans economic, social and environmental objectives including poverty and hunger alleviation, equitable economic growth, access to resources, and the protection of water, air and ecosystems. Between 1990 and 2015, the UN monitored a set of eight Millennium Development Goals (MDGs). They reported progress in reducing poverty, easing hunger and child mortality, and improving access to clean water and sanitation. But with millions remaining in poor health, living in poverty, and facing serious problems associated with climate change, pollution and land use change, the UN decided that more needed to be done. In 2015, the UN Sustainable Development Goals (SDGs) were endorsed as part of the 2030 Agenda for Sustainable Development. The 17 SDGs (Figure FAQ 5.1) apply to all countries and have a timeline for success by 2030. The SDGs seek to eliminate extreme poverty and hunger; ensure health, education, peace, safe water, and clean energy for all; promote inclusive and sustainable consumption, cities, infrastructure and economic growth; reduce inequality including gender inequality; combat climate change and protect oceans and terrestrial ecosystems.

Climate change and sustainable development are fundamentally connected. Previous IPCC reports found that climate change can undermine sustainable development, and that well-designed mitigation and adaptation responses can support poverty alleviation, food security, healthy ecosystems, equality and other dimensions of sustainable development. Limiting global warming to 1.5°C would require mitigation actions and adaptation measures to be taken at all levels. These adaptation and mitigation actions would include reducing emissions and increasing resilience through technology and infrastructure choices, as well as changing behaviour and policy. These actions can interact with sustainable development objectives in positive ways that strengthen sustainable development, known as synergies. Or negative ways, where sustainable development is hindered or reversed, known as trade-offs.

An example of a synergy is sustainable forest management, which can prevent emissions from deforestation and take up carbon to reduce warming at reasonable cost. It can work synergistically with other dimensions of sustainable development by providing food (SDG 2), cleaning water (SDG 6) and protecting ecosystems (SDG 15). Other examples of synergies are when climate adaptation measures, such as coastal or agricultural projects, empower women and benefit local incomes, health and ecosystems.

An example of a trade-off can occur if ambitious climate change mitigation compatible with 1.5°C changes land use in ways that have negative impacts on sustainable development. An example could be turning natural forests, agricultural areas, or land under indigenous or local ownership to plantations for bioenergy production. If not managed carefully, such changes could undermine dimensions of sustainable development by threatening food and water security, creating conflict over land rights, and causing biodiversity loss. Another trade-off could occur for some countries, assets, workers, and infrastructure already in place if a
switch is made from fossil fuels to other energy sources without adequate planning for such a transition. Trade-offs can be minimised if effectively managed as when care is taken to improve bioenergy crop yields to reduce harmful land-use change or where workers are retrained for employment in lower carbon sectors.

Limiting temperatures to 1.5°C can make it much easier to achieve the SDGs, but it is also possible that pursuing the SDGs could result in trade-offs with efforts to limit climate change. There are trade-offs when people escaping from poverty and hunger consume more energy or land and thus increase emissions, or if goals for economic growth and industrialization increase fossil fuel consumption and greenhouse gas emissions. Conversely, efforts to reduce poverty and gender inequalities, and to enhance food, health and water security can reduce vulnerability to climate change. Other synergies can occur when coastal and ocean ecosystem protection reduces the impacts of climate change on these systems. The sustainable development goal of affordable and clean energy (SDG 7) specifically targets access to renewable energy and energy efficiency, important to ambitious mitigation and limiting warming to 1.5°C.

The link between sustainable development and limiting global warming to 1.5°C is recognized by the Sustainable Development Goal for climate action (SDG 13) which seeks to combat climate change and its impacts while acknowledging that the UNFCCC is the primary international, intergovernmental forum for negotiating the global response to climate change.

The challenge is to put in place sustainable development policies and actions that reduce deprivation, alleviate poverty and ease ecosystem degradation while also lowering emissions, reducing climate change impacts and facilitating adaptation. It is important to strengthen synergies and minimize trade-offs when planning climate change adaptation and mitigation actions. Unfortunately, not all trade-offs can be avoided or minimised, but careful planning and implementation can build the enabling conditions for long-term sustainable development.

FAQ 5.1, Figure 1: Climate change action is one of the United Nations Sustainable Development Goals (SDGs) and is connected to sustainable development more broadly. Actions to reduce climate risk can interact with other sustainable development objectives in positive ways (synergies) and negative ways (trade-offs).
FAQ 5.2: What are the pathways to achieving poverty reduction and reducing inequalities while reaching the 1.5°C world?

Summary: There are ways to limit global warming to 1.5°C above pre-industrial levels. Of the pathways that exist, some simultaneously achieve sustainable development. They entail a mix of measures that lower emissions and reduce the impacts of climate change, while contributing to poverty eradication and reducing inequalities. Which pathways are possible and desirable will differ between and within regions and nations. This is due to the fact that development progress to date has been uneven and climate-related risks are unevenly distributed. Flexible governance would be needed to ensure that such pathways are inclusive, fair, and equitable to avoid poor and disadvantaged populations becoming worse off. ‘Climate-Resilient Development Pathways’ (CRDPs) offer possibilities to achieve both equitable and low-carbon futures.

Issues of equity and fairness have long been central to climate change and sustainable development. Equity, like equality, aims to promote justness and fairness for all. This is not necessarily the same as treating everyone equally, since not everyone comes from the same starting point. Often used interchangeably with fairness and justice, equity implies implementing different actions in different places, all with a view to creating an equal world that is fair for all and where no one is left behind.

The Paris Agreement states that it “will be implemented to reflect equity… in the light of different national circumstances” and calls for “rapid reductions” of greenhouse gases to be achieved “on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty”. Similarly, the United Nations Sustainable Development Goals (SDGs) include targets to reduce poverty and inequalities, and to ensure equitable and affordable access to health, water, and energy for all.

The principles of equity and fairness are important for considering pathways that limit warming to 1.5°C in a way that is liveable for every person and species. They recognise the uneven development status between richer and poorer nations, the uneven distribution of climate impacts (including on future generations), and the uneven capacity of different nations and people to respond to climate risks. This is particularly true for those who are highly vulnerable to climate change such as indigenous communities in the Arctic, people whose livelihoods depend on agriculture or coastal and marine ecosystems, and inhabitants of small-island developing states. The poorest people will continue to experience climate change through the loss of income and livelihood opportunities, hunger, adverse health effects, and displacement.

Well-planned adaptation and mitigation measures are essential to avoid exacerbating inequalities or creating new injustices. Pathways that are compatible with limiting warming to 1.5°C and aligned with the SDGs consider mitigation and adaptation options that reduce inequalities in terms of who benefits, who pays the costs, and who is affected by possible negative consequences. Attention to equity ensures that disadvantaged people can secure their livelihoods and live in dignity, and that those who experience mitigation or adaptation costs have financial and technical support to enable fair transitions.

Climate-resilient development pathways (CRDPs) describe trajectories that pursue the dual goal of limiting warming to 1.5°C while strengthening sustainable development. This includes eradicating poverty as well as reducing vulnerabilities and inequalities for regions, countries, communities, businesses, and cities. These trajectories entail a mix of adaptation and mitigation measures consistent with profound societal and systems transformations. The goals are to meet the short-term SDGs, achieve longer-term sustainable development, reduce emissions toward net zero around the middle of the century, build resilience and enhance human capacities to adapt, all while paying close attention to equity and well-being for all.

The characteristics of CRDPs will differ across communities and nations, and will be based on deliberations with a diverse range of people, including those most affected by climate change and by possible routes toward transformation. For this reason, there are no standard methods for designing CRDPs or for monitoring their progress toward climate-resilient futures. However, examples from around the world demonstrate that flexible and inclusive governance structures and broad participation often help support
iterative decision-making, continuous learning, and experimentation. Such inclusive processes can also help to overcome weak institutional arrangements and power structures that may further exacerbate inequalities.

**FAQ 5.2, Figure 1:** Climate-resilient development pathways (CRDPs) describe trajectories that pursue the dual goal of limiting warming to 1.5°C while strengthening sustainable development. Decision-making that achieves the SDGs, lowers greenhouse gas emissions, and limits global warming could help lead to a climate-resilient world, within the context of enhancing adaptation.

Ambitious actions already underway around the world can offer insight into CRDPs for limiting warming to 1.5°C. For example, some countries have adopted clean energy and sustainable transport while creating environmentally friendly jobs and supporting social welfare programs to reduce domestic poverty. Other examples teach us about different ways to promote development through practices inspired by community values. For instance, *Buen Vivir*, a Latin American concept based on indigenous ideas of communities living in harmony with nature, is aligned with peace, diversity, solidarity, rights to education, health, and safe food, water, and energy, and well-being and justice for all. The Transition Movement, with origins in Europe, promotes equitable and resilient communities through low-carbon living, food self-sufficiency, and citizen science. Such examples indicate that pathways that reduce poverty and inequalities while limiting warming to 1.5°C are possible and that they can provide guidance on pathways towards socially desirable, equitable, and low-carbon futures.
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### Chapter 5 – Table 5.3

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<th>Table 5.3.a1</th>
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<td>Poverty reduction via financial savings (1.6)</td>
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<td>Improved warmth and comfort</td>
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<td>Energy efficiency interventions lead to cost savings which are realized due to reduced energy intensity that further lead to poverty reduction. Participants with low incomes experience greater benefits. Energy efficiency and biomass strategies benefit poor more than wind and solar whose benefits are captured by industry. Carbon mitigation can increase or decrease inequalities. The distributional costs of new energy policies (e.g., supporting renewables and energy efficiency) are dependent on instrument design. If costs fall disproportionately on the poor, then this could impair progress towards universal energy access and, by extension, counteract the fight to eliminate poverty. (Quoted from McCollum et al., 2018; Smart Home Technology)</td>
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<td>Using the improved stoves supports local food security and has significantly impacted on food security. By making fuel lasting longer, the improved stoves also help improve food security and provide a better buffer against fuel shortages induced by climate change-related events such as droughts, floods or hurricanes (Berners-Price et al., 2017)</td>
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<td>Access to modern energy forms (electricity, clean cook-stoves, high-quality lighting) is fundamental to human development since the energy services made possible by these forms help alleviate chronic and persistent poverty. Strength of the impact varies in the literature. (Quoted from McCollum et al., 2018)</td>
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<td>Modern energy access is critical to enhance agricultural yields/ productivity, decrease post-harvest losses, and mechanize agriculture processes, which can add food security. However, large-scale bioenergy and food production may compete for scarce land and other inputs (e.g., water, fertilizers), depending on how and where biomass supplies are grown and the indirect land use change impacts that result. If not implemented thoughtfully, this could lead to higher food prices globally, and thus reduced access to affordable food for the poor. Enhanced agricultural production can ameliorate the situation by allowing as much bioenergy to be produced on as little land as possible. (Quoted from McCollum et al., 2018)</td>
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<tr>
<td></td>
<td>Access to modern energy services can contribute to fewer injuries and diseases related to traditional fuel collection and burning, as well as utilization of biomass for cooking. Access to modern energy services can facilitate improved health care provision, medicine and surgical services, utilization of powered medical equipment, and dissemination of health-related information and education. Such services can also enable thermal comfort in homes and contribute to food preservation and safety. (Quoted from McCollum et al., 2018)</td>
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</table>

<table>
<thead>
<tr>
<th>Industry</th>
<th>Disease and Mortality (1.2.1/2.2.4/3.5.4)</th>
<th>Score</th>
<th>Evidence</th>
<th>Agreement</th>
<th>Confidence</th>
</tr>
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<tbody>
<tr>
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<td>Disease and Mortality (1.2.1/2.2.4/3.5.4)</td>
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<td></td>
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<tr>
<td></td>
<td>Improved warmth and comfort</td>
<td>+2</td>
<td>No direct interaction</td>
<td></td>
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<tr>
<td></td>
<td>Healthy lives and well-being (4.3.2)</td>
<td>+2</td>
<td>No direct interaction</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Equal Access to Educational Institutions (4.9.2/4.3.2)</td>
<td>+2</td>
<td>No direct interaction</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** The table above includes a summary of key points related to energy efficiency improvements and their implications. The scores indicate the level of evidence and agreement concerning the impacts. The table is designed to provide a clear and structured overview of the key energy-related themes and their associated benefits. For a full reference, please consult the original sources listed in the text.
## Transport

### Behavioural response

<table>
<thead>
<tr>
<th>Equal right to economic resources access basic services (1.1, 1.4, 1.5, 2.1)</th>
<th>Road Traffic Accidents (3.4/3.6)</th>
<th>Equal Safe Access to Educational Institutions (4.1/4.2/4.3/4.4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>[0]</td>
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</tbody>
</table>

**The costs of daily mobility can have important economic stress impacts not only impacting urban family with low mobility, but in countries with high levels of car dependence, the costs of motoring can be burdensome, raising questions of affordability for households with limited economic resources. Economic crisis public transport authorities may react by reducing levels of service and increasing fares, likely exacerbating the situation for low-income households.**

Robson et al. (2004); Cassing (2017)

### Accelarating energy efficiency improvement

<table>
<thead>
<tr>
<th>End Poverty in all its forms everywhere (1.1, 1.4, 1.5, 2.1)</th>
<th>Reduce biomass from hazardous air pollution (3.4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>[0]</td>
</tr>
</tbody>
</table>

**For many in all its forms everywhere (1.1, 1.4, 1.5, 2.1) | Reduce biomass from hazardous air pollution (3.4) |
| [0] | [0] |

**Over the number of public bus in Sweden is receiving attention more than efficiency improvement. With more electrification, electricity price goes up and affordability can worsen for poor unless redistributive policies are in place.**

Ilipit (2017)

### Improved access & fuel switches to modern low-carbon energy

<table>
<thead>
<tr>
<th>End Poverty in all its forms everywhere (1.1, 1.4, 1.5, 2.1)</th>
<th>Equal Safe Access to Educational Institutions (4.1/4.2/4.3/4.4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
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</tbody>
</table>

**Increasingly volatile global oil prices have raised concerns for the vulnerability of households to fuel price increases. Pricing measures as a key component of sustainable transport policy need to consider equity. Poor pro-poor mitigation policies are needed to reduce climate impact risk to social welfare for example investing more and better in infrastructure by leveraging private resources and using designs that account for future climate change and the related uncertainty. Communities in poor areas cope with and adapt to multiple-stressors including climate change. Coping strategies provide short-term relief but in the long-term may negatively affect development goals. And impede generate a trade-off between adaptation, mitigation and development. Public cities with storms and due to high commuting costs many walk to work places which limit access in Latin American triplicate inequality leading to productivity and living standards.**

Dolton and Sape (2017); Hagglingen et al. (2011); Sukull, Tomlins, and Strange (2014); Lall, Henderson, and Venables (2017); Corporacion Andina de Fomento (2017); Lall, Henderson, and Venables (2017); Corporacion Andina de Fomento (2017); Xylia et al (2017)

<table>
<thead>
<tr>
<th>SR1.5 Final Government Draft</th>
<th>Chapter 5 - Table 5.3</th>
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</thead>
<tbody>
<tr>
<td>Do not cite, quote or distribute</td>
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<tr>
<td></td>
<td>Non-Biomass renewables</td>
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</tr>
<tr>
<td>Form Employment and Incomes (2.2)</td>
<td>Large-scale bioenergy production could lead to the creation of agricultural jobs, as well as higher farm wages and more diversified income streams for farmers. Modern energy access can make marginal lands more cultivable, thus potentially generating on-farm jobs and incomes; on the other hand, greater farm mechanization can also displace labor. On the other hand, large-scale bioenergy production could alter the structure of global agricultural markets in a way that is, potentially, unfavorable to small-scale food production; see SD2 (McCollum et al., 2018).</td>
</tr>
</tbody>
</table>

**Do note cite, quote or distribute**
SR1.5 Final Government Draft

Chapter 5 - Table 5.3

Do note cite, quote or distribute
<table>
<thead>
<tr>
<th>Chapter 5 - Table 5.3</th>
<th>Reducing Deforestation, REDD+</th>
<th>Poverty Reduction (1.2)</th>
<th>Food Security and Promotion of Sustainable Agriculture (2.2-2.4)</th>
<th>Enhanced Weathering</th>
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<tbody>
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<tr>
<td><strong>Partnerships between local forest managers, community enterprises and private sector companies can support local economies and livelihoods, and boost regional and national economic growth.</strong></td>
<td><strong>Food security, may lead to the conservation of productive land under forest, including community forests, into agricultural production. In a similar fashion, the production of biomass for energy purposes (DOE) may reduce land available for food production and/or for community forest activities.</strong> Katila et al., 2017; Efforts by the Government of Zambia to reduce emissions by REDD+ have contributed emission control, reforestation and afforestation valued at 2.5% of the country's GDP. Katila et al., 2017; Turpie, Warr, &amp; Ingram (2015); Epstein and Theuer (2017); Dooley and Kartha (2016).</td>
<td><strong>SR1.5 Final Government Draft</strong></td>
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<table>
<thead>
<tr>
<th>Industry</th>
<th>Accelerating energy efficiency improvement</th>
<th>Score</th>
<th>Evidences</th>
<th>Agreement</th>
<th>Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Knowledge and still needed to promote sustainable development (1.7)</td>
<td>8</td>
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<tr>
<td></td>
<td>There is need for skill in managing house energy efficiency. Sometimes ESCOs also help energy audit but many times absence of skill acts as barrier for energy efficiency improvement. In many countries especially in developing countries these act as barriers.</td>
<td></td>
<td></td>
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<td></td>
<td>Johansson and Thollander (2018); Aspening and Thollander (2013)</td>
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<td>No direct interaction</td>
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<tr>
<td></td>
<td>Empowerment and inclusion (10.1/10.2/10.3/10.4)</td>
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<tr>
<td></td>
<td>McCollum et al. (2018); Cameron et al. (2016); Casillas and Kammen (2012); Fay et al. (2015); Hallegate et al. (2016); Hirth and Ueckerdt (2013); Jakob and Steckel (2014); Johansson and Thollander (2018); Aspening and Thollander (2013); Lawrence et al (2018); Griffin et al (2017)</td>
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<td>No direct interaction</td>
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<td>Incentives that can switch</td>
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<td>No direct interaction</td>
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<td></td>
<td>Decarbonisation/ CCS/ CCU</td>
<td>8</td>
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<td>No direct interaction</td>
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<td>Buildings</td>
<td>8</td>
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<td></td>
<td>Behavioral response</td>
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<td>8</td>
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<tr>
<td></td>
<td>Gender equality and women empowerment (5.1/5.4)</td>
<td>8</td>
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<tr>
<td></td>
<td>Efficient cookstoves lead to empowerment of rural and indigenous women.</td>
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<td></td>
<td>Berry et al. (2017); Bhujwai Jaya et al. (2014)</td>
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<td></td>
<td>Improved access &amp; fuel switch to modern low carbon energy</td>
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<tr>
<td></td>
<td>Women’s Safety &amp; Health (3.2/3.3/3.4/3.5)</td>
<td>8</td>
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<tr>
<td></td>
<td>Improved access to electric lighting can improve women’s safety and girls’ school enrollment.</td>
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<tr>
<td></td>
<td>McCollum et al. (2018); Acresguzoglu (2009); Acresguzoglu et al. (2014); ICSU, ISSC (2015); Tabellini (2010)</td>
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<td>No direct interaction</td>
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<tr>
<td></td>
<td>Environmental justice (16.7)</td>
<td>8</td>
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<tr>
<td></td>
<td>Hult et al. found that consumption perspective strengthens the environmental justice discourse. (x) it claims to be a more just way of calculating global and local environmental effects while possibly also increasing the participatory environmental resource.</td>
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<tr>
<td></td>
<td>McCollum et al. (2018); Cayla and Osso (2013); Dinkelman (2011); Pachauri et al. (2012); Pueyo et al. (2013)</td>
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<tr>
<td></td>
<td>No direct interaction</td>
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**Chapter 5 - Table 5.3**

Do not cite, quote or distribute
### Behavioural response

<table>
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<th>Behavioural response</th>
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<th>Change in Transport Energy Demand Growth</th>
<th>Change in Transport Energy Demand Growth</th>
<th>Change in Transport Energy Demand Growth</th>
<th>Change in Transport Energy Demand Growth</th>
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<td>Reduce Inequality (10.2)</td>
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<td>Accountable and transparent institutions at all levels (16.6, 16.8)</td>
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<td>0</td>
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<tr>
<td>Help promote global partnership (17.1, 17.3, 17.5, 17.6, 17.7)</td>
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</table>

**Transport**

- Recognize Women's unpaid Work (5.1/5.4) / Opportunities for Women (5.1/5.5)
- Ensure responsive, inclusive, participatory decision making (16.7)
- Help promote global partnership (17.1, 17.3, 17.5, 17.6, 17.7)

#### Accelerating energy efficiency improvement

- No Direct Interaction

- Lucas & Pangbourne (2014); Figueres et al. (2014); Mamelle (2015); Walks (2015); Belton et al. (2017)

#### Improved access & fuel switch to modern low-carbon energy

- No Direct Interaction

- Lucas & Pangbourne; Figueres et al. (2014)
## SR1.5 Final Government Draft

### Chapter 5 - Table 5.3

Do not cite, quote or distribute

<table>
<thead>
<tr>
<th>Replacing coal</th>
<th>Non-biomass renewables</th>
<th>solar, wind, hydro</th>
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<tbody>
<tr>
<td><strong>Score</strong></td>
<td><strong>Evidence</strong></td>
<td><strong>Agreement</strong></td>
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<tr>
<td><strong>Interaction</strong></td>
<td><strong>Score</strong></td>
<td><strong>Evidence</strong></td>
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<tr>
<td>International cooperation</td>
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| Decentralized renewable energy systems (e.g., home- or village-scale solar power) can reduce the burden on girls and women of procuring traditional biomass. |

<table>
<thead>
<tr>
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<tr>
<th>Nuclear/Advanced Nuclear</th>
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<table>
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<tr>
<th>CCS, Fossil</th>
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<th>Advanced coal</th>
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<tr>
<td>No direct interaction</td>
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Irlar et al. (2017) states that off-grid and micro-scale energy development offers an alternative path to fossil-fuel use and top-down resource management as they democratize the grid and increase marginalized communities’ access to renewable energy, education and health care.

---

McCollum et al. (2018) and Cass et al. (2010) discuss the potential for decentralized renewable energy systems (e.g., home- or village-scale solar power) to reduce the burden on girls and women of procuring traditional biomass. This approach can empower communities and increase their participation in energy decision-making processes within communities. (Quote from McCollum et al., 2018)

---

Continued use of nuclear power poses a constant risk of proliferation.

---

The energy justice framework serves as an important decision-making tool in order to understand how different principles of justice can inform energy systems and policies. Eis et al. (2017) states that off-grid and micro-scale energy development offers an alternative path to fossil-fuel use and top-down resource management as they democratize the grid and increase marginalized communities’ access to renewable energy, education and health care.

---

Increased use of biomass and biomass-energy systems can reduce the burden on girls and women of procuring traditional biomass. Decentralized renewable energy systems (e.g., home- or village-scale solar power) can enable a more participatory, democratic process for managing energy-related decisions within communities. (Quote from McCollum et al., 2018)

---

International cooperation (in policy) and collaboration (in science) is required for the protection of shared resources. Fragmented approaches have been shown to be more costly. Specific to SDG7, to achieve the targets for energy access, renewables, and efficiency, it will be critical that all countries: (i) are able to mobilize the necessary financial resources (e.g., via taxes on fossil energy, sustainable financing, foreign direct investment, financial transfers from industrialized to developing countries); (ii) are willing to disseminate knowledge and share innovative technologies between each other; (iii) follow recognized international trade rules while at the same time ensuring that the least developed countries are able to take part in that trade; (iv) respect each other’s policy space and decisions; (v) forge new partnerships between their public and private entities and within civil society; and (vi) support the collection of high-quality, timely, and reliable data relevant to the furthering their missions. There is some disagreement in the literature on the effect of some of the above strategies, such as free trade. Regarding international agreements, “no-regrets options”, where all sides gain through cooperation, are seen as particularly beneficial (e.g., nuclear test ban treaties) (McCollum et al., 2018).
Resource mobilization and Strengthen Partnership (17.2/17.3)

Chapter 5 - Table 5.3

No direct interaction

No direct interaction

Strong and effective Institutions and responsive decision making (16.4/16.7/16.9)

Appropriate incentives to reduce food waste may require some policy innovation and experimentation, but a strong commitment for designing and monitoring them seems essential. (Quoted from Radel et al. (2014))

A financial incentive to minimise waste could be created through effective taxation (e.g. by taxing foods with the highest wastage rates, or by increasing taxes on waste disposal). Decision makers should try to integrate agricultural, environmental and nutritional objectives through appropriate policy measures to achieve sustainable healthy diets, with reduction in food waste. It is surprising that politicians and policy makers demonstrate little regarding the need of having strategies to reduce meat consumption, and to encourage more sustainable eating practices in Netherlands.

Denton (2002); Jost et al. (2015); Morton (2007)

Livelihood (Demetriades and Esplen, 2008).

Women often have an especially important role to play in adaptation, because of their gendered indigenous knowledge on matters such as agriculture (Terry, 2009). Without access to land, credit and agricultural technologies, women farmers face major constraints in their capacity to diversify into alternative livelihoods. (Demetriades and Esplen, 2008)

Equal access to economic resources, promote empowerment of women (5.5/5.a/5.b)

Empower economic and political inclusion of all, irrespective of sex (10.2)

Greatly impacted by the policies. Source—on the supply side—rather than on the demand side as supply-side policies have lower carbon cost than demand-side policies. The role of livestock system emissions in emission reductions depends on the level of the carbon price and which emissions sector is targeted by the policies. (Quoted from Bajželj et al. (2014))

Decision makers should try to integrate agricultural, environmental and nutritional objectives through appropriate policy measures to achieve sustainable healthy diets, with reduction in food waste. It is surprising that politicians and policy makers demonstrate little regarding the need of having strategies to reduce meat consumption, and to encourage more sustainable eating practices in Netherlands.

Denton (2002); Jost et al. (2015); Demetriades and Esplen (2008)

Build effective, accountable and inclusive institutions (16.4/16.7/16.9)

Most of the animal farming activities such as fodder collection, feeding, are performed by women. Besides, considerable involvement and contribution of women, considerable gender inequalities also exist in Indian villages in terms of accessing natural resources, extension services, marketing opportunities and financial services as well as in exercising their decision making powers. Therefore, there is a need to correct gender bias in livestock sector. Efforts are needed to increase the capacity of women to negotiate with confidence and meet their strategic needs. Access, control and management of small ruminants, grazing areas and feed resources empower women and lead to an overall positive impact on the welfare of the household.

Garnett (2011); Dagevos and Voordouw (2013)

Responsible decision making (16.7)

Empower economic and political inclusion of all, irrespective of sex (10.2)

To minimize the economic and social costs, policies should target emissions at their source—theon the supply side—rather than on the demand side as supply-side policies have lower carbon cost than demand-side policies. The role of livestock system emissions in emission reductions depends on the level of the carbon price and which emissions sector is targeted by the policies. (Quoted from Bajželj et al. (2014))

Improve domestic capacity for tax collection (17.2)

The role of livestock system emissions in emission reductions depends on the level of the carbon price and which emissions sector is targeted by the policies (Havlík et al. (2014)). Mechanisms for effecting behavioral change in livestock systems need to be better understood by implementing combinations of instruments and taxes simultaneously in different parts of the world (Herrero and Thornton, 2010).

Herrero and Thornton (2010)

Improve domestic capacity for tax collection (17.2)

Empower economic and political inclusion of all, irrespective of sex (10.2)

To minimize the economic and social costs, policies should target emissions at their source—theon the supply side—rather than on the demand side as supply-side policies have lower carbon cost than demand-side policies. The role of livestock system emissions in emission reductions depends on the level of the carbon price and which emissions sector is targeted by the policies. (Quoted from Bajželj et al. (2014))

Strong and effective Institutions and responsive decision making (16.4/16.7/16.9)

Appropriate incentives to reduce food waste may require some policy innovation and experimentation, but a strong commitment for designing and monitoring them seems essential. (Quoted from Radel et al. (2014))
<table>
<thead>
<tr>
<th>Forest</th>
<th>Reduced deforestation, REDD+</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Opportunities for Women [1.2/5.1]</strong></td>
</tr>
<tr>
<td></td>
<td>Women have been less involved in REDD+ initiatives [pilot project design decisions and processes than men. Girls and women have an important role in forestry activities, related to fuel-wood, forest food and medicine. Their empowerment contributes to sustainable forestry as well as reducing inequality (Katila et al., 2017).]</td>
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<td>[1.4]</td>
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<td>[16]</td>
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<thead>
<tr>
<th>Reduced inequality, empowerment and inclusion [12.1/12.2/13.1/10.4]</th>
<th><strong>Opportunities for Women [1.2/5.1]</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Urgent developed country-to-support, through multilateral and bilateral channels, the development of REDD+ national strategies or action plans and implementation (Lima et al., 2017). Girls and women have an important role in forestry activities, related to fuel-wood, forest-food and medicine. Their empowerment contributes to sustainable forestry as well as reducing inequality (Katila et al., 2017).</td>
<td>[1.4]</td>
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<td>[16]</td>
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<thead>
<tr>
<th>Build effective, accountable and inclusive institutions, Responsible decision making [16.4/16.7/16.8]</th>
<th><strong>Opportunities for Women [1.2/5.1]</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Institutional building (National Forest Monitoring Systems, Safeguard Information Systems, etc.), with full and effective participation of all relevant countries (Lima et al., 2017). REDD+ actions also deliver non-carbon benefits e.g. local socioeconomic benefits, governance improvements, Lima et al., 2015). Forest governance is another central aspect in recent studies, including debate on decentralization of forest management, logging concessions in public owned commercially valuable forests, and timber certification, primarily in temperate forests (Bustamante et al., 2014).</td>
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<td>To provide financial and technological support to developing countries to make emission reductions. Be supported by adequate and predictable financial and technological support, including support for capacity-building (Lima et al., 2017). Partnerships in the forms of significant aid money from, e.g., Norway, other bilateral donors, and the World Bank's Forest Carbon Partnership Facility (FCPF) are forthcoming (Moore). Estimates of opportunity cost for REDD are very low. Lower costs and/or higher carbon prices could combine to protect more forests, including those with lower carbon content. Conversely, where the cost of action is high, a large amount of additional funding would be required for the forest to be protected (Miles and Kapos, 2008). Forest governance is another central aspect in recent studies, including debate on decentralization of forest management, logging concessions in public owned commercially valuable forests, and timber certification, primarily in temperate forests (Bustamante et al., 2014). Partnerships between local forest managers, community enterprises and private sector companies can support local economies and livelihoods, and boost regional and national economic growth (Katila et al., 2017).</td>
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<td>Financing at the national and international level is required to grow more tree plantings, restore land, create awareness education factsheets, providing training of local communities regarding the benefits of afforestation and reforestation. Article 12 of the Kyoto Protocol further sets a Clean Development Mechanism through which countries in Annex I earn “certified emissions reductions” through projects implemented in developing countries (Montanarella and Alva, 2015). Afforestation and reforestation in India are being carried out under various programmes, namely social forestry initiated in the early 1980s, Joint Forest Management Programme initiated in 1990, afforestation under National Afforestation and Eco-development Board (NAEB) programmes since 1992, and private farmer and industry initiated plantation forestry. If the current rate of afforestation and reforestation is assumed to continue, the carbon stock could increase of 3% by 2030 (Ravindranath, Chaturvedi, and Murthy, 2008).</td>
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<td>Indonesia’s forest industries may seek advantages through non-price competition—perhaps by highlighting discreet working conditions or the existence of a union—or to see trade associations or government agencies promoting the country as a responsible sourcing location (Barthley, 2010). In the absence of domestic legal instruments providing incentives to improve sustainability of sourcing, it appears that initiatives to engage the major importing enterprises in developing responsible sourcing practices and policies is a practical approach. Unless initiatives involve all the major importers, they are unlikely to be successful since the high costs associated with accreditation would increase production costs for these firms relative to their competitors (Huq, Wilkes, Sun and Terheggen, 2013).</td>
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### Industry

#### Water efficiency and pollution prevention (6.3, 6.4, 6.6)

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Sustainable production (6.3, 6.4, 6.6)

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Sustainable use and management of natural resources (12.2)

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### Buildings

#### Water efficiency and pollution prevention (6.3, 6.4, 6.6)

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### Improving access and fuel switch to modern low carbon energy

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### Water efficiency and pollution prevention (6.3, 6.4, 6.6)

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### Healthy forest ecosystems (6.4, 6.5, 6.6, 6.7, 6.8)

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Reduced deforestation (15.3)

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## Footnotes

- Sustainable consumption results from their urban sample survey indicate that technical failure is far surpassed by user demand change, policy change are essential for encouraging these large risky investments.
- Improved access and fuel switch to modern low-carbon energy.
- Food security can support water and sanitation technologies. If energy access is supported with water-invasive energy sources, there could be tradeoffs with water intensity.
- Sustainable production (6.3, 6.4, 6.6)

## References

- Supino et al. (2015); Fan et al. (2017); Leider et al. (2015); Zheng et al. (2016); Shi et al.
- Sustainable use and management of natural resources (12.2)
- Sustainable production (6.3, 6.4, 6.6)
- Sustainable use and management of natural resources (12.2)
- Healthy forest ecosystems (6.4, 6.5, 6.6, 6.7, 6.8)
- Reduced deforestation (15.3)
<table>
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<tr>
<th>Water efficiency and pollution prevention (6.3/4.6/6.4)</th>
<th>Ensure Sustainable Consumption &amp; Production patterns (12.3)</th>
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<td>Improved access &amp; fuel switch to modern low-carbon energy</td>
<td>Urban carbon mitigation must consider the supply chain management of imported goods, their production efficiency within the city, the consumption patterns of urban consumers, and the responsibility of the ultimate consumers outside the city. Important for climate policy of monitoring the CO2 clusters that dominate CO2 emissions in global supply chains because they offer insights on where climate policy can be effectively directed.</td>
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Hejazi et al. (2015); Song et al. (2016); Fricko et al. (2016); Pietzcker et al. (2013); Figueroa et al. (2014); IPCC AR5 WG3 (2014); Creutzig et al., (2015)

Accelerating energy efficiency improvement

<table>
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<tr>
<th>Water efficiency and pollution prevention (6.3/4.6/6.4)</th>
<th>Ensure Sustainable Consumption &amp; Production patterns (12.3/12.8)</th>
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</thead>
<tbody>
<tr>
<td>Due to persistent reliance on fossil fuels, it is posited that transport is more difficult to decarbonize than other sectors. This study partially confirms that transport is less reactive to given carbon taxes than the non-transport sectors: in the first half of the century, transport mitigation is delayed by 10–30 years compared to non-transport mitigation. The extent to which earlier mitigation is possible strongly depends on implemented technologies and model structure.</td>
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Vidic et al. (2013); Tiedemann et al. (2016); Fricko et al. (2016); Holland et al. (2016)

Conversely, changes in efficiency measures in the transport sector that lead to reduced transport demand can lead to reduced transport energy supply. As water is used to produce a number of important transport fuels, the reduction in transport demand is anticipated to reduce water consumption and wastewater, resulting in more clean water for other sectors and the environment.

Vidic et al. (2013); Tiedemann et al. (2016); Fricko et al. (2016); Holland et al. (2016)

Urban carbon mitigation must consider the supply chain management of imported goods, their production efficiency within the city, the consumption patterns of urban consumers, and the responsibility of the ultimate consumers outside the city. Important for climate policy of monitoring the CO2 clusters that dominate CO2 emissions in global supply chains because they offer insights on where climate policy can be effectively directed.

Vidic et al. (2013); Hehnner and Luderer (2011); Heinonen et al. (2015); Gallego, Montero and Salas (2014); Abramitzki and Peters (2015); Gössling and Metzler (2017); Azevedo and Leal (2017)

Relational complex transport behavior resulting in significant growth in energy-inefficient car choices, as well as differences in mobility patterns (distance driven, driving styles) and actual fuel consumption between different car segments all affect the non-progress on transport decarbonisation. Consumption choices, and individual lifestyles are shaped both for the form of the surrounding urbanization. Major behavioral changes and emissions reductions require understanding of this relational complexity, consideration of potential interactions with other policies and the local context and implementation of both command-and-control as well as market-based measures.

Stanley, Hensher and Loader (2011); Heinonen et al. (2015); Gallego, Montero and Salas (2014); Abramitzki and Peters (2015); Gössling and Metzler (2017); Azevedo and Leal (2017)

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Lin et al. (2015); Kagawa et al. (2015); Felix et al (2016)
Increased use of biomass energy efficiency and pollution prevention (6.3/4.7/6.4) / Access to improved water sources

Fossil energy conversion can lead to increased water stress when irrigated food crops and water-intensive processing steps are used. Biomass crops can alter flow over land and through soils as well as require fertilizer and this can reduce water availability and quality. Planting bioenergy crops on marginal lands or in some situations to replace existing crops can lead to reductions in soil erosion and fertilizer inputs, improving water quality. Planting bioenergy crops on marginal lands or in some situations to replace existing crops can lead to reductions in soil erosion and fertilizer inputs, improving water quality.

McCollum et al. (2018); Banerjee et al. (2012); Bhattacharyya et al. (2014); Cameron et al. (2018); Rohi et al. (2012); Schwartz et al. (2014)

Healthy Terrestrial Ecosystems (5.1/4.1/4.5/1.4)

Protecting terrestrial ecosystems, sustainably managing forests, halting deforestation, preventing biodiversity loss and controlling invasive alien species could potentially clash with renewable energy expansion. If that were to happen, constraining large-scale utilization of bioenergy or hydropower. Good governance, cross-jurisdictional coordination, and sound implementation practices are critical for minimizing trade-offs (McCollum et al., 2018).

McCollum et al. (2018); Smith et al. (2010); Smith et al. (2014); Acheampong M., Ertem F.C., Kappler B., Neubauer P. (2017)

No direct interaction

Healthy Terrestrial Ecosystems (5.1/4.1/4.5/1.4)

Safety and waste concerns, uranium mining and milling

IPCC AR5 WG3 (2014); Visschers and Siegrist (2012); Greenberg (2013a); Kim et al. (2013); Visschers and Siegrist (2012); Bokdam et al. (2008); Syring and Ozturk-Sy- ring (2009); Cernus et al. (2011); Abeame (2011)

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### SCoring Evidence Agreement Confidence Interactions

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#### Water efficiency and pollution prevention (6.3/6.4/6.6)

- Reduced loss and waste in food systems, processing, distribution and dietary change.
- Increased water efficiency and reduced water use demand in livestock and crop production.
- Reduced nutrient levels in wastewater and decreased ammonia emissions.

#### More sustainable Consumption & Production patterns (12.3/12.4/12.5)

- Increased direct meat consumption, including livestock, dairy, and egg consumption.
- Increased direct meat consumption, including livestock, dairy, and egg consumption.
- Increased direct meat consumption, including livestock, dairy, and egg consumption.

#### Conservation of Biodiversity and restoration of land (15.1/15.5/15.9)

- Increased conservation of biodiversity and natural habitats.
- Increased protection of biodiversity hotspots.
- Increased restoration of degraded land.

---

**Notes:**
- Data and evidence were collected from various sources including scientific publications, reports, and government documents.
- The scoring system ranges from 0 (no direct interaction) to 3 (strong direct interaction).
- The confidence level is indicated by the number of agreements and evidence provided.

---

**References:**
- Smith (2016); Behnassi, Boussaid and Gopichandran (2014); Bustamante (2014)
- Smith (2016); Behnassi, Boussaid and Gopichandran (2014); Bustamante (2014)
- Smith (2016); Behnassi, Boussaid and Gopichandran (2014); Bustamante (2014)

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**Footnotes:**
- Footnotes are provided for additional information and context.
- The table includes a summary of key findings and recommendations for future actions.

---

**Image:**
- Images are included to visually represent data and findings.

---

**Table 5.3:**
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- The table includes a summary of key findings and recommendations for future actions.
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**Chapter 5:**
- Chapter 5 discusses the role of agriculture and livestock in global greenhouse gas emissions and provides recommendations for sustainable practices.
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### Table 5.3

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<th>Reduced Emissions, Avoided</th>
<th>Reduce Sustainable Consumption</th>
<th>Conservation of Biodiversity, Nurturing of Biodiversity Recuperation</th>
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<td></td>
<td>Reduced Emission to Forests</td>
<td>Reduce the human pressure on</td>
<td>Reduce the anthropogenic pressure on the environment.</td>
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<td>Management alters the hydrological cycle which could be a positive or negative from a water perspective and is dependent on existing conditions. Carelessness of ecosystem services—indirectly could help countries maintain water resilience. Forests provide sustainable and regenerative services and help in water purification.</td>
<td>protection of forests, including actions to address drivers of deforestation.</td>
<td>No direct interaction.</td>
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Improved access & fuel

Creutzig et al. (2014); Connolly et al. (2014); Islar et al. (2017); Mittlefehldt (2016); Bilgily

electrical demand in Karachi, Pakistan.

Demand for autonomous motivation on energy savings behaviour is greater than that of

furnaces & CCS for iron steel means high energy demand, electric melting in glass can

influence can drive energy savings in users exposed to energy consumption feedback. (McCollum et al., 2018).

in appropriate mix of industries (china) can maintain energy savings gain. supplying surplus

manginenergy efficiency opens up opportunoties in energy service delivery sector. (Quote from McCollum et al., 2018), roof top solar in Macau make cities...

New jobs for

enhance energy efficiency and use of nonrenewable

furnaces & CCS for iron steel means high energy demand, electric melting in glass can

electric consumption. (Quote from McCollum et al., 2018), roof top solar in Macau make cities...

New jobs for

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New jobs for
### Chapter 5 - Table 5.3

<table>
<thead>
<tr>
<th>Transport</th>
<th>Behavioral response</th>
<th>Carbon emissions reduction</th>
<th>Innovation in energy efficiency</th>
<th>Build Resilient Infrastructure</th>
<th>Make cities &amp; Human Settlements Inclusive, Safe, Resilient</th>
</tr>
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| Note: | - | - | - | - | - |

**Policy contradictions:** Many sustainable policies, such as those promoting renewable energy, face challenges in implementation due to various constraints and co-existing goals. For instance, promoting biofuels can lead to increased land use and deforestation, which can offset the environmental benefits. Similarly, electric vehicles require significant investment in renewable energy infrastructure, which may not always be feasible in resource-limited settings.

**Impacts on Transportation:**

- **Behavioural response:** Reducing carbon emissions through changes in behaviour (e.g., walking, cycling) can be effective in the short term but may require significant public education and infrastructure development.
- **Policy contradictions:** Policies aimed at reducing carbon emissions from transportation can face contradictions, such as the need for infrastructure investment in parallel with behavioural changes.

**Table 5.3:**

- **Increased carbon footprint:** The transition to cleaner energy sources can sometimes lead to increased carbon emissions, especially in the case of increased electricity demand.
- **Mitigation strategies:** A combination of strategies, including both technological advancements and behavioural changes, is necessary to effectively reduce carbon emissions.

**Key findings:**

- **Improved access & fuel efficiency improvement:** Increasing access to affordable fuel and improving efficiency can reduce carbon emissions, with the latter often being more effective in the long term.
- **Promote sustainable, inclusive economic growth:** Strategies that promote economic growth while reducing carbon emissions can be beneficial in the long term.

**References:**

Ahmad S., Puppim de Oliveira J.A., 2016; Figueroa M.J., Ribeiro S.K., 2013; Gouldson et al. (2015); Karkatsoulis et al. (2016); Song et al. (2016);(Suckall, Tompkins, & Stringer, 2014)
<table>
<thead>
<tr>
<th>Interaction Score</th>
<th>Evidence Score</th>
<th>Agreement Score</th>
<th>Confidence Score</th>
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<tbody>
<tr>
<td><strong>Replacing coal</strong></td>
<td>Non-biomass renewables: solar, wind, hydro</td>
<td>Decarbonization of the energy system through an up-scaling of renewables will greatly facilitate access to clean, affordable and reliable energy. Hydropower plays an increasingly important role for the global electricity supply. This mitigation option is in line with the targets of SDG7 under the context of a transition to modern biomass.</td>
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<td>Innovation and Growth: [8.1/8.2/8.4]</td>
<td><strong>[9]</strong></td>
<td><strong>[8]</strong></td>
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<td><strong>Increased use of biomass</strong></td>
<td>Increased use of modern biomass will facilitate access to clean, affordable and reliable energy. This mitigation option is in line with the targets of SDG7.</td>
<td>Decarbonization of the energy system through an up-scaling of renewables will greatly facilitate access to clean, affordable and reliable energy.</td>
<td>4</td>
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<td>Nuclear/Advanced Reactor</td>
<td>Increased use of nuclear power can provide stable baseload power supply and reduce price volatility.</td>
<td>Access to modern and sustainable energy will be critical to sustain economic growth.</td>
<td>4</td>
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<tr>
<td>CCS: Bio energy</td>
<td>Increased use of modern biomass will facilitate access to clean, affordable and reliable energy.</td>
<td>See positive impacts of bio-energy use.</td>
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<td>Advanced CCU: Fossil</td>
<td>Advanced and cleaner fossil-fuel technology in line with the targets of SDG7.</td>
<td>See positive impacts of CCU in industrial demand.</td>
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<td>Disaster Preparedness and Prevention: [11.1]</td>
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**Notes:**
- **[9]** indicates strong evidence and high confidence.
- **[8]** indicates moderate evidence and moderate confidence.
- **[7]** indicates weak evidence and low confidence.
- **[6]** indicates negative evidence and low confidence.
- **[5]** indicates weak evidence and negative confidence.

**References:**
- Cherian (2010); Rogelj (2013); Cherian (2013); Jingura and Kamusoko (2016).
- IPCC AR5 WG3 (2014); Marra and Palmer (2011); Greenberg (2013a); Schwenk-Ferrero (2013a); Skipperud et al. (2013); Tyler et al. (2013a).
- See positive impacts of CCS/CCU in industrial demand. See positive impacts of bio-energy use and CCS/CCU in industrial demand.
- McCollum et al. (2018); Daai et al. (2013); Hallegatte et al. (2016); IPCC (2014); Rohrl et al. (2012); Tully (2006).
- Advanced CCU: Fossil
- Advanced and cleaner fossil-fuel technology in line with the targets of SDG7.
- IPCC AR5 WG3 (2014); Vgorogt et al. (2013); Maruksen et al. (2013); IPCC (2006); Benson et al. (2000); Etkinhaus et al. (2006); Bradley and Thompson (2012); Johnson et al. (2013); Benson et al. (2013).
**Agriculture & Livestock**

**Behavioral response: Sustainable healthy diets and reduced food waste**

- Energy Efficiency, universal access to electricity [2, 3, 4]
  - ↑ (+1)
  - ↓ (+1)

- Exploiting the increasingly decoupled interactions between crops and livestock could be an efficient way to deliver dermal benefits for human nutrition and reduce overall methane emissions (Quoted from Catessa, M., Thornton, P. K. (2010)).

- The trade of wood pellets from clean wood waste should be facilitated with less transport costs. Responsible sourcing, besides temperature control and biodiversity enhancement goals. People’s preference for local timber products can also help reduce habitat fragmentation and deforestation.

- Many urban tree plantations worldwide have higher growth rates which can provide higher rates of returns for investors. Agroforestry initiatives that offer significant opportunities for smallholder farmers can also help reduce dependency and degradation through increased forest cover in urban areas.

- The region’s potential for human nutrition and reduced overall methane emissions (Quoted from Catessa, M., Thornton, P. K. (2010)).

- Similarly, the benefits of responsible sourcing, besides temperature control and biodiversity enhancement goals.

**Vegetable-based greenhouse gas reduction and soil carbon sequestration**

- Sustainable and modern energy [2, 3]
  - ↓ (+1)
  - ↓ (+1)

- Many developing countries including China will benefit from CBA’s given the central role of agriculture in their economic and social development (Quoted from Behnassi, M., A. P. A. H. S. A., A. (2014)).

- Many developing countries including China will benefit from CBA’s given the central role of agriculture in their economic and social development (Quoted from Behnassi, M., A. P. A. H. S. A., A. (2014)).

**Forestry**

- Be role of the government in the provision of local and sustainable fuelwood is critical (Quoted from Behnassi, M., A. P. A. H. S. A., A. (2014)).

- Many urban tree plantations worldwide have higher growth rates which can provide higher rates of returns for investors. Agroforestry initiatives that offer significant opportunities for smallholder farmers can also help reduce dependency and degradation through increased forest cover in urban areas.

- The world’s potential for human nutrition and reduced overall methane emissions (Quoted from Catessa, M., Thornton, P. K. (2010)).

- The benefits of responsible sourcing, besides temperature control and biodiversity enhancement goals.

**Afforestation and reforestation**

- Energy Efficiency, universal access to electricity [2, 3, 4]
  - ↑ (+1)
  - ↓ (+1)

- Exploiting the increasingly decoupled interactions between crops and livestock could be an efficient way to deliver dermal benefits for human nutrition and reduce overall methane emissions (Quoted from Catessa, M., Thornton, P. K. (2010)).

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- The region’s potential for human nutrition and reduced overall methane emissions (Quoted from Catessa, M., Thornton, P. K. (2010)).

- Similarly, the benefits of responsible sourcing, besides temperature control and biodiversity enhancement goals.

**Biorefinery**

- Sustainable and modern energy [2, 3]
  - ↓ (+1)
  - ↓ (+1)

- Many developing countries including China will benefit from CBA’s given the central role of agriculture in their economic and social development (Quoted from Behnassi, M., A. P. A. H. S. A., A. (2014)).

- Many developing countries including China will benefit from CBA’s given the central role of agriculture in their economic and social development (Quoted from Behnassi, M., A. P. A. H. S. A., A. (2014)).

**Water**

- Ocean iron fertilization [2, 3]
  - No direct interaction

- The role of the government in the provision of local and sustainable fuelwood is critical (Quoted from Behnassi, M., A. P. A. H. S. A., A. (2014)).

- Similarly, the benefits of responsible sourcing, besides temperature control and biodiversity enhancement goals.

**Ocean**

- Ocean iron fertilization [2, 3]
  - No direct interaction

- The role of the government in the provision of local and sustainable fuelwood is critical (Quoted from Behnassi, M., A. P. A. H. S. A., A. (2014)).

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- The benefits of responsible sourcing, besides temperature control and biodiversity enhancement goals.
Glossary

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Date of Draft: 4/06/18

Notes: TSU compiled version. Note that subterms are in italics beneath main terms.
1.5°C-consistent emissions pathways

See Pathways.

1.5°C warmer worlds

Projected worlds in which global warming has reached and, unless otherwise indicated, been limited to 1.5°C above pre-industrial levels. There is no single 1.5°C warmer world and projections of 1.5°C warmer worlds look different depending on whether it is considered on a near-term transient trajectory or at climate equilibrium after several millennia, and, in both cases, if it occurs with or without overshoot. Within the 21st century, several aspects play a role for the assessment of risk and potential impacts in 1.5°C warmer worlds: the possible occurrence, magnitude and duration of an overshoot, the way in which emissions reductions are achieved, the ways in which policies might be able to influence the resilience of human and natural systems, and the nature of the regional and sub-regional risks. Beyond the 21st century, several elements of the climate system would continue to change even if the global mean temperatures remain stable, including further increases of sea level.

2030 Agenda for Sustainable Development

A UN resolution in September 2015 adopting a plan of action for people, planet and prosperity in a new global development framework anchored in 17 Sustainable Development Goals (UN, 2015).

See also Sustainable Development Goals (SDGs).

Acceptability of policy or system change

The extent to which a policy or system change is evaluated unfavourably or favourably, or rejected or supported, by members of the general public (public acceptability) or politicians or governments (political acceptability). Acceptability may vary from totally unacceptable/fully rejected to totally acceptable/fully supported; individuals may differ in how acceptable policies or system changes are believed to be.

Adaptability

See Adaptive capacity.

Adaptation

In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.

Incremental adaptation

Adaptation that maintains the essence and integrity of a system or process at a given scale. [Footnote: This definition builds from the definition used in Park et al. (2012).]

Transformational adaptation

Adaptation that changes the fundamental attributes of a socio-ecological system in anticipation of climate change and its impacts.

Adaptation limits

The point at which an actor’s objectives (or system needs) cannot be secured from intolerable risks through adaptive actions.
Hard adaptation limit - No adaptive actions are possible to avoid intolerable risks.
Soft adaptation limit - Options are currently not available to avoid intolerable risks through adaptive action.

See also Adaptation options, Adaptive capacity, and Maladaptive actions (Maladaptation).

Adaptation behaviour
See Human behaviour.

Adaptation limits
See Adaptation.

Adaptation options
The array of strategies and measures that are available and appropriate for addressing adaptation. They include a wide range of actions that can be categorized as structural, institutional, ecological or behavioural.

See also Adaptation, Adaptive capacity, and Maladaptive actions (Maladaptation).

Adaptation pathways
See Pathways.

Adaptive capacity
The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences. [Footnote: This glossary entry builds from definitions used in previous IPCC reports and the Millennium Ecosystem Assessment (MEA, 2005).]

See also Adaptation, Adaptation options, and Maladaptive actions (Maladaptation).

Adaptive governance
See Governance.

Aerosol
A suspension of airborne solid or liquid particles, with a typical size between a few nanometres and 10 μm that reside in the atmosphere for at least several hours. The term aerosol, which includes both the particles and the suspending gas, is often used in this report in its plural form to mean aerosol particles. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in several ways: through both interactions that scatter and/or absorb radiation and through interactions with cloud microphysics and other cloud properties, or upon deposition on snow or ice covered surfaces thereby altering their albedo and contributing to climate feedback. Atmospheric aerosols, whether natural or anthropogenic, originate from two different pathways: emissions of primary particulate matter (PM), and formation of secondary PM from gaseous precursors. The bulk of aerosols are of natural origin. Some scientists use group labels that refer to the chemical composition, namely: sea salt, organic carbon, black carbon (BC), mineral species (mainly desert dust), sulphate, nitrate, and ammonium. These labels are, however, imperfect as aerosols combine particles to create complex mixtures.
See also short-lived climate forcers (SLCF), and Black carbon (BC).

**Afforestation**
Planting of new forests on lands that historically have not contained forests. [Footnote: For a discussion of the term forest and related terms such as afforestation, reforestation and deforestation, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000), information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013) and the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).]

See also Reforestation, Deforestation, and Reducing Emissions from Deforestation and Forest Degradation (REDD+).

**Agreement**
In this report, the degree of agreement within the scientific body of knowledge on a particular finding is assessed based on multiple lines of evidence (e.g., mechanistic understanding, theory, data, models, expert judgement) and expressed qualitatively (Mastrandrea et al., 2010).

See also Evidence, Confidence, Likelihood, and Uncertainty.

**Air pollution**
Degradation of air quality with negative effects on human health, the natural or built environment, due to the introduction by natural processes or human activity in the atmosphere of substances (gases, aerosols) which have a direct (primary pollutants) or indirect (secondary pollutants) harmful effect.

See also Aerosol, and short-lived climate forcers (SLCF).

**Albedo**
The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the surface albedo of soils ranges from high to low, and vegetation-covered surfaces and the oceans have a low albedo. The Earth's planetary albedo changes mainly through varying cloudiness, snow, ice, leaf area and land cover changes.

**Ambient persuasive technology**
Technological systems and environments that are designed to change human cognitive processing, attitudes and behaviours without the need for the user’s conscious attention.

**Anomaly**
The deviation of a variable from its value averaged over a reference period.

See also Reference period.

**Anthropocene**
The ‘Anthropocene’ is a proposed new geological epoch resulting from significant human-driven changes to the structure and functioning of the Earth System, including the climate system. Originally
proposed in the Earth System science community in 2000, the proposed new epoch is undergoing a formalization process within the geological community based on the stratigraphic evidence that human activities have changed the Earth System to the extent of forming geological deposits with a signature that is distinct from those of the Holocene, and which will remain in the geological record. Both the stratigraphic and Earth System approaches to defining the Anthropocene consider the mid-20th Century to be the most appropriate starting date, although others have been proposed and continue to be discussed. The Anthropocene concept has been taken up by a diversity of disciplines and the public to denote the substantive influence humans have had on the state, dynamics and future of the Earth System.

See also Holocene.

**Anthropogenic**

Resulting from or produced by human activities.

*See also Anthropogenic emissions, and Anthropogenic removals.*

**Anthropogenic emissions**

Emissions of greenhouse gases (GHGs), precursors of GHGs and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use and land use changes (LULUC), livestock production, fertilisation, waste management, and industrial processes.

*See also Anthropogenic, and Anthropogenic removals.*

**Anthropogenic removals**

Anthropogenic removals refer to the withdrawal of GHGs from the atmosphere as a result of deliberate human activities. These include enhancing biological sinks of CO_2_ and using chemical engineering to achieve long term removal and storage. Carbon capture and storage (CCS) from industrial and energy-related sources, which alone does not remove CO_2_ in the atmosphere, can reduce atmospheric CO_2_ if it is combined with bioenergy production (BECCS).

*See also Anthropogenic emissions, Bioenergy with carbon dioxide capture and storage (BECCS), and Carbon dioxide capture and storage (CCS).*

**Artificial intelligence (AI)**

Computer systems able to perform tasks normally requiring human intelligence, such as visual perception and speech recognition.

**Atmosphere**

The gaseous envelope surrounding the earth, divided into five layers — the troposphere which contains half of the earth's atmosphere, the stratosphere, the mesosphere, the thermosphere, and the exosphere, which is the outer limit of the atmosphere. The dry atmosphere consists almost entirely of nitrogen (78.1% volume mixing ratio) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93% volume mixing ratio), helium and radiatively active greenhouse gases (GHGs) such as carbon dioxide (CO_2_ ) (0.04% volume mixing ratio) and ozone (O_3_). In addition, the atmosphere contains the GHG water vapour (H_2O_), whose amounts are highly variable but typically around 1% volume mixing ratio. The atmosphere also contains clouds and aerosols.
See also Troposphere, Stratosphere, Greenhouse gas (GHG), and Hydrological cycle.

Atmosphere-ocean general circulation model (AOGCM)
See Climate model.

Attribution
See Detection and attribution.

Baseline scenario
In much of the literature the term is also synonymous with the term business-as-usual (BAU) scenario, although the term BAU has fallen out of favour because the idea of business as usual in century-long socio-economic projections is hard to fathom. In the context of transformation pathways, the term baseline scenarios refers to scenarios that are based on the assumption that no mitigation policies or measures will be implemented beyond those that are already in force and/or are legislated or planned to be adopted. Baseline scenarios are not intended to be predictions of the future, but rather counterfactual constructions that can serve to highlight the level of emissions that would occur without further policy effort. Typically, baseline scenarios are then compared to mitigation scenarios that are constructed to meet different goals for greenhouse gas (GHG) emissions, atmospheric concentrations or temperature change. The term baseline scenario is often used interchangeably with reference scenario and no policy scenario.

See also Emission scenario, and Mitigation scenario.

Biochar
Stable, carbon-rich material produced by heating biomass in an oxygen-limited environment. Biochar may be added to soils to improve soil functions and to reduce greenhouse gas emissions from biomass and soils, and for carbon sequestration. [Footnote: This definition builds from IBI (2018)]

Biodiversity
Biological diversity means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems (UN, 1992).

Bioenergy
Energy derived from any form of biomass or its metabolic by-products.

See also Biomass and Biofuel.

Bioenergy with carbon dioxide capture and storage (BECCS)
Carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility. Note that depending on the total emissions of the BECCS supply chain, carbon dioxide can be removed from the atmosphere.

See also Bioenergy, and Carbon dioxide capture and storage (CCS).
**Biofuel**
A fuel, generally in liquid form, produced from biomass. Biofuels currently include bioethanol from sugarcane or maize, biodiesel from canola or soybeans, and black liquor from the paper-manufacturing process.

*See also Biomass, and Bioenergy.*

**Biomass**
Living or recently-dead organic material.

*See also Bioenergy, and Biofuel.*

**Biophilic urbanism**
Designing cities with green roofs, green walls and green balconies to bring nature into the densest parts of cities in order to provide green infrastructure and human health benefits.

*See also Green infrastructure.*

**Black carbon (BC)**
Operationally defined aerosol species based on measurement of light absorption and chemical reactivity and/or thermal stability. It is sometimes referred to as soot. BC is mostly formed by the incomplete combustion of fossil fuels, biofuels, and biomass but it also occurs naturally. It stays in the atmosphere only for days or weeks. It is the most strongly light-absorbing component of particulate matter (PM) and has a warming effect by absorbing heat into the atmosphere and reducing the albedo when deposited on snow or ice.

*See also Aerosol.*

**Blue carbon**
Blue carbon is the carbon captured by living organisms in coastal (e.g., mangroves, salt marshes, seagrasses) and marine ecosystems, and stored in biomass and sediments.

**Burden sharing (also referred to as Effort sharing)**
In the context of mitigation, burden sharing refers to sharing the effort of reducing the sources or enhancing the sinks of greenhouse gases (GHGs) from historical or projected levels, usually allocated by some criteria, as well as sharing the cost burden across countries.

**Business as usual (BAU)**
*See Baseline scenario.*

**Carbon budget**
This term refers to three concepts in the literature: (1) an assessment of carbon cycle sources and sinks on a global level, through the synthesis of evidence for fossil-fuel and cement emissions, land-use change emissions, ocean and land CO$_2$ sinks, and the resulting atmospheric CO$_2$ growth rate. This is referred to as the global carbon budget; (2) the estimated cumulative amount of global carbon dioxide emissions that that is estimated to limit global surface temperature to a given level above a
reference period, taking into account global surface temperature contributions of other GHGs and climate forcers; (3) the distribution of the carbon budget defined under (2) to the regional, national, or sub-national level based on considerations of equity, costs or efficiency.

*See also Remaining carbon budget.*

**Carbon cycle**
The term used to describe the flow of carbon (in various forms, e.g., as carbon dioxide (CO₂), carbon in biomass, and carbon dissolved in the ocean as carbonate and bicarbonate) through the atmosphere, hydrosphere, terrestrial and marine biosphere and lithosphere. In this report, the reference unit for the global carbon cycle is GtCO₂ or GtC (Gigatonne of carbon = 1 GtC = 10¹⁵ grams of carbon. This corresponds to 3.667 GtCO₂).

**Carbon dioxide (CO₂)**
A naturally occurring gas, CO₂ is also a by-product of burning fossil fuels (such as oil, gas and coal), of burning biomass, of land use changes (LUC) and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas (GHG) that affects the Earth's radiative balance. It is the reference gas against which other GHGs are measured and therefore has a Global Warming Potential (GWP) of 1.

*See also Greenhouse gas (GHG). See also Land use and land-use change. See also Global Warming Potential (GWP).*

**Carbon dioxide capture and storage (CCS)**
A process in which a relatively pure stream of carbon dioxide (CO₂) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere. Sometimes referred to as Carbon Capture and Storage. See also Carbon dioxide capture and utilisation (CCU), Bioenergy with carbon dioxide capture and storage (BECCS), and Sequestration.

**Carbon dioxide capture and utilisation (CCU)**
A process in which CO₂ is captured and then used to produce a new product. If the CO₂ is stored in a product for a climate-relevant time horizon, this is referred to as carbon dioxide capture, utilisation and storage (CCUS). Only then, and only combined with CO₂ recently removed from the atmosphere, can CCUS lead to carbon dioxide removal. CCU is sometimes referred to as Carbon dioxide capture and use.

*See also Carbon dioxide capture and storage (CCS).*

**Carbon dioxide capture, utilisation and storage (CCUS)**
*See Carbon dioxide capture and utilisation (CCU).*

**Carbon dioxide removal (CDR)**
Carbon Dioxide Removal methods refer to processes that remove CO₂ from the atmosphere by either increasing biological sinks of CO₂ or using chemical processes to directly bind CO₂. CDR is classified as a special type of mitigation.
See also Mitigation (of climate change), Greenhouse gas removal (GGR), Negative emissions, Sink.

Carbon intensity
The amount of emissions of carbon dioxide (CO₂) released per unit of another variable such as Gross Domestic Product (GDP), output energy use or transport.

Carbon neutrality
Achieving net zero carbon dioxide emissions at a global scale through the balance of residual carbon dioxide emissions with the same amount of carbon dioxide removal.

See also Climate neutrality.

Carbon price
The price for avoided or released carbon dioxide (CO₂) or CO₂-equivalent emissions. This may refer to the rate of a carbon tax, or the price of emission permits. In many models that are used to assess the economic costs of mitigation, carbon prices are used as a proxy to represent the level of effort in mitigation policies.

Carbon sequestration
The process of storing carbon in a carbon pool.

See also Blue carbon, Carbon dioxide capture and storage (CCS), Uptake, and Sink.

Carbon sink
See Sink.

Clean Development Mechanism (CDM)
A mechanism defined under Article 12 of the Kyoto Protocol through which investors (governments or companies) from developed (Annex B) countries may finance greenhouse gas (GHG) emission reduction or removal projects in developing countries (Non-Annex B), and receive Certified Emission Reduction Units (CERs) for doing so. The CERs can be credited towards the commitments of the respective developed countries. The CDM is intended to facilitate the two objectives of promoting sustainable development (SD) in developing countries and of helping industrialized countries to reach their emissions commitments in a cost-effective way.

Climate
Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.
**Climate-compatible development (CCD)**
A form of development building on climate strategies that embrace development goals and development strategies that integrate climate risk management, adaptation and mitigation. Source: (Mitchell and Maxwell, 2010)

**Climate change**
Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: ‘a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods’. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition and climate variability attributable to natural causes.

*See also Climate variability, Global warming, Ocean acidification, and Detection and attribution.*

**Climate change commitment**
Climate change commitment is defined as the unavoidable future climate change resulting from inertia in the geophysical and socio-economic systems. Different types of climate change commitment are discussed in the literature (see subterms). Climate change commitment is usually quantified in terms of the further change in temperature, but it includes other future changes, for example in the hydrological cycle, in extreme weather events, in extreme climate events, and in sea level.

*Constant composition commitment*
The constant composition commitment is the remaining climate change that would result if atmospheric composition and hence radiative forcing were held fixed at a given value. It results from the thermal inertia of the ocean and slow processes in the cryosphere and land surface.

*Zero emissions commitment*
The zero emissions commitment is the climate change commitment that would result from setting anthropogenic emissions to zero. It is determined by both inertia in physical climate system components (ocean, cryosphere, land surface) and carbon cycle inertia.

*Constant emissions commitment*
The constant emissions commitment is the committed climate change that would result from keeping anthropogenic emissions constant.

*Feasible scenario commitment*
The feasible scenario commitment is the climate change that corresponds to the lowest emission scenario judged feasible.

*Infrastructure commitment*
The infrastructure commitment is the climate change that would result if existing greenhouse gas and aerosol emitting infrastructure were used until the end of its expected lifetime.
**Climate extreme (extreme weather or climate event)**
The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are referred to collectively as ‘climate extremes.’

*See also Extreme weather event.*

**Climate feedback**
An interaction in which a perturbation in one climate quantity causes a change in a second and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is enhanced. The initial perturbation can either be externally forced or arise as part of internal variability.

**Climate governance**
*See Governance.*

**Climate justice**
*See Justice.*

**Climate model**
A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes and accounting for some of its known properties. The climate system can be represented by models of varying complexity; that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrizations are involved. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate and for operational purposes, including monthly, seasonal and interannual climate predictions.

*See also Earth system model (ESM).*

**Climate neutrality**
Concept of a state in which human activities result in no net effect on the climate system. Achieving such a state would require balancing of residual emissions with emission (carbon dioxide) removal as well as accounting for regional or local biogeophysical effects of human activities that, for example, affect surface albedo or local climate.

*See also Carbon neutrality.*

**Climate projection**
A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases (GHGs) and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative forcing scenario used, which is in turn based on assumptions.
concerning, for example, future socioeconomic and technological developments that may or may not be realized.

**Climate-resilient development pathways (CRDPs)**
Trajectories that strengthen sustainable development and efforts to eradicate poverty and reduce inequalities while promoting fair and cross-scaler adaptation to and resilience in a changing climate. They raise the ethics, equity, and feasibility aspects of the deep societal transformation needed to drastically reduce emissions to limit global warming (e.g., to 1.5°C) and achieve desirable and liveable futures and well-being for all.

**Climate-resilient pathways**
Iterative processes for managing change within complex systems in order to reduce disruptions and enhance opportunities associated with climate change.

*See also* Pathways, Climate-resilient development pathways (CRDPs), Development pathways, and Transformation pathways.

**Climate services**
Climate services refers to information and products that enhance users' knowledge and understanding about the impacts of climate change and/or climate variability so as to aid decision-making of individuals and organizations and enable preparedness and early climate change action. Products can include climate data products.

**Climate sensitivity**
Climate sensitivity refers to the change in the annual global mean surface temperature in response to a change in the atmospheric CO₂ concentration or other radiative forcing.

*Equilibrium climate sensitivity*
Refers to the equilibrium (steady state) change in the annual global mean surface temperature following a doubling of the atmospheric carbon dioxide (CO₂) concentration. As a true equilibrium is challenging to define in climate models with dynamic oceans, the equilibrium climate sensitivity is often estimated through experiments in AOGCMs where CO₂ levels are either quadrupled or doubled from pre-industrial levels and which are integrated for 100-200 years. The climate sensitivity parameter (units: °C (W m⁻²)⁻¹) refers to the equilibrium change in the annual global mean surface temperature following a unit change in radiative forcing.

*Effective climate sensitivity*
An estimate of the global mean surface temperature response to a doubling of the atmospheric carbon dioxide (CO₂) concentration that is evaluated from model output or observations for evolving non-equilibrium conditions. It is a measure of the strengths of the climate feedbacks at a particular time and may vary with forcing history and climate state, and therefore may differ from equilibrium climate sensitivity.

*Transient climate response*
The change in the global mean surface temperature, averaged over a 20-year period, centered at the time of atmospheric CO₂ doubling, in a climate model simulation in which CO₂ increases at 1% yr⁻¹ from pre-industrial. It is a measure of the strength of climate feedbacks and the timescale of ocean heat uptake.
Climate-smart agriculture (CSA)
Climate-smart agriculture (CSA) is an approach that helps to guide actions needed to transform and reorient agricultural systems to effectively support development and ensure food security in a changing climate. CSA aims to tackle three main objectives: sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change; and reducing and/or removing greenhouse gas emissions, where possible (source: FAO).

Climate system
The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and land-use change.

Climate target
Climate target refers to a temperature limit, concentration level, or emissions reduction goal used towards the aim of avoiding dangerous anthropogenic interference with the climate system. For example, national climate targets may aim to reduce greenhouse gas emissions by a certain amount over a given time horizon, for example those under the Kyoto Protocol.

Climate variability
Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

See also Climate change.

Common but Differentiated Responsibilities and Respective Capabilities (CBDR-RC)
Common but Differentiated Responsibilities and Respective Capabilities (CBDR–RC) is a key principle in the United Nations Framework Convention on Climate Change (UNFCCC) that recognises the different capabilities and differing responsibilities of individual countries in tackling climate change. The principle of CBDR–RC is embedded in the 1992 UNFCCC treaty. The convention states: “… the global nature of climate change calls for the widest possible cooperation by all countries and their participation in an effective and appropriate international response, in accordance with their common but differentiated responsibilities and respective capabilities and their social and economic conditions.” Since then the CBDR-RC principle has guided the UN climate negotiations.

CO₂ equivalent (CO₂-eq) emission
The amount of carbon dioxide (CO₂) emission that would cause the same integrated radiative forcing or temperature change, over a given time horizon, as an emitted amount of a greenhouse gas (GHG) or a mixture of GHGs. There are a number of ways to compute such equivalent emissions and choose appropriate time horizons. Most typically, the CO₂-equivalent emission is obtained by multiplying the emission of a GHG by its Global Warming Potential (GWP) for a 100 year time horizon. For a mix of GHGs it is obtained by summing the CO₂-equivalent emissions of each gas. CO₂-equivalent emission is a common scale for comparing emissions of different GHGs but does not imply equivalence of the
corresponding climate change responses. There is generally no connection between CO$_2$-equivalent emissions and resulting CO$_2$-equivalent concentrations.

**Conference of the Parties (COP)**
The supreme body of UN conventions, such as the United Nations Framework Convention on Climate Change (UNFCCC), comprising parties with a right to vote that have ratified or acceded to the convention.

*See also United Nations Framework Convention on Climate Change (UNFCCC).*

**Confidence**
The robustness of a finding based on the type, amount, quality and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement across multiple lines of evidence. In this report, confidence is expressed qualitatively (Mastrandrea et al., 2010). See Section 1.6 for the list of confidence levels used.

*See also Agreement, Evidence, Likelihood, and Uncertainty.*

**Co-benefits**
The positive effects that a policy or measure aimed at one objective might have on other objectives, thereby increasing the total benefits for society or the environment. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors. Co-benefits are also referred to as ancillary benefits.

**Conservation agriculture**
A coherent group of agronomic and soil management practices that reduce the disruption of soil structure and biota.

**Constant composition commitment**
*See Climate change commitment.*

**Constant emissions commitment**
*See Climate change commitment.*

**Coping capacity**
The ability of people, institutions, organizations, and systems, using available skills, values, beliefs, resources, and opportunities, to address, manage, and overcome adverse conditions in the short to medium term. [Footnote: This glossary entry builds from the definition used in UNISDR (2009) and IPCC (2012a).]

*See also Resilience.*

**Cost-benefit analysis**
Monetary assessment of all negative and positive impacts associated with a given action. Cost-benefit analysis enables comparison of different interventions, investments or strategies and reveal how a
given investment or policy effort pays off for a particular person, company or country. Cost-benefit analyses representing society's point of view are important for climate change decision making, but there are difficulties in aggregating costs and benefits across different actors and across timescales.

*See also Discounting.*

**Cost-effectiveness**
A measure of the cost at which policy goal or outcome is achieved. The lower the cost the greater the cost-effectiveness.

*See also Integrated models.*

**Coupled Model Intercomparison Project (CMIP)**
The Coupled Model Intercomparison Project (CMIP) is a climate modelling activity from the World Climate Research Programme (WCRP) which coordinates and archives climate model simulations based on shared model inputs by modelling groups from around the world. The CMIP3 multi-model data set includes projections using SRES scenarios. The CMIP5 data set includes projections using the Representative Concentration Pathways. The CMIP6 phase involves a suite of common model experiments as well as an ensemble of CMIP-endorsed model intercomparison projects (MIPs).

**Cumulative emissions**
The total amount of emissions released over a specified period of time.

*See also Carbon budget, and Transient climate response to cumulative CO₂ emissions (TCRE).*

**Deforestation**
Conversion of forest to non-forest. For a discussion of the term forest and related terms such as afforestation, reforestation and deforestation, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000). [Footnote: See also information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013) and the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).]

*See also Afforestation, Reforestation, and Reducing Emissions from Deforestation and Forest Degradation (REDD+).*

**Demand and supply-side measures**

*Demand-side measures*
Policies and programmes for influencing the demand for goods and/or services. In the energy sector, demand-side management aims at reducing the demand for electricity and other forms of energy required to deliver energy services.

*Supply-side measures*
Policies and programmes for influencing how a certain demand for goods and/or services is met. In the energy sector, for example, supply-side mitigation measures aim at reducing the amount of greenhouse gas emissions emitted per unit of energy produced.
See also Mitigation measures.

**Demand-side measures**  
*See Demand and supply-side measures.*

**Detection**  
*See Detection and attribution.*

**Detection and attribution**  
Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%. Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence.

**Discounting**  
A mathematical operation that aims to make monetary (or other) amounts received or expended at different times (years) comparable across time. The discounter uses a fixed or possibly time-varying discount rate from year to year that makes future value worth less today (if the discount rate is positive). The choice of discount rate(s) is debated as it is a judgement based on hidden and/or explicit values.

**Discount rate**  
*See Discounting.*

**(Internal) Displacement**  
Internal displacement refers to the forced movement of people within the country they live in. Internally displaced persons (IDPs) are “Persons or groups of persons who have been forced or obliged to flee or to leave their homes or places of habitual residence, in particular as a result of or in order to avoid the effects of armed conflict, situations of generalized violence, violations of human rights or natural or human-made disasters, and who have not crossed an internationally recognized State border.” (UNCHR, 1998).

*See also Migration.*

**Distributive equity**  
*See Equity.*

**Distributive justice**  
*See Justice.*
Downscaling
Downscaling is a method that derives local- to regional-scale (up to 100 km) information from larger-scale models or data analyses. Two main methods exist: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution, or high-resolution global models. The empirical/statistical methods are based on observations and develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the driving model remains an important limitation on quality of the downscaled information. The two methods can be combined, e.g., applying empirical/statistical downscaling to the output of a regional climate model, consisting of a dynamical downscaling of a global climate model.

Drought
A period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought is a relative term (see Box 3-3), therefore any discussion in terms of precipitation deficit must refer to the particular precipitation-related activity that is under discussion. For example, shortage of precipitation during the growing season impinges on crop production or ecosystem function in general (due to soil moisture drought, also termed agricultural drought), and during the runoff and percolation season primarily affects water supplies (hydrological drought). Storage changes in soil moisture and groundwater are also affected by increases in actual evapotranspiration in addition to reductions in precipitation. A period with an abnormal precipitation deficit is defined as a meteorological drought.

See also Soil moisture.

Megadrought
A megadrought is a very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more.

Decarbonisation
The process by which countries, individuals or other entities aim to achieve zero fossil carbon existence. Typically refers to a reduction of the carbon emissions associated with electricity, industry and transport.

Decoupling
Decoupling (in relation to climate change) is where economic growth is no longer strongly associated with consumption of fossil fuels. Relative decoupling is where both grow but at different rates. Absolute decoupling is where economic growth happens but fossil fuels decline.

Deliberative governance
See Governance.

Development pathways
See Pathways.

Direct air carbon dioxide capture and storage (DACCS)
Chemical process by which CO₂ is captured directly from the ambient air, with subsequent storage. Also known as direct air capture and storage (DACS).
Disaster
Severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery.

See also Hazard.

Disaster risk management (DRM)
Processes for designing, implementing, and evaluating strategies, policies, and measures to improve the understanding of disaster risk, foster disaster risk reduction and transfer, and promote continuous improvement in disaster preparedness, response, and recovery practices, with the explicit purpose of increasing human security, well-being, quality of life, and sustainable development.

Disruptive innovation
Disruptive innovation is demand-led technological change that leads to significant system change and is characterized by strong exponential growth.

Double dividend
The extent to which revenues generated by policy instruments, such as carbon taxes or auctioned (tradeable) emission permits can (1) contribute to mitigation and (2) offset part of the potential welfare losses of climate policies through recycling the revenue in the economy by reducing other distortionary taxes.

Early warning systems (EWS)
The set of technical, financial and institutional capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare to act promptly and appropriately to reduce the possibility of harm or loss. Dependent upon context, EWS may draw upon scientific and/or Indigenous knowledge. EWS are also considered for ecological applications e.g., conservation, where the organisation itself is not threatened by hazard but the ecosystem under conservation is (an example is coral bleaching alerts), in agriculture (for example, warnings of ground frost, hailstorms) and in fisheries (storm and tsunami warnings). This glossary entry builds from the definitions used in UNISDR (2009) and IPCC (2012a).

Earth system feedbacks
See Climate feedback.

Earth system model (ESM)
A coupled atmosphere–ocean general circulation model in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric CO₂ or compatible emissions. Additional components (e.g., atmospheric chemistry, ice sheets, dynamic vegetation, nitrogen cycle, but also urban or crop models) may be included.

See also Climate model.
Ecosystem
An ecosystem is a functional unit consisting of living organisms, their non-living environment and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms, or are influenced by the effects of human activities in their environment.

See also Ecosystem services.

Ecosystem services
Ecological processes or functions having monetary or non-monetary value to individuals or society at large. These are frequently classified as (1) supporting services such as productivity or biodiversity maintenance, (2) provisioning services such as food or fibre, (3) regulating services such as climate regulation or carbon sequestration, and (4) cultural services such as tourism or spiritual and aesthetic appreciation.

Effective climate sensitivity
See Climate sensitivity.

Effective radiative forcing
See Radiative forcing.

Electric vehicle (EV)
A vehicle whose propulsion is powered fully or mostly by electricity.

Battery electric vehicle (BEV)
A vehicle whose propulsion is entirely electric without any internal combustion engine.

Plug-in hybrid electric vehicle (PHEV)
A vehicle whose propulsion is mostly electric with batteries re-charged from an electric source but extra power and distance are provided by a hybrid internal combustion engine.

El niño-southern oscillation (ENSO)
The term El Niño was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. It has since become identified with warming of the tropical Pacific Ocean east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. This coupled atmosphere–ocean phenomenon, with preferred time scales of two to about seven years, is known as the El Niño-Southern Oscillation (ENSO). It is often measured by the surface pressure anomaly difference between Tahiti and Darwin and/or the sea surface temperatures in the central and eastern equatorial Pacific. During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This phenomenon has a great impact on the wind, sea surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and
in many other parts of the world, through global teleconnections. The cold phase of ENSO is called La Niña.

**Emission scenario**
A plausible representation of the future development of emissions of substances that are radiatively active (e.g., greenhouse gases (GHGs), aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change, energy and land use) and their key relationships. Concentration scenarios, derived from emission scenarios, are often used as input to a climate model to compute climate projections.

*See also Baseline scenario, Mitigation scenario, Representative Concentration Pathways (RCPs) (under Pathways), Shared socio-economic pathways (SSPs) (under Pathways), Scenario, Socio-economic scenario, and Transformation pathway.*

**Emissions trading**
A market-based instrument aiming at meeting a mitigation objective in an efficient way. A cap on GHG emissions is divided in tradeable emission permits that are allocated by a combination of auctioning and handing out free allowances to entities within the jurisdiction of the trading scheme. Entities need to surrender emission permits equal to the amount of their emissions (e.g., tonnes of CO$_2$). An entity may sell excess permits to entities that can avoid the same amount of emissions in a cheaper way. Trading schemes may occur at the intra-company, domestic, or international level (e.g., the flexibility mechanisms under the Kyoto Protocol and the EU-ETS) and may apply to carbon dioxide (CO$_2$), other greenhouse gases (GHGs), or other substances.

**Emission trajectories**
A projected development in time of the emission of a greenhouse gas (GHG) or group of GHGs, aerosols, and GHG precursors.

*See also Pathways.*

**Enabling conditions**
Conditions that affect the feasibility of adaptation and mitigation options, and can accelerate and scale-up systemic transitions that would limit temperature increase to 1.5°C and enhance capacities of systems and societies to adapt to the associated climate change, while achieving sustainable development, eradicating poverty and reducing inequalities. Enabling conditions include finance, technological innovation, strengthening policy instruments, institutional capacity, multi-level governance, and changes in human behaviour and lifestyles. They also include inclusive processes, attention to power asymmetries and unequal opportunities for development and reconsideration of values.

*See also Feasibility.*

**Energy efficiency**
The ratio of output or useful energy or energy services or other useful physical outputs obtained from a system, conversion process, transmission or storage activity to the input of energy (measured as kWh kWh$^{-1}$, tonnes kWh$^{-1}$ or any other physical measure of useful output like tonne-km transported). Energy efficiency is often described by energy intensity. In economics, energy intensity describes the
ratio of economic output to energy input. Most commonly energy efficiency is measured as input energy over a physical or economic unit, i.e. kWh USD\(^{-1}\) (energy intensity), kWh tonne\(^{-1}\). For buildings, it is often measured as kWh m\(^2\), and for vehicles as km liter\(^{-1}\) or liter km\(^{-1}\). Very often in policy "energy efficiency" is intended as the measures to reduce energy demand through technological options such as insulating buildings, more efficient appliances, efficient lighting, efficient vehicles, etc.

**Energy security**
The goal of a given country, or the global community as a whole, to maintain an adequate, stable and predictable energy supply. Measures encompass safeguarding the sufficiency of energy resources to meet national energy demand at competitive and stable prices and the resilience of the energy supply; enabling development and deployment of technologies; building sufficient infrastructure to generate, store and transmit energy supplies and ensuring enforceable contracts of delivery.

**Enhanced weathering**
Enhancing the removal of carbon dioxide from the atmosphere through dissolution of silicate and carbonate rocks by grinding these minerals to small particles and actively applying them to soils, coasts or oceans.

**(Model) Ensemble**
A group of parallel model simulations characterising historical climate conditions, climate predictions, or climate projections. Variation of the results across the ensemble members may give an estimate of modelling-based uncertainty. Ensembles made with the same model but different initial conditions only characterize the uncertainty associated with internal climate variability, whereas multi-model ensembles including simulations by several models also include the impact of model differences. Perturbed parameter ensembles, in which model parameters are varied in a systematic manner, aim to assess the uncertainty resulting from internal model specifications within a single model. Remaining sources of uncertainty unaddressed with model ensembles are related to systematic model errors or biases, which may be assessed from systematic comparisons of model simulations with observations wherever available.

*See also* Climate projection.

**Equality**
A principle that ascribes equal worth to all human beings, including equal opportunities, rights, and obligations, irrespective of origins.

**Inequality**
Uneven opportunities and social positions, and processes of discrimination within a group or society, based on gender, class, ethnicity, age, and (dis)ability, often produced by uneven development. Income inequality refers to gaps between highest and lowest income earners within a country and between countries.

*See also* Equity, Ethics, and Fairness.

**Equilibrium climate sensitivity**
*See* Climate sensitivity.
Equity
Equity is the principle of fairness in burden sharing and is a basis for understanding how the impacts and responses to climate change, including costs and benefits, are distributed in and by society in more or less equal ways. It is often aligned with ideas of equality, fairness and justice and applied with respect to equity in the responsibility for, and distribution of, climate impacts and policies across society, generations, and gender, and in the sense of who participates and controls the processes of decision making.

Distributive equity
Equity in the consequences, outcomes, costs and benefits of actions or policies. In the case of climate change or climate policies for different people, places and countries, including equity aspects of sharing burdens and benefits for mitigation and adaptation.

Gender equity
Ensuring equity in that women and men have the same rights, resources and opportunities. In the case of climate change gender equity recognizes that women are often more vulnerable to the impacts of climate change and may be disadvantaged in the process and outcomes of climate policy.

Inter-generational equity
Equity between generations that acknowledges that the effects of past and present emissions, vulnerabilities and policies impose costs and benefits for people in the future and of different age groups.

Procedural equity
Equity in the process of decision making including recognition and inclusiveness in participation, equal representation, bargaining power, voice and equitable access to knowledge and resources to participate.

See also Equality, Ethics and Fairness.

Ethics
Ethics involves questions of justice and value. Justice is concerned with right and wrong, equity and fairness, and, in general, with the rights to which people and living beings are entitled. Value is a matter of worth, benefit, or good.

See also Equality, Equity, and Fairness.

Evidence
Data and information used in the scientific process to establish findings. In this report, the degree of evidence reflects the amount, quality, and consistency of scientific/technical information on which the Lead Authors are basing their findings.

See also Agreement, Confidence, Likelihood, and Uncertainty.

Exposure
The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected.

See also Hazard, Risk, and Vulnerability.
**Extratropical Cyclone**
Any cyclonic-scale storm that is not a tropical cyclone. Usually refers to a middle- or high-latitude migratory storm system formed in regions of large horizontal temperature variations. Sometimes called extratropical storm or extratropical low.

*See also Tropical cyclone.*

**Extreme weather or climate event**
*See Climate extreme (extreme weather or climate event).*

**Extreme weather event**
An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).

*See also Heat wave, and Climate extreme (extreme weather or climate event)*

**Fairness**
Impartial and just treatment without favouritism or discrimination in which each person is considered of equal worth with equal opportunity.

*See also Equity, Equality and Ethics.*

**Feasible scenario commitment**
*See Climate change commitment.*

**Feasibility**
The degree to which climate goals and response options are considered possible and/or desirable. Feasibility depends on geophysical, ecological, technological, economic, social and institutional conditions for change. Conditions underpinning feasibility are dynamic, spatially variable, and may vary between different groups.

*See also Enabling conditions.*

**Feedback**
*See Climate feedback.*

**Flexible governance**
*See Governance.*
Flood
The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods.

Food security
A situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO, 2001).

Food wastage
Food wastage encompasses food loss (the loss of food during production and transportation) and food waste (the waste of food by the consumer) (FAO, 2013).

Forcing
See Radiative forcing.

Forest
A vegetation type dominated by trees. Many definitions of the term forest are in use throughout the world, reflecting wide differences in biogeophysical conditions, social structure and economics. For a discussion of the term forest and related terms such as afforestation, reforestation and deforestation, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000). [Footnote: See also information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013) and the Report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).]

See also Afforestation, Deforestation, and Reforestation.

Fossil fuels
Carbon-based fuels from fossil hydrocarbon deposits, including coal, oil, and natural gas.

Framework Convention on Climate Change
See United Nations Framework Convention on Climate Change (UNFCCC).

Gender equity
See Equity.

General purpose technologies (GPT)
General Purpose Technologies can be or are used pervasively in a wide range of sectors in ways that fundamentally change the modes of operation of those sectors (Helpman, 1998). Examples include the steam engine, power generator and motor, ICT, and biotechnology.
Geoengineering
In this report, separate consideration is given to the two main approaches considered as ‘geoengineering’ in some of the literature: solar radiation modification (SRM) and carbon dioxide removal (CDR). Because of this separation, the term ‘geoengineering’ is not used in this report. See also Carbon dioxide removal (CDR) and Solar radiation modification (SRM).

Glacier
A perennial mass of ice, and possibly firn and snow, originating on the land surface by the recrystallisation of snow and showing evidence of past or present flow. A glacier typically gains mass by accumulation of snow, and loses mass by melting and ice discharge into the sea or a lake if the glacier terminates in a body of water. Land ice masses of continental size (>50 000 km²) are referred to as ice sheets.

See also Ice sheet.

Global climate model (also referred to as general circulation model, both abbreviated as GCM)
See Climate model.

Global mean surface temperature (GMST)
Area-weighted global average of land surface air temperature over land and sea surface temperatures, unless otherwise specified, normally expressed relative to a specified reference period.

See also Land surface air temperature, and Sea surface temperature (SST).

Global warming
An increase in global mean surface temperature (GMST) averaged over a 30-year period, relative to 1850-1900 unless otherwise specified. For periods shorter than 30 years, global warming refers to the estimated average temperature over the 30 years centred on that shorter period, accounting for the impact of any temperature fluctuations or trend within those 30 years.

See also Climate change, Climate variability, and Global mean surface temperature (GMST).

Governance
A comprehensive and inclusive concept of the full range of means for deciding, managing, implementing and monitoring policies and measures. Whereas government is defined strictly in terms of the nation-state, the more inclusive concept of governance recognizes the contributions of various levels of government (global, international, regional, sub-national and local) and the contributing roles of the private sector, of nongovernmental actors, and of civil society to addressing the many types of issues facing the global community.

Adaptive governance
An emerging term in the literature for the evolution of formal and informal institutions of governance that prioritize social learning in planning, implementation and evaluation of policy through iterative social learning to steer the use and protection of natural resources, ecosystem services and common pool natural resources, particularly in situations of complexity and uncertainty.
Climate governance
Purposeful mechanisms and measures aimed at steering social systems towards preventing, mitigating, or adapting to the risks posed by climate change (Jagers and Stripple, 2003).

Deliberative governance
Deliberative governance involves decision making through inclusive public conversation which allows opportunity for developing policy options through public discussion rather than collating individual preferences through voting or referenda (although the later governance mechanisms can also be proceeded and legitimated by public deliberation processes).

Flexible governance
Strategies of governance at various levels, which prioritize the use of social learning and rapid feedback mechanisms in planning and policy making, often through incremental, experimental and iterative management processes.

Governance capacity
The ability of governance institutions, leaders, and non-state and civil society to plan, co-ordinate, fund, implement, evaluate and adjust policies and measures over the short, medium and long term, adjusting for uncertainty, rapid change and wide ranging impacts and multiple actors and demands.

Multi-level governance
Multi-level governance refers to negotiated, non-hierarchical exchanges between institutions at the transnational, national, regional and local levels. Multi-level governance identifies relationships among governance processes at these different levels. Multi-level governance does include negotiated relationships among institutions at different institutional levels and also a vertical ‘layering’ of governance processes at different levels. Institutional relationships take place directly between, transnational, regional and local levels, thus bypassing the state level (Peters and Pierre, 2001).

Participatory governance
A governance system that enables direct public engagement in decision-making using a variety of techniques for example, referenda, community deliberation, citizen juries or participatory budgeting. The approach can be applied in formal and informal institutional contexts from national to local, but is usually associated with devolved decision making. [Footnote: This definition builds from Fung and Olin Wright (2003) and Sarmiento and Tilly (2018).]

Governance capacity
See Governance.

Green infrastructure
The interconnected set of natural and constructed ecological systems, green spaces and other landscape features. It includes planted and indigenous trees, wetlands, parks, green open spaces and original grassland and woodlands, as well as possible building and street level design interventions that incorporate vegetation. Green infrastructure provides services and functions in the same way as conventional infrastructure. This definition builds from Culwick and Bobbins (2016).

Greenhouse gas (GHG)
Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H₂O), carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄)
and ozone (O₃) are the primary GHGs in the earth's atmosphere. Moreover, there are a number of entirely human-made GHGs in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO₂, N₂O and CH₄, the Kyoto Protocol deals with the GHGs sulphur hexafluoride (SF₆), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

See also Carbon dioxide (CO₂), Methane (CH₄), and Ozone (O₃).

**Greenhouse gas removal (GGR)**
Withdrawal of a GHG and/or a precursor from the atmosphere by a sink.

See also Carbon dioxide removal (CDR), and Negative emissions.

**Gross domestic product (GDP)**
The sum of gross value added, at purchasers' prices, by all resident and non-resident producers in the economy, plus any taxes and minus any subsidies not included in the value of the products in a country or a geographic region for a given period, normally one year. GDP is calculated without deducting for depreciation of fabricated assets or depletion and degradation of natural resources.

**Gross fixed capital formation (GFCF)**
One component of the GDP that corresponds to the total value of acquisitions, minus disposals of fixed assets during one year by the business sector, governments and households, plus certain additions to the value of non-produced assets (such as subsoil assets or major improvements in the quantity, quality or productivity of land).

**Halocarbons**
A collective term for the group of partially halogenated organic species, which includes the chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), halons, methyl chloride and methyl bromide. Many of the halocarbons have large Global Warming Potentials. The chlorine and bromine-containing halocarbons are also involved in the depletion of the ozone layer.

**Hazard**
The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.

See also Disaster, Exposure, Risk, and Vulnerability.

**Heating, ventilation, and air conditioning (HVAC)**
Heating, ventilation and air conditioning technology is used to control temperature and humidity in an indoor environment, be it in buildings or in vehicles, providing thermal comfort and healthy air quality to the occupants. HVAC systems can be designed for an isolated space, an individual building or a distributed heating and cooling network within a building structure or a district heating system. The latter provides economies of scale and also scope for integration with solar heat, natural seasonal cooling/heating etc.
Heat wave
A period of abnormally hot weather. Heat waves and warm spells have various and in some cases overlapping definitions.

See also Extreme weather event.

Holocene
The Holocene is the current interglacial geological epoch, the second of two epochs within the Quaternary period, the preceding being the Pleistocene. The International Commission on Stratigraphy defines the start of the Holocene at 11,650 years before 1950.

See also Anthropocene.

Human behaviour
The way in which a person acts in response to a particular situation or stimulus. Human actions are relevant at different levels, from international, national, and sub-national actors, to NGO, firm-level actors, and communities, households, and individual actions.

Adaptation behaviour
Human actions that directly or indirectly affect the risks of climate change impacts.

Mitigation behaviour
Human actions that directly or indirectly influence mitigation.

Human behavioural change
A transformation or modification of human actions. Behaviour change efforts can be planned in ways that mitigate climate change and/or reduce negative consequences of climate change impacts.

Human rights
Rights that are inherent to all human beings, universal, inalienable, and indivisible, typically expressed and guaranteed by law. They include the right to life, economic, social, and cultural rights, and the right to development and self-determination (based upon the definition by the UN Office of the High Commissioner).

Procedural rights
Rights to a legal procedure to enforce substantive rights.

Substantive rights
Basic human rights, including the right to the substance of being human such as life itself, liberty and happiness.

Human security
A condition that is met when the vital core of human lives is protected, and when people have the freedom and capacity to live with dignity. In the context of climate change, the vital core of human lives includes the universal and culturally specific, material and non-material elements necessary for people to act on behalf of their interests and to live with dignity.
Human system
Any system in which human organizations and institutions play a major role. Often, but not always, the term is synonymous with society or social system. Systems such as agricultural systems, urban systems, political systems, technological systems, and economic systems are all human systems in the sense applied in this report.

Hydrological cycle
The cycle in which water evaporates from the oceans and the land surface, is carried over the Earth in atmospheric circulation as water vapour, condenses to form clouds, precipitates as rain or snow, which on land can be intercepted by trees and vegetation, potentially accumulates as snow or ice, provides runoff on the land surface, infiltrates into soils, recharges groundwater, discharges into streams, flows out into the oceans, and ultimately evaporates again from the ocean or land surface. The various systems involved in the hydrological cycle are usually referred to as hydrological systems.

Ice sheet
A mass of land ice of continental size that is sufficiently thick to cover most of the underlying bed, so that its shape is mainly determined by its dynamics (the flow of the ice as it deforms internally and/or slides at its base). An ice sheet flows outward from a high central ice plateau with a small average surface slope. The margins usually slope more steeply, and most ice is discharged through fast flowing ice streams or outlet glaciers, in some cases into the sea or into ice shelves floating on the sea. There are only two ice sheets in the modern world, one on Greenland and one on Antarctica. During glacial periods there were others.

See also Glacier.

Impacts (consequences, outcomes)
The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather and climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and wellbeing, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Impacts may be referred to as consequences or outcomes, and can be adverse or beneficial.

See also Adaptation, Exposure, Hazard, Loss and Damage, and loss and damages, and Vulnerability.

(climate change) Impact assessment
The practice of identifying and evaluating, in monetary and/or non-monetary terms, the effects of climate change on natural and human systems.

Incremental adaptation
See Adaptation.

Indigenous knowledge
Indigenous knowledge refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings. For many Indigenous peoples, Indigenous knowledge informs decision-making about fundamental aspects of life, from day-to-day
activities to longer term actions. This knowledge is integral to cultural complexes, which also encompass language, systems of classification, resource use practices, social interactions, values, ritual and spirituality. These distinctive ways of knowing are important facets of the world’s cultural diversity. This definition builds on UNESCO (2018).

**Indirect land-use change**
*See Land-use change.*

**Industrial revolution**
A period of rapid industrial growth with far-reaching social and economic consequences, beginning in Britain during the second half of the 18th century and spreading to Europe and later to other countries including the United States. The invention of the steam engine was an important trigger of this development. The industrial revolution marks the beginning of a strong increase in the use of fossil fuels, initially coal, and hence emission of carbon dioxide (CO₂).

*See also Pre-industrial.*

**Industrialized/developed/developing countries**
There are a diversity of approaches for categorizing countries on the basis of their level of development, and for defining terms such as industrialized, developed, or developing. Several categorizations are used in this report. (1) In the United Nations system, there is no established convention for designating of developed and developing countries or areas. (2) The United Nations Statistics Division specifies developed and developing regions based on common practice. In addition, specific countries are designated as Least Developed Countries (LCD), landlocked developing countries, small island developing states, and transition economies. Many countries appear in more than one of these categories. (3) The World Bank uses income as the main criterion for classifying countries as low, lower middle, upper middle, and high income. (4) The UNDP aggregates indicators for life expectancy, educational attainment, and income into a single composite Human Development Index (HDI) to classify countries as low, medium, high, or very high human development.

**Inequality**
*See Equality.*

**Information and communication technology (ICT)**
An umbrella term that includes any information and communication device or application, encompassing: computer systems, network hardware and software, cellphone, etc.

**Infrastructure commitment**
*See Climate change commitment.*

**Institution**
Institutions are rules and norms held in common by social actors that guide, constrain and shape human interaction. Institutions can be formal, such as laws and policies, or informal, such as norms and conventions. Organizations - such as parliaments, regulatory agencies, private firms, and community bodies - develop and act in response to institutional frameworks and the incentives they
frame. Institutions can guide, constrain and shape human interaction through direct control, through incentives, and through processes of socialization.

See also Institutional capacity.

**Institutional capacity**
Institutional capacity comprises building and strengthening individual organisations and providing technical and management training to support integrated planning and decision-making processes between organisations and people, as well as empowerment, social capital, and an enabling environment, including the culture, values and power relations (Willems and Baumert, 2003).

**Integrated assessment**
A method of analysis that combines results and models from the physical, biological, economic and social sciences and the interactions among these components in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it.

See also Integrated assessment model (IAM).

**Integrated assessment model (IAM)**
Integrated assessment models (IAMs) integrate knowledge from two or more domains into a single framework. They are one of the main tools for undertaking integrated assessments.

One class of IAM used in respect of climate change mitigation may include representations of: multiple sectors of the economy, such as energy, land use and land use change; interactions between sectors; the economy as a whole; associated GHG emissions and sinks; and reduced representations of the climate system. This class of model is used to assess linkages between economic, social and technological development and the evolution of the climate system.

Another class of IAM additionally includes representations of the costs associated with climate change impacts, but includes less detailed representations of economic systems. These can be used to assess impacts and mitigation in a cost-benefit framework and have been used to estimate the social cost of carbon.

**Integrated water resources management (IWRM)**
A process which promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

**Inter-generational equity**
See Equity.

**Inter-generational justice**
See Justice.

**Internal variability**
See Climate variability.
Internet of Things (IoT)
The network of computing devices embedded in everyday objects such as cars, phones and computers, connected via the internet, enabling them to send and receive data.

Iron fertilisation
See Ocean fertilisation.

Irreversibility
A perturbed state of a dynamical system is defined as irreversible on a given timescale, if the recovery timescale from this state due to natural processes is substantially longer than the time it takes for the system to reach this perturbed state.

See also Tipping point.

Justice
Justice is concerned with ensuring that people get what is due to them setting out the moral or legal principles of fairness and equity in the way people are treated, often based on the ethics and values of society.

Climate justice
Justice that links development and human rights to achieve a human-centred approach to addressing climate change, safeguarding the rights of the most vulnerable people and sharing the burdens and benefits of climate change and its impacts equitably and fairly. This definitions builds upon the one used by the Mary Robinson Foundation - Climate Justice.

Distributive justice
Justice in the allocation of economic and non-economic costs and benefits across society.

Inter-generational justice
Justice in the distribution of economic and non-economic costs and benefits across generations.

Procedural justice
Justice in the way outcomes are brought about including who participates and is heard in the processes of decision making.

Social justice
Just or fair relations within society that seek to address the distribution of wealth, access to resources, opportunity, and support according to principles of justice and fairness.

See also Equity, Ethics, Fairness, and Human rights.

Kyoto Protocol
The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) is an international treaty adopted in December 1997 in Kyoto, Japan, at the Third Session of the Conference of the Parties (COP3) to the UNFCCC. It contains legally binding commitments, in addition to those included in the UNFCCC. Countries included in Annex B of the Protocol (mostly OECD countries and countries with economies in transition) agreed to reduce their anthropogenic greenhouse gas (GHG) emissions (carbon dioxide (CO$_2$), methane (CH$_4$), nitrous oxide (N$_2$O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF$_6$)) by at least 5%
below 1990 levels in the first commitment period (2008-2012). The Kyoto Protocol entered into force on 16 February 2005 and as of May 2018 had 192 Parties (191 States and the European Union). A second commitment period was agreed in December 2012 at COP18, known as the Doha Amendment to the Kyoto Protocol, in which a new set of Parties committed to reduce GHG emissions by at least 18% below 1990 levels in the period from 2013 to 2020. However, as of May 2018, the Doha Amendment had not received sufficient ratifications to enter into force.

See also United Nations Framework Convention on Climate Change (UNFCCC), and Paris Agreement.

**Land surface air temperature**
The near-surface air temperature over land, typically measured at 1.25-2 m above the ground using standard meteorological equipment.

**Land use**
Land use refers to the total of arrangements, activities and inputs undertaken in a certain land cover type (a set of human actions). The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, conservation and city dwelling). In national greenhouse gas inventories, land use is classified according to the IPCC land use categories of forest land, cropland, grassland, wetland, settlements, other.

See also Land-use change.

**Land-use change (LUC)**
Land-use change involves a change from one land use category to another.

*Indirect land-use change (iLUC)*
Refers to market-mediated or policy-driven shifts in land use that cannot be directly attributed to land use management decisions of individuals or groups. For example, if agricultural land is diverted to fuel production, forest clearance may occur elsewhere to replace the former agricultural production.

*Land use, land-use change and forestry (LULUCF)*
In the context of national greenhouse gas (GHG) inventories under the UNFCCC, LULUCF is a GHG inventory sector that covers anthropogenic emissions and removals of GHG from carbon pools in managed lands, excluding non-CO₂ agricultural emissions. Following the 2006 IPCC Guidelines for National GHG Inventories, “anthropogenic” land-related GHG fluxes are defined as all those occurring on “managed land”, i.e., “where human interventions and practices have been applied to perform production, ecological or social functions”. Since managed land may include CO₂ removals not considered as “anthropogenic” in some of the scientific literature assessed in this report (e.g., removals associated with CO₂ fertilisation and N deposition), the land-related net GHG emission estimates included in this report are not necessarily directly comparable with LULUCF estimates in National GHG Inventories.

See also Afforestation, Deforestation, Reforestation and the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000).

**Land use, land-use change and forestry (LULUCF)**
See Land use, land-use change and forestry (LULUCF).
Lifecycle assessment (LCA)
Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product or service throughout its life cycle. This definition builds from ISO (2018).

Likelihood
The chance of a specific outcome occurring, where this might be estimated probabilistically. Likelihood is expressed in this report using a standard terminology (Mastrandrea et al., 2010). See Section 1.6 for the list of likelihood qualifiers used.

See also Agreement, Evidence, Confidence, and Uncertainty.

Livelihood
The resources used and the activities undertaken in order to live. Livelihoods are usually determined by the entitlements and assets to which people have access. Such assets can be categorised as human, social, natural, physical, or financial.

Local knowledge
Local knowledge refers to the understandings and skills developed by individuals and populations, specific to the places where they live. Local knowledge informs decision-making about fundamental aspects of life, from day-to-day activities to longer term actions. This knowledge is a key element of the social and cultural systems which influence observations of, and responses to climate change; it also informs governance decisions. This definition builds on UNESCO (2018)

Lock-in
A situation in which the future development of a system, including infrastructure, technologies, investments, institutions, and behavioural norms, is determined or constrained (“locked in”) by historic developments.

Long-lived climate forcers (LLCF)
Long-lived climate forcers refer to a set of well-mixed greenhouse gases with long atmospheric lifetimes. This set of compounds includes carbon dioxide and nitrous oxide, together with some fluorinated gases. They have a warming effect on climate. These compounds accumulate in the atmosphere at decadal to centennial timescales, and their effect on climate hence persists for decades to centuries after their emission. On timescales of decades to a century already emitted emissions of long-lived climate forcers can only be abated by greenhouse gas removal (GGR).

See also Short-lived climate forcers (SLCF).

Loss and Damage, and losses and damages
Research has taken Loss and Damage (capitalized letters) to refer to political debate under the UNFCCC following the establishment of the Warsaw Mechanism on Loss and Damage in 2013, which is to “address loss and damage associated with impacts of climate change, including extreme events and slow onset events, in developing countries that are particularly vulnerable to the adverse effects of climate change.” Lowercase letters (losses and damages) have been taken to refer broadly to harm from (observed) impacts and (projected) risks (see Mechler et al., 2018).
Maladaptive actions (Maladaptation)
Actions that may lead to increased risk of adverse climate-related outcomes, including via increased GHG emissions, increased vulnerability to climate change, or diminished welfare, now or in the future. Maladaptation is usually an unintended consequence.

Market exchange rates (MER)
The rate at which a currency of one country can be exchanged with the currency of another country. In most economies such rates evolve daily while in others there are official conversion rates that are adjusted periodically.

See also Purchasing power parity (PPP).

Market failure
When private decisions are based on market prices that do not reflect the real scarcity of goods and services but rather reflect market distortions, they do not generate an efficient allocation of resources but cause welfare losses. A market distortion is any event in which a market reaches a market clearing price that is substantially different from the price that a market would achieve while operating under conditions of perfect competition and state enforcement of legal contracts and the ownership of private property. Examples of factors causing market prices to deviate from real economic scarcity are environmental externalities, public goods, monopoly power, information asymmetry, transaction costs, and non-rational behaviour.

Measurement, reporting and verification (MRV)

Measurement
“The process of data collection over time, providing basic datasets, including associated accuracy and precision, for the range of relevant variables. Possible data sources are field measurements, field observations, detection through remote sensing and interviews.” Source: UN REDD

Reporting
“The process of formal reporting of assessment results to the UNFCCC, according to predetermined formats and according to established standards, especially the Intergovernmental Panel on Climate Change (IPCC) Guidelines and GPG (Good Practice Guidance).” Source: UN REDD

Verification
“The process of formal verification of reports, for example, the established approach to verify national communications and national inventory reports to the UNFCCC.” Source: UN REDD

Megadrought
See Drought.

Methane (CH₄)
One of the six greenhouse gases (GHGs) to be mitigated under the Kyoto Protocol and is the major component of natural gas and associated with all hydrocarbon fuels. Significant emissions occur as a result of animal husbandry and agriculture and their management represents a major mitigation option.
**Migration**
The International Organization for Migration (IOM) defines migration as “The movement of a person or a group of persons, either across an international border, or within a State. It is a population movement, encompassing any kind of movement of people, whatever its length, composition and causes; it includes migration of refugees, displaced persons, economic migrants, and persons moving for other purposes, including family reunification.” (IOM, 2018).

**Migrant**
The International Organization for Migration (IOM) defines a migrant as “any person who is moving or has moved across an international border or within a State away from his/her habitual place of residence, regardless of (1) the person’s legal status; (2) whether the movement is voluntary or involuntary; (3) what the causes for the movement are; or (4) what the length of the stay is.” (IOM, 2018).

*See also (Internal) Displacement.*

**Millennium Development Goals (MDGs)**
A set of eight time-bound and measurable goals for combating poverty, hunger, disease, illiteracy, discrimination against women and environmental degradation. These goals were agreed at the UN Millennium Summit in 2000 together with an action plan to reach the goals by 2015.

**Mitigation (of climate change)**
A human intervention to reduce emissions or enhance the sinks of greenhouse gases. Note that this encompasses carbon dioxide removal (CDR) options.

**Mitigation behaviour**
*See Human behaviour.*

**Mitigation measures**
In climate policy, mitigation measures are technologies, processes or practices that contribute to mitigation, for example renewable energy (RE) technologies, waste minimization processes, public transport commuting practices.

*See also Policies (for mitigation and adaptation).*

**Mitigation option**
A technology or practice that reduces GHG emissions or enhances sinks.

**Mitigation pathways**
*See Pathways.*

**Mitigation scenario**
A plausible description of the future that describes how the (studied) system responds to the implementation of mitigation policies and measures.
See also Emission scenario, Pathways, Socio-economic scenarios, and Stabilisation (of GHG or CO₂-equivalent concentration).

Monitoring and evaluation (M&E)
Monitoring and evaluation refers to mechanisms put in place at national to local scales to respectively monitor and evaluate efforts to reduce greenhouse gas emissions and/or adapt to the impacts of climate change with the aim of systematically identifying, characterizing and assessing progress over time.

Motivation (of an individual)
An individual’s reason or reasons for acting in a particular way; individuals may consider various consequences of actions, including financial, social, affective, and environmental consequences. Motivation can arise from outside (extrinsic) or inside (intrinsic) the individual.

Multi-level governance
See Governance.

Narratives
Qualitative descriptions of plausible future world evolutions, describing the characteristics, general logic and developments underlying a particular quantitative set of scenarios. Narratives are also referred to in the literature as “storylines”.

See also Scenario, Scenario storyline and Pathways.

Nationally Determined Contributions (NDCs)
A term used under the United Nations Framework Convention on Climate Change (UNFCCC) whereby a country that has joined the Paris Agreement outlines its plans for reducing its emissions. Some countries NDCs also address how they will adapt to climate change impacts, and what support they need from, or will provide to, other countries to adopt low-carbon pathways and to build climate resilience. According to Article 4 paragraph 2 of the Paris Agreement, each Party shall prepare, communicate and maintain successive NDCs that it intends to achieve. In the lead up to 21st Conference of the Parties in Paris in 2015, countries submitted Intended Nationally Determined Contributions (INDCs). As countries join the Paris Agreement, unless they decide otherwise, this INDC becomes their first Nationally Determined Contribution (NDC).

See also United Nations Framework Convention on Climate Change (UNFCCC), and Paris agreement.

Negative emissions
Removal of greenhouse gases (GHGs) from the atmosphere by deliberate human activities, i.e. in addition to the removal that would occur via natural carbon cycle processes. For CO₂, negative emissions can be achieved with direct capture of CO₂ from ambient air, bioenergy with carbon capture and sequestration (BECCS), afforestation, reforestation, biochar, ocean alkalization, among others.

See also Net negative emissions, Net-zero emissions, Carbon dioxide removal (CDR), and Greenhouse gas removal (GGR).
Net negative emissions
A situation of net negative emissions is achieved when, as result of human activities, more greenhouse gases are removed from the atmosphere than are emitted into it. Where multiple greenhouse gases are involved, the quantification of negative emissions depends on the climate metric chosen to compare emissions of different gases (such as Global warming potential, Global temperature change potential, and others, as well as the chosen time horizon).

See also Negative emissions, Net-zero emissions and Net-zero CO₂ emissions.

Net-zero CO₂ emissions
Conditions in which any remaining anthropogenic carbon dioxide (CO₂) emissions are balanced globally by anthropogenic CO₂ removals. Net-zero CO₂ emissions are also referred to as carbon neutrality.

See also Net-zero emissions, Carbon neutrality and Net negative emissions.

Net-zero emissions
Net-zero emissions are achieved when emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals. Where multiple greenhouse gases are involved, the quantification of net-zero emissions depends on the climate metric chosen to compare emissions of different gases (such as Global warming potential, global temperature change potential, and others, as well as the chosen time horizon).

See also Net-zero CO₂ emissions, Negative emissions, Net negative emission, and Carbon neutrality.

Nitrous oxide (N₂O)
One of the six greenhouse gases (GHGs) to be mitigated under the Kyoto Protocol. The main anthropogenic source of N₂O is agriculture (soil and animal manure management), but important contributions also come from sewage treatment, fossil fuel combustion, and chemical industrial processes. N₂O is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical forests.

Non-overshoot pathways
See Pathways.

Ocean acidification (OA)
Ocean acidification refers to a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide (CO₂) from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean. Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity (IPCC, 2011, p. 37).

Ocean fertilisation
Deliberate increase of nutrient supply to the near-surface ocean in order to enhance biological production through which additional carbon dioxide from the atmosphere is sequestered. This can be achieved by the addition of micro-nutrients or macro-nutrients. Ocean fertilisation is regulated by the London Protocol.
Overshoot
The temporary exceedance of a specified level of global warming, such as 1.5°C. Overshoot implies a peak followed by a decline in global warming, achieved through anthropogenic removal of CO₂ exceeding remaining CO₂ emissions globally.

See also Pathways (Subterms: Overshoot pathways, Non-overshoot Pathways).

Overshoot pathways
See Pathways.

Ozone (O₃)
Ozone, the triatomic form of oxygen (O₃), is a gaseous atmospheric constituent. In the troposphere, it is created both naturally and by photochemical reactions involving gases resulting from human activities (smog). Tropospheric ozone acts as a greenhouse gas. In the stratosphere, it is created by the interaction between solar ultraviolet radiation and molecular oxygen (O₂). Stratospheric ozone plays a dominant role in the stratospheric radiative balance. Its concentration is highest in the ozone layer.

Paris Agreement
The Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) was adopted on December 2015 in Paris, France, at the 21st session of the Conference of the Parties (COP) to the UNFCCC. The agreement, adopted by 196 Parties to the UNFCCC, entered into force on 4 November 2016 and as of May 2018 had 195 Signatories and was ratified by 177 Parties. One of the goals of the Paris Agreement is “Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels”, recognising that this would significantly reduce the risks and impacts of climate change. Additionally, the Agreement aims to strengthen the ability of countries to deal with the impacts of climate change. The Paris Agreement is intended to become fully effective in 2020.

See also United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol, and Nationally Determined Contributions (NDCs).

Participatory governance
See Governance.

Pathways
The temporal evolution of natural and/or human systems towards a future state. Pathway concepts range from sets of quantitative and qualitative scenarios or narratives of potential futures to solution-oriented decision-making processes to achieve desirable societal goals. Pathway approaches typically focus on biophysical, techno-economic, and/or socio-behavioural trajectories and involve various dynamics, goals, and actors across different scales.

1.5°C-consistent pathway
A pathway of emissions of greenhouse gases and other climate forcers that provides an approximately one-in-two to two-in-three chance, given current knowledge of the climate response, of global warming either remaining below 1.5°C or returning to 1.5°C by around 2100 following an overshoot.
**Adaptation pathways**
A series of adaptation choices involving trade-offs between short-term and long-term goals and values. These are processes of deliberation to identify solutions that are meaningful to people in the context of their daily lives and to avoid potential maladaptation.

**Development pathways**
Development pathways are trajectories based on an array of social, economic, cultural, technological, institutional, and biophysical features that characterise the interactions between human and natural systems and outline visions for the future, at a particular scale.

**Mitigation pathways**
A mitigation pathway is a temporal evolution of a set of mitigation scenario features, such as greenhouse gas emissions and socio-economic development.

**Overshoot pathways**
Pathways that exceed the stabilization level (concentration, forcing, or temperature) before the end of a time horizon of interest (e.g., before 2100) and then decline towards that level by that time. Once the target level is exceeded, removal by sinks of greenhouse gases is required. *See also Overshoot.*

**Non-overshoot pathways**
Pathways that stay below the stabilization level (concentration, forcing, or temperature) during the time horizon of interest (e.g., until 2100).

**Representative concentration pathways (RCPs)**
Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover (Moss et al., 2008). The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasizes the fact that not only the long-term concentration levels, but also the trajectory taken over time to reach that outcome are of interest (Moss et al., 2010). RCPs were used to develop climate projections in CMIP5.

**RCP2.6**
One pathway where radiative forcing peaks at approximately 3 W m$^{-2}$ and then declines to be limited at 2.6 W m$^{-2}$ in 2100 (the corresponding Extended Concentration Pathway, or ECP, has constant emissions after 2100).

**RCP4.5 and RCP6.0**
Two intermediate stabilisation pathways in which radiative forcing is limited at approximately 4.5 W m$^{-2}$ and 6.0 W m$^{-2}$ in 2100 (the corresponding ECPs have constant concentrations after 2150).

**RCP8.5**
One high pathway which leads to >8.5 W m$^{-2}$ in 2100 (the corresponding ECP has constant emissions after 2100 until 2150 and constant concentrations after 2250). *See also CMIP, and Shared socio-economic pathways (SSPs).*

**Shared socio-economic pathways (SSPs)**
Shared socio-economic pathways (SSPs) were developed to complement the RCPs with varying socio-economic challenges to adaptation and mitigation (O’Neill et al., 2014). Based on five narratives, the SSPs describe alternative socio-economic futures in the absence of climate policy intervention, comprising sustainable development (SSP1), regional rivalry (SSP3), inequality (SSP4), fossil–fueled development (SSP5), and a middle-of-the-road development (SSP2) (O’Neill, 2000;
O’Neill et al., 2017; Riahi et al., 2017). The combination of SSP-based socio-economic scenarios and Representative Concentration Pathway (RCP)-based climate projections provides an integrative frame for climate impact and policy analysis.

Transformation pathways
Trajectories describing consistent sets of possible futures of greenhouse gas (GHG) emissions, atmospheric concentrations, or global mean surface temperatures implied from mitigation and adaptation actions associated with a set of broad and irreversible economic, technological, societal, and behavioural changes. This can encompass changes in the way energy and infrastructure are used and produced, natural resources are managed and institutions are set up and in the pace and direction of technological change (TC).

See also Scenario, Scenario storyline, Emission scenario, Mitigation scenario, Baseline scenario, Stabilisation (of GHG or CO₂-equivalent concentration), and Narratives.

Peri-urban areas
Peri-urban areas are those parts of a city that appear to be quite rural but are in reality strongly linked functionally to the city in its daily activities.

Permafrost
Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years.

pH
pH is a dimensionless measure of the acidity of a solution given by its concentration of hydrogen ions ([H⁺]). pH is measured on a logarithmic scale where pH = -log₁₀[H⁺]. Thus, a pH decrease of 1 unit corresponds to a 10-fold increase in the concentration of H⁺, or acidity.

Policies (for climate change mitigation and adaptation)
Policies are taken and/or mandated by a government - often in conjunction with business and industry within a single country, or collectively with other countries - to accelerate mitigation and adaptation measures. Examples of policies are support mechanisms for renewable energy supplies, carbon or energy taxes, fuel efficiency standards for automobiles, etc.

Political economy
The set of interlinked relationships between people, the state, society and markets as defined by law, politics, economics, customs and power that determine the outcome of trade and transactions and the distribution of wealth in a country or economy.

Poverty
Poverty is a complex concept with several definitions stemming from different schools of thought. It can refer to material circumstances (such as need, pattern of deprivation or limited resources), economic conditions (such as standard of living, inequality or economic position) and/or social relationships (such as social class, dependency, exclusion, lack of basic security or lack of entitlement).

See also Poverty eradication.
Poverty eradication
A set of measures to end poverty in all its forms everywhere.

See also Sustainable Development Goals (SDGs).

Precursors
Atmospheric compounds that are not greenhouse gases (GHGs) or aerosols, but that have an effect on GHG or aerosol concentrations by taking part in physical or chemical processes regulating their production or destruction rates.

See also Aerosol, and Greenhouse gas (GHG).

Pre-industrial
The multi-century period prior to the onset of large-scale industrial activity. The reference period 1850-1900 is used to approximate pre-industrial global mean surface temperature (GMST) in this report.

See also Industrial revolution.

Procedural equity
See Equity.

Procedural justice
See Justice.

Procedural rights
See Human rights.

Projection
A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realized.

See also Climate projection, Scenario, and Pathways.

Purchasing power parity (PPP)
The purchasing power of a currency is expressed using a basket of goods and services that can be bought with a given amount in the home country. International comparison of, for example, gross domestic products (GDP) of countries can be based on the purchasing power of currencies rather than on current exchange rates. PPP estimates tend to lower the gap between the per capita GDP in industrialised and developing countries.

See also Market exchange rate (MER).
Radiative forcing
Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in W m$^{-2}$) at the tropopause or top of atmosphere due to a change in an driver of climate change, such as a change in the concentration of carbon dioxide or the output of the Sun. The traditional radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called instantaneous if no change in stratospheric temperature is accounted for. The radiative forcing once rapid adjustments are accounted for is termed the effective radiative forcing. Radiative forcing is not to be confused with cloud radiative forcing, which describes an unrelated measure of the impact of clouds on the radiative flux at the top of the atmosphere.

Reasons for concern (RFCs)
Elements of a classification framework, first developed in the IPCC Third Assessment Report, which aims to facilitate judgments about what level of climate change may be dangerous (in the language of Article 2 of the UNFCCC) by aggregating risks from various sectors, considering hazards, exposures, vulnerabilities, capacities to adapt, and the resulting impacts.

Reducing Emissions from Deforestation and Forest Degradation (REDD+)
An effort to create financial value for the carbon stored in forests, offering incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable development (SD). It is therefore a mechanism for mitigation that results from avoiding deforestation. REDD+ goes beyond deforestation and forest degradation, and includes the role of conservation, sustainable management of forests and enhancement of forest carbon stocks. The concept was first introduced in 2005 in the 11th Session of the Conference of the Parties (COP) in Montreal and later given greater recognition in the 13th Session of the COP in 2007 at Bali and inclusion in the Bali Action Plan which called for 'policy approaches and positive incentives on issues relating to reducing emissions from deforestation and forest degradation in developing countries (REDD) and the role of conservation, sustainable management of forests and enhancement of forest carbon stock in developing countries'. Since then, support for REDD has increased and has slowly become a framework for action supported by a number of countries.

Reference period
The period relative to which anomalies are computed.

See also Anomalies.

Reference scenario
See Baseline scenario.

Reforestation
Planting of forests on lands that have previously contained forests but that have been converted to some other use. [Footnote: For a discussion of the term forest and related terms such as afforestation, reforestation and deforestation, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000), information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013), the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).]
See also Deforestation, and Afforestation, and Reducing Emissions from Deforestation and Forest Degradation (REDD+).

Region
A region is a relatively large-scale land or ocean area characterized by specific geographical and climatological features. The climate of a land-based region is affected by regional and local scale features like topography, land use characteristics and large water bodies, as well as remote influences from other regions, in addition to global climate conditions. The IPCC defines a set of standard regions for analyses of observed climate trends and climate model projections (see Fig. 3.2; AR5, SREX).

Remaining carbon budget
Cumulative global CO₂ emissions from the start of 2018 to the time that CO₂ emissions reach net-zero that would result in a given level of global warming.

See also Carbon budget.

Representative concentration pathways (RCPs)
See Pathways

Resilience
The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation.[Footnote: This definition builds from the definition used by Arctic Council (2013).]

See also Hazard, Risk, and Vulnerability.

Risk
The potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain. In the context of the assessment of climate impacts, the term risk is often used to refer to the potential for adverse consequences of a climate-related hazard, or of adaptation or mitigation responses to such a hazard, on lives, livelihoods, health and wellbeing, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Risk results from the interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence.

Risk assessment
The qualitative and/or quantitative scientific estimation of risks.

See also Risk, Risk management, and Risk perception.

Risk management
Plans, actions, strategies or policies to reduce the likelihood and/or consequences of risks or to respond to consequences.
Risk perception
The subjective judgment that people make about the characteristics and severity of a risk.

See also Risk, Risk assessment, and Risk management.

Runoff
The flow of water over the surface or through the subsurface, which typically originates from the part of liquid precipitation and/or snow/ice melt that does not evaporate or refreeze, and is not transpired.

See also Hydrological cycle.

Scenario
A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change (TC), prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions.

See also Baseline scenario, Emission scenario, Mitigation scenario and Pathways.

Scenario storyline
A narrative description of a scenario (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces and the dynamics of their evolution. Also referred to as ‘narratives’ in the scenario literature.

See also Narratives.

Sea ice
Ice found at the sea surface that has originated from the freezing of seawater. Sea ice may be discontinuous pieces (ice floes) moved on the ocean surface by wind and currents (pack ice), or a motionless sheet attached to the coast (land-fast ice). Sea ice concentration is the fraction of the ocean covered by ice. Sea ice less than one year old is called first-year ice. Perennial ice is sea ice that survives at least one summer. It may be subdivided into second-year ice and multi-year ice, where multiyear ice has survived at least two summers.

Sea level change (sea level rise/sea level fall)
Sea level can change, both globally and locally (relative sea level change) due to (1) a change in ocean volume as a result of a change in the mass of water in the ocean, (2) changes in ocean volume as a result of changes in ocean water density, (3) changes in the shape of the ocean basins and changes in the Earth’s gravitational and rotational fields, and (4) local subsidence or uplift of the land. Global mean sea level change resulting from change in the mass of the ocean is called barystatic. The amount of barystatic sea level change due to the addition or removal of a mass of water is called its sea level equivalent (SLE). Sea level changes, both globally and locally, resulting from changes in water density are called steric. Density changes induced by temperature changes only are called thermosteric, while density changes induced by salinity changes are called halosteric. Barystatic and
steric sea level changes do not include the effect of changes in the shape of ocean basins induced by the change in the ocean mass and its distribution.

**Sea surface temperature (SST)**
The sea surface temperature is the subsurface bulk temperature in the top few meters of the ocean, measured by ships, buoys, and drifters. From ships, measurements of water samples in buckets were mostly switched in the 1940s to samples from engine intake water. Satellite measurements of skin temperature (uppermost layer; a fraction of a millimeter thick) in the infrared or the top centimeter or so in the microwave are also used, but must be adjusted to be compatible with the bulk temperature.

**Sendai Framework for Disaster Risk Reduction**
The Sendai Framework for Disaster Risk Reduction 2015-2030 outlines seven clear targets and four priorities for action to prevent new, and to reduce existing disaster risks. The voluntary, non-binding agreement recognizes that the State has the primary role to reduce disaster risk but that responsibility should be shared with other stakeholders including local government, the private sector and other stakeholders, with the aim for the substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries.

**Sequestration**
*See Uptake.*

**Shared socio-economic pathways (SSPs)**
*See Pathways.*

**Short-lived climate forcers (SLCF)**
Short-lived climate forcers refers to a set of compounds that are primarily composed of those with short lifetimes in the atmosphere compared to well-mixed greenhouse gases, and are also referred to as near-term climate forcers. This set of compounds includes methane, which is also a well-mixed greenhouse gas, as well as ozone and aerosols, or their precursors, and some halogenated species that are not well-mixed greenhouse gases. These compounds do not accumulate in the atmosphere at decadal to centennial timescales, and so their effect on climate is predominantly in the first decade after their emission, although their changes can still induce long-term climate effects such as sea-level change. Their effect can be cooling or warming. A subset of exclusively warming short-lived climate forcers is referred to as short-lived climate pollutants.

*See also Long-lived climate forcers (LLCF).*

**Short-lived climate pollutants (SLCP)**
*See Short-lived climate forcers (SLCF).*

**Sink**
A reservoir (natural or human, in soil, ocean, and plants) where a greenhouse gas, an aerosol or a precursor of a greenhouse gas is stored. Note that UNFCCC Article 1.8 refers to a sink as any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere.
See also Sequestration, and Uptake.

**Small Island Developing States (SIDS)**
Small Island Developing States (SIDS), as recognised by the United Nations OHRLLS (Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States), are a distinct group of developing countries facing specific social, economic and environmental vulnerabilities (UN-OHRLLS, 2011). They were recognized as a special case both for their environment and development at the Rio Earth Summit in Brazil in 1992. Fifty eight countries and territories are presently classified as SIDS by the UN OHRLLS, with 38 being UN member states and 20 being Non-UN Members or Associate Members of the Regional Commissions (UN-OHRLLS, 2018).

**Social costs**
The full costs of an action in terms of social welfare losses, including external costs associated with the impacts of this action on the environment, the economy (GDP, employment) and on the society as a whole.

**Social cost of carbon (SCC)**
The net present value of aggregate climate damages (with overall harmful damages expressed as a number with positive sign) from one more tonne of carbon in the form of carbon dioxide (CO$_2$), conditional on a global emissions trajectory over time.

**Social inclusion**
A process of improving the terms of participation in society, particularly for people who are disadvantaged, through enhancing opportunities, access to resources, and respect for rights (UN, 2016).

**Social justice**
*See Justice.*

**Social learning**
A process of social interaction through which people learn new behaviours, capacities, values, and attitudes.

**Social value of mitigation activities (SVMA)**
Social, economic and environmental value of mitigation activities that include, in addition to their climate benefits, their co-benefits to adaptation and sustainable development objectives.

**Social-ecological systems**
An integrated system that includes human societies and ecosystems, in which humans are part of nature. The functions of such a system arise from the interactions and interdependence of the social and ecological subsystems. The system’s structure is characterized by reciprocal feedbacks, emphasising that humans must be seen as a part of, not apart from, nature. [Footnote: This definition...
builds from Arctic Council (2016) and Berkes and Folke (1998).

**Societal (social) transformation**

See Transformation.

**Socio-economic scenario**

A scenario that describes a possible future in terms of population, gross domestic product (GDP), and other socio-economic factors relevant to understanding the implications of climate change.

See also Reference scenario, Emission scenario, Mitigation scenario and Pathways.

**Socio-technical transitions**

Socio-technical transitions are where technological change is associated with social systems and the two are inextricably linked.

**Soil carbon sequestration (SCS)**

Land management changes which increase the soil organic carbon content, resulting in a net removal of CO$_2$ from the atmosphere.

**Soil moisture**

Water stored in the soil in liquid or frozen form. Root-zone soil moisture is of most relevance for plant activity.

**Solar radiation management**

See Solar radiation modification (SRM).

**Solar radiation modification (SRM)**

Solar radiation modification refers to the intentional modification of the Earth's shortwave radiative budget with the aim of reducing warming. Artificial injection of stratospheric aerosols, marine cloud brightening and land surface albedo modification are examples of proposed SRM methods. SRM does not fall within the definitions of mitigation and adaptation (IPCC, 2012b, p. 2). Note that in the literature SRM is also referred to as solar radiation management or albedo enhancement.

**Stabilisation (of GHG or CO$_2$-equivalent concentration)**

A state in which the atmospheric concentrations of one greenhouse gas (GHG) (e.g., carbon dioxide) or of a CO$_2$-equivalent basket of GHGs (or a combination of GHGs and aerosols) remains constant over time.

**Stranded assets**

Assets exposed to devaluations or conversion to ‘liabilities’ because of unanticipated changes in their initially expected revenues due to innovations and/or evolutions of the business context, including changes in public regulations at the domestic and international levels.
**Stratosphere**
The highly stratified region of the atmosphere above the troposphere extending from about 10 km (ranging from 9 km at high latitudes to 16 km in the tropics on average) to about 50 km altitude.

*See also Atmosphere, and Troposphere.*

**Subnational actor**
Subnational actors include state/provincial, regional, metropolitan and local/municipal governments as well as non-party stakeholders, such as civil society, the private sector, cities and other subnational authorities, local communities and indigenous peoples.

**Substantive rights**
*See Human rights.*

**Supply-side measures**
*See Demand and supply-side measures.*

**Surface temperature**
*See Global mean surface temperature (GMST), Land surface air temperature, and Sea surface temperature (SST).*

**Sustainability**
A dynamic process that guarantees the persistence of natural and human systems in an equitable manner.

**Sustainable development (SD)**
Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987) and balances social, economic and environmental concerns.

*See also Sustainable Development Goals (SDGs) and Development pathways (under Pathways).*

**Sustainable Development Goals (SDGs)**
The 17 global goals for development for all countries established by the United Nations through a participatory process and elaborated in the 2030 Agenda for Sustainable Development, including ending poverty and hunger; ensuring health and wellbeing, education, gender equality, clean water and energy, and decent work; building and ensuring resilient and sustainable infrastructure, cities and consumption; reducing inequalities; protecting land and water ecosystems; promoting peace, justice and partnerships; and taking urgent action on climate change.

*See also Sustainable development (SD).*

**SDG-interaction score**
A seven-point scale (Nilsson et al., 2016) used to rate interactions between mitigation options and the SDGs. Scores range from +3 (indivisible) to -3 (cancelling), with a zero score indicating ‘consistent’
but with neither a positive or negative interaction. The scale, as applied in this report, also includes: direction (whether the interaction is uni- or bi-directional), and confidence as assessed per IPCC guidelines.

**Technology transfer**
The exchange of knowledge, hardware and associated software, money and goods among stakeholders, which leads to the spread of technology for adaptation or mitigation. The term encompasses both diffusion of technologies and technological cooperation across and within countries.

**Tipping point**
A level of change in system properties beyond which a system reorganizes, often abruptly, and does not return to the initial state even if the drivers of the change are abated. For the climate system, it refers to a critical threshold when global or regional climate changes from one stable state to another stable state.

*See also Irreversibility.*

**Transformation**
A change in the fundamental attributes of natural and human systems.

*Societal (social) transformation*
A profound and often deliberate shift initiated by communities toward sustainability, facilitated by changes in individual and collective values and behaviours, and a fairer balance of political, cultural, and institutional power in society.

**Transformation pathways**
*See Pathways.*

**Transformational adaptation**
*See Adaptation.*

**Transformative change**
A system wide change. This requires more than technological change to consideration of social and economic factors that with technology can bring about rapid change at scale.

**Transient climate response**
See Climate sensitivity.

**Transient climate response to cumulative CO$_2$ emissions** (TCRE)
The transient global average surface temperature change per unit cumulative CO$_2$ emissions, usually 1000 GtC. TCRE combines both information on the airborne fraction of cumulative CO$_2$ emissions (the fraction of the total CO$_2$ emitted that remains in the atmosphere, which is determined by carbon cycle processes) and on the transient climate response (TCR).
See also Transient climate response (TCR) (under Climate sensitivity).

**Transit-oriented development (TOD)**
An approach urban development that maximizes the amount of residential, business and leisure space within walking distance of efficient public transport, so as to enhance mobility of citizens, the viability of public transport and the value of urban land in mutually supporting ways.

**Transition**
The process of changing from one state or condition to another in a given period of time. Transition can be in individuals, firms, cities, regions and nations, and can be based on incremental or transformative change.

**Tropical cyclone**
The general term for a strong, cyclonic-scale disturbance that originates over tropical oceans. Distinguished from weaker systems (often named tropical disturbances or depressions) by exceeding a threshold wind speed. A tropical storm is a tropical cyclone with one-minute average surface winds between 18 and 32 m s\(^{-1}\). Beyond 32 m s\(^{-1}\), a tropical cyclone is called a hurricane, typhoon, or cyclone, depending on geographic location.

See also Extratropical cyclone.

**Troposphere**
The lowest part of the atmosphere, from the surface to about 10 km in altitude at mid-latitudes (ranging from 9 km at high latitudes to 16 km in the tropics on average), where clouds and weather phenomena occur. In the troposphere, temperatures generally decrease with height.

See also Atmosphere, and Stratosphere.

**Uncertainty**
A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, incomplete understanding of critical processes, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts) (see IPCC, 2004; Mastrandrea et al., 2010; Moss and Schneider, 2000).

See also Confidence, and Likelihood.

**United Nations Framework Convention on Climate Change (UNFCCC)**
The UNFCCC was adopted in May 1992 and opened for signature at the 1992 Earth Summit in Rio de Janeiro. It entered into force in March 1994 and as of May 2018 had 197 Parties (196 States and the European Union). The Convention’s ultimate objective is the “stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”. The provisions of the Convention are pursued and implemented by two treaties: the Kyoto Protocol and the Paris Agreement.
See also Kyoto Protocol, and Paris Agreement.

**Uptake**
The addition of a substance of concern to a reservoir.
See also Carbon sequestration and Sink.

**Vulnerability**
The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

*See also Exposure, Hazard, and Risk.*

**Water cycle**
*See Hydrological cycle.*

**Wellbeing**
A state of existence that fulfils various human needs, including material living conditions and quality of life, as well as the ability to pursue one’s goals, to thrive, and feel satisfied with one’s life. Ecosystem well-being refers to the ability of ecosystems to maintain their diversity and quality.

**Zero emissions commitment**
*See Climate change commitment.*
References


IOM (2018). Key Migration Terms. Available at: https://www.iom.int/key-migration-terms.


Changes to the Underlying Scientific-Technical Assessment to ensure consistency with the approved Summary for Policymakers

1. Background
Consistent with Section 4.5 of Appendix A to the Principles Governing IPCC Work, Coordinating Lead Authors have identified some changes to the underlying report to ensure consistency with the language used in the approved Summary for Policymakers or to provide additional clarification as agreed at the Joint Working Group Session. These changes do not alter any substantive findings of the final draft of the underlying report as distributed to governments on 29 August 2018. Note that the final draft of the underlying report is also subject to copy-editing and corrections in proof as normally applied to scientific reports.

2. Changes to be made to the underlying report
The following table lists those changes that will be made in the underlying report following the line by line approval of its Summary for Policymakers. Note that page and line numbers for the SPM are based on the numbering used in the revised final draft as distributed to Governments on 30 September 2018; page and line numbers for the underlying report are based on the numbering used in the final draft as distributed to Governments on 29 August 2018.

<table>
<thead>
<tr>
<th>SPM Page:Line or Section</th>
<th>Chapter</th>
<th>Chapter Page:Line</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>5:20</td>
<td>1</td>
<td>4:30</td>
<td>Reconcile confidence assessment to medium for general statement about past emissions committing us to 1.5°C on all timescales.</td>
</tr>
<tr>
<td>4:8</td>
<td>1</td>
<td>7:40</td>
<td>Avoid the use of 1.5C-consistent pathways throughout Chapter 1, clarifying whether statements are referring to no-or-limited-overshoot versus high-overshoot in all cases.</td>
</tr>
<tr>
<td>14:2</td>
<td>1</td>
<td>32:1</td>
<td>CDR is considered distinct from the above mitigation activities&quot;, or some equivalent usage that does not imply explicitly that CDR is considered a type of mitigation. Propagate throughout chapter.</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1:46</td>
<td>Revise figure in FAQ and associated TA description including table of parameters in simple model used to ensure precise consistency with final production version of SPM1. Revisions are of the order of individual line thicknesses and hence do not affect the visual impact and message of the figure.</td>
</tr>
<tr>
<td>5:22-23</td>
<td>1</td>
<td>26:11</td>
<td>*&quot;Around 2040&quot; was revised to &quot;likely between 2030 and 2052&quot; requires traceability to the chapter. Insert on page 26, line 11, following &quot;immediately&quot;: &quot;Applying a similar approach to the multi-dataset average GMST used in this report, now at 1.04°C, increasing at 0.215°C per decade, and accounting for correlated uncertainties between estimated warming level and warming rate, gives a one-standard-error range for warming reaching 1.5°C of 2030 to 2052.</td>
</tr>
<tr>
<td>13:40</td>
<td>2</td>
<td>13:12</td>
<td>At end of sentence after &quot;both CO2 and non-CO2 emissions&quot; add <em>(see glossary)</em> due to trickleback of new footnote on non-CO2 emissions that's related to the final C1.2 but is related to the non-CO2 discussion that occurs here in the FG0 SPM.</td>
</tr>
<tr>
<td>3:24</td>
<td>2</td>
<td>8:53</td>
<td>after &quot;emission pathway&quot; add <em>(see glossary)</em> due to trickleback of new definition that may now be added to glossary</td>
</tr>
<tr>
<td>C2.3</td>
<td>2</td>
<td>55</td>
<td>Table 2.6: split to distinguish &quot;no or low overshoot&quot; and &quot;high overshoot&quot; pathways</td>
</tr>
<tr>
<td>C2.3</td>
<td>2</td>
<td>55</td>
<td>Table 2.7: split to distinguish &quot;no or low overshoot&quot; and &quot;high overshoot&quot; pathways</td>
</tr>
</tbody>
</table>
Section 2.4.2: Include ranges for subset of pathways consistent with their use in SPM

Section 2.4.3: Include ranges for subset of pathways consistent with their use in SPM

2030 emissions, interquartile emission ranges and year ranges estimated from Table 2.4 need adding to ES

2010 emissions, interquartile emission ranges and year ranges calculated from Table 2.4 need adding to Section 2.3

Insert surface air temperature based remaining budgets into Table 2.2 through extra rows at 0.5°C and 1.0°C. These remaining carbon budgets for 0.5°C are 840, 560, and 420 Gt CO2 for a 33, 50, and 66% probability, respectively, given a historical GSAT warming of 0.97°C (and thus 1.5°C from 1850-1900); and 2030, 1500, and 1170 Gt CO2 for a 33, 50, and 66% probability, respectively, for 1.03°C (or 2°C from 1850-1900).

41 Gt CO2 needs to be 43 +/− 3 Gt CO2 - and add high confidence

show AR5 budget and ranges from 2018 start of surface air temperature from new table row

show AR5 budget and ranges from 2018 start of surface air temperature from new table row in ES

introduce framing of total carbon budget context in 2.2.2 and historic emissions to date from Table 2.1 and give medium confidence to historic emissions to date. Matching footnote 1 for C1.3

explain reason for 300 Gt CO2 difference from AR5 and level of confidence

Add sentence on AR5 difference in Executive Summary, explicitly mentioning the 300 Gt CO2

Add "more thereafter" to ES feedbacks estimate

Update Figure 2.3 for baselines from both budget estimates

Replace figure 2.3 illustrating two types of temperature change

Add "more thereafter" to ES feedbacks estimate

Exchange 50% uncertainty range in budgets with absolute uncertainty range

Include scenario selection in caption Figure 2.5

Replace "avoiding the need" with "reducing the reliance"

Add the following sentence at the end of the 1st paragraph of section 2.5.2.1: "Explicit carbon pricing is briefly addressed here to the extent it pertains to the scope of Chapter 2. For detailed policy issues about carbon pricing see Section 4.4.5."

Delete last sentence "Considering incomplete……. (see section 4.4.5.2)."

Move sentences "In addition, the revenue recycling effect…….is achieved (Sands, 2018)." to p.80 line 16 and insert them right after "(Sonenschein et al., 2018)."

Replace "price of carbon" with "carbon price"

Delete "would need to" and add "s" to "increase"

Replace "the price of carbon" with "carbon pricing"

Add "including conditional" to "(NDC)" in the caption. i.e. "(NDC", including conditional NDCs)

Change 1.5°C-consistent pathway to 1.5°C pathway

Adjust wording in description of SSP narratives for consistency with SPM3b
| C3   | 2   | 2.3.4 | Adjust ranges to pathways limiting warming with no or limited overshoot |
| C1   | 2   | 2.3.2 | Adjust ranges to pathways limiting warming with no or limited overshoot |
| C1, D1 | 2  | 2.3.5 | Adjust ranges to pathways limiting warming with no or limited overshoot |
| 25:35 | 2  | 27:1  | Change 1.5°C-consistent pathway to 1.5°C pathway                     |
| 25:35 | 2  | 28:35 | Change 1.5°C-consistent pathway to 1.5°C pathway                     |
| 25:35 | 2  | 28:54 | Change 1.5°C-consistent pathway to 1.5°C pathway                     |
| 25:35 | 2  | 39:11 | Change 1.5°C-consistent pathway to 1.5°C pathway                     |
| 25:35 | 2  | 39:37 | Change 1.5°C-consistent pathway to 1.5°C pathway                     |
| 25:35 | 2  | 44:22 | Change 1.5°C-consistent pathway to 1.5°C pathway                     |
| 25:35 | 2  | 46:8  | Change 1.5°C-consistent pathway to 1.5°C pathway                     |
| C1.3  | 2  | 17    | give footnote explaining that the table left column is globally surface air temperature from a base of either GMST or surface air temperature |
| C1.3  | 2  | 48    | Update Figure 2.10 with budgets mentioned in SPM.                    |
| C2.3  | 2  | 54    | Figure 2.16: split to distinguish "no or low overshoot" and "high overshoot" pathways |
| C2.3  | 2  | 56    | Figure 2.17: split to distinguish "no or low overshoot" and "high overshoot" pathways |
| C2.2  | 2  | 6     | Update ranges in ES to pathway definitions used in SPM               |
| C2.2  | 2  | 6     | Update ranges in ES to pathway definitions used in SPM               |
| 3     | 131:2 | 3    | Figure 3.20 & Figure 3.21 add confidence to embers bars             |
| 3     | 131:2 & 133:1 | 3    | Correct caption of Figure 3.20 & 3.21 to match approved version of SPM2 caption |
| 3     | 131:2 / 132:28 | 3    | Titles, Figure caption and subtitles in embers figures in Ch 3 need to be modified to match the SPM version. |
| 7:38 (B4.2) | 3    | p8 (ES), p52 | Changes to allow indicative range to be given in (new) B2.1. Text that allows indicative range for GMSLR for 1.5°C at 2100. Reword ES accordingly. |
| 7:38 (B4.1) | 3    | p8    | Reword final line of ES statement on GMSLR on threshold temperatures. |
| 9:6 (B2.3)   | 3    | p9, p165, p136 | Reword ES statement and subsection summary on permafrost to include projected range; amend range given in on 3.5.2.5 RFC1 |
| 9:14 (B3.1)  | 3    | p8, p50 | Clarify timescale on sea ice recovery (decadal) in summary of subsection and ES |
| 9:14 (B3.1)  | 3    | p8, p50 | Add definition for ice-free Arctic in section and ES (as footnote). AR5 "nearly ice-free when the sea ice extent is less than 106 km2 for at least five consecutive years." |
| 10:39 (B5.7) | 3    | p 140-1 | Update confidence associated with RCF5 (medium)                      |
| B3.2 | 3    | p.68:23 | Change 7 to 6.5% (and consider ES statement p. 9: 110)               |

| 3     | 6:27 | Replace "Changes in temperature extremes and heavy precipitation indices are detectable in observations for the 1991-2010 period compared with 1960-1979, when a global warming of approximately 0.5°C occurred (high confidence). The observed tendencies over that time frame are consistent with attributed changes since the mid-20th century (high confidence) (3.3.1, 3.3.2, 3.3.3)," with "Trends in intensity and frequency of some climate and weather extremes have been detected over time spans during which about 0.5°C of global warming occurred (medium confidence). This assessment is based on several lines of evidence, including attribution studies for changes in extremes since 1950. (3.2, 3.3.1, 3.3.2, 3.3.3, 3.3.4),." |
| 3     | 6:31 | Add: "Several regional changes in climate are assessed to occur with global warming up to 1.5°C compared to pre-industrial levels, including warming of extreme temperatures in many regions (high confidence), increases in frequency, intensity and/or amount of heavy precipitation in several regions (high confidence), and an increase in intensity or frequency of droughts in some regions (medium confidence). (3.3.1, 3.3.2, 3.3.3, 3.3.4, Table 3.2)" |
Replace "Substantial changes in regional climate occur between 1.5°C and 2°C [...]" with "Climate models project robust differences in regional climate between present-day and global warming of 1.5°C, and between 1.5°C and 2°C; ROBUST is here used to mean that at least two thirds of climate models show the same sign of changes at the grid point scale, and that differences in large regions are statistically significant [...].";

PROJECTED differences in impacts between different levels of global warming are determined with respect to changes in global mean surface air temperature (This is not strictly a trickle back since it was proposed by the authors prior to the approval session following comments on the FGD version of the SPM, but it is required to support changes in SPM; Exception: "mean" in "global mean surface air temperature" was added as a result of a comment from the floor).

Tropical cyclones are projected to decrease in frequency but with an increase in the number of very intense cyclones (limited evidence, low confidence). Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C global warming (medium confidence).

Heavy precipitation when aggregated at global scale is projected to be higher at 2.0°C than at 1.5°C of global warming (medium confidence).

Drought, precipitation deficits, and risks associated with water availability

It should also be noted that attributed changes in extremes since 1950 that were reported in the IPCC AR5 report (IPCC, 2013) generally correspond to changes in global warming of about 0.5°C (see 3.SM.1)

This in particular also applies to attributed changes in extremes since 1950 that were reported in the IPCC AR5 report (IPCC, 2013; see also 3.SM.1)

These analyses suggest that increases in drought, dryness or precipitation deficits are projected at 1.5°C or 2°C global warming in some regions compared to the pre-industrial or present-day conditions, as well as between these two global warming levels, although there is substantial variability in signals depending on the considered indices or climate models (Lehner et al. 2017, Schleussner et al. 2017, Greve et al. 2018) (medium confidence). Generally, the clearest signals are found for the Mediterranean region (medium confidence).

Add in column "projected changes at 1.5°C [...]": "Increases in drought, dryness or precipitation deficits projected in some regions compared to the pre-industrial or present-day conditions, but substantial variability in signals depending on considered indices or climate model (medium confidence)."

Total pages: 16
Add in column "projected changes at 2°C [...]": "Increases in drought, dryness or precipitation deficits projected in some regions compared to the pre-industrial or present-day conditions, but substantial variability in signals depending on considered indices or climate model (medium confidence)."

The text for the "observed change" column should stay the same. However, the remaining text (currently a single column for 1.5 degrees C of warming, 2 degrees C of warming and differences between 1.5 and 2 degrees C of warming) should be removed. Text should then be added to the three different columns as follows: changes at 1.5°C [...] "Increases in heavy precipitation associated with tropical cyclones (medium confidence)”; changes at 2°C [...] "Further increases in heavy precipitation associated with tropical cyclones (medium confidence)"; Differences between 2°C and 1.5° [...] "Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C global warming (medium confidence); Limited evidence that the global number of tropical cyclones will be lower under 2°C of global warming compared to under 1.5°C of warming, but an increase in the number of very intense cyclones (low confidence)".

Figure 3-20 - Change text: ‘Risks for specific natural, managed and human systems’ to ‘Risks and/or impacts for specific natural, managed and human systems’

Figure 3-20 -Text describing colours here needs to be same as that is SPM figure (which it currently is)

Figure 3-20 - Delete the text “Assessment of risks at 2°C or higher are beyond the scope of the present assessment” as in SPSM2

Figure 3-20 - Remove 2.5°C from both y-axes as in SPM-2

Figure 3-20 - Remove text ‘0.87°C’ and add grey band labelled ‘2006–2016’ in top and bottom figures – like in SPM-2 figure.

Figure 3-20 - Remove text: "The average global surface temperature was converted to GMST for marine related embers (warm water corals, mangroves, and small scale fisheries, low latitude) by adjusting for the small difference between GMST and SST across a range of CMIP5 climate models" - Just like in SPM2

Figure 3-20 - Change text: ‘y axes (top and bottom) need to be: ‘Global mean surface temperature change above pre-industrial levels (°C).’ Just like in SPM2

Figure 3-20 - Edge of all embers above 0.87°C need to be dashed as in SPM-2 figure.
| SPM2 | 3 | 131 |
| SPM2 | 3 | 88  |
| SPM2 | 3 | 88  |
| SPM2 | 3 | 88  |
| SPM2 | 3 | 88  |
| SPM2 | 3 | 88  |
| SPM2 | 3 | 132 |
| SPM2 | 3 | 132 |
| SPM2 | 3 | 132 |
| SPM2 | 3 | 132 |
| SPM2 | 3 | 131 |

- Figure 3-20 - Add confidence levels as letters as per figure SPM-2. The lines connect the transition temperatures - as in SPM2.
- Figure 3-18 - Change text: ‘Risks and adaptation limits for specific marine and coastal organisms, ecosystems and sectors’ to ‘Risks and/or impacts for specific marine and coastal organisms, ecosystems and sectors’
- Figure 3-18 - Text describing colours here needs to be same as that is SPM figure (which it currently is)
- Figure 3-18 - Delete the text “Assessment of risks at 2°C or higher are beyond the scope of the present assessment” as in SPSM2
- Figure 3-18 - Remove 2.5°C from both y-axes as in SPM2
- Figure 3-18 - Remove text ‘0.87°C’ and add grey band labelled ‘2006–2016’ in top and bottom figures – like in SPM-2.
- Figure 3-18 - Change text: ‘y axes (top and bottom) need to be: ‘Global mean surface temperature change above pre-industrial levels (°C).’ Just like in SPM2
- Figure 3-18 - Edge of all embers above 0.87°C need to be dashed as in SPM-2 figure.
- Figure 3-18 - Add confidence levels as letters as per figure SPM-2. The lines connect the transition temperatures - as in SPM2.
- Figure 3-21 - Change text: ‘Risks associated with Reasons for Concern’ to ‘Risks and/or impacts associated with Reasons for Concern’
- Figure 3-21 - Text describing colours here needs to be same as that is SPM figure (which it currently is)
- Figure 3-21 - Remove 2.5°C from both y-axes as in SPM2
- Figure 3-21 - Remove text ‘0.87°C’ and add grey band labelled ‘2006–2016’ in top and bottom figures – like in SPM-2.
- Figure 3-21 - Change text: ‘y axes (top and bottom) need to be: ‘Global mean surface temperature change above pre-industrial levels (°C).’ Just like in SPM2
- Figure 3-21 - Edge of all embers above 0.87°C need to be dashed as in SPM-2 figure.
- Figure 3-21 - Add confidence levels as letters as per figure SPM-2. The lines connect the transition temperatures - as in SPM2.
- Figure 3-21 - Delete the text “Assessment of risks at 2°C or higher are beyond the scope of the present assessment” as in SPSM2

Change: “Any increase in global temperature (e.g., +0.5°C) is expected to affect human health (high confidence). Risks are lower at 1.5°C than at 2°C for heat-related morbidity and mortality (very high confidence), particularly in urban areas because of urban heat island effects (high confidence). Risks of ozone-related mortality would also be lower at 1.5°C than at 2°C of global warming assuming that emissions related to the formation of ozone remain the same (high confidence), and the same applies to risks of undernutrition (medium confidence). Risks are projected to change for some vector-borne diseases, such as malaria and dengue fever (high confidence), with positive or negative trends
| Page | 3-10:7-8 | Change: "Global warming of 1.5°C (as opposed to 2°C) is projected to reduce climate induced impacts on crop yield and nutritional content in some regions (high confidence)." to "Limiting warming to 1.5°C, compared with 2°C, is projected to result in smaller net reductions in yields of maize, rice, wheat, and potentially other cereal crops, particularly in sub-Saharan Africa, Southeast Asia, and Central and South America; and in the CO2 dependent, nutritional quality of rice and wheat (high confidence)."

| Page | 3-10:12-13 | Change: "Risks of food shortages are lower in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon at 1.5°C of global warming when compared to 2°C (medium confidence)." to "Reductions in projected food availability are larger at 2°C than at 1.5°C of global warming in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon (medium confidence)."

| Page | 3-9:45-46 | Change: "Risks to water scarcity are greater at 2°C than at 1.5°C of global warming in some regions (medium confidence)." to "Depending on future socioeconomic conditions, limiting global warming to 1.5°C, compared to 2°C, may reduce the proportion of the world population exposed to a climate-change induced increase in water stress by up to 50%, although there is considerable variability between regions (medium confidence)."

| Page | 3-9:46 to 3-10:1-3 | Delete the text "Limiting global warming to 1.5°C would approximately halve the fraction of world population expected to suffer water scarcity as compared to 2°C, although there is considerable variability between regions (medium confidence). Socioeconomic drivers, however, are expected to have a greater influence on these risks than the changes in climate (medium confidence)"

| Page | 3-11:28-32 | Change: "Globally, the projected impacts on economic growth in a 1.5°C warmer world are larger than those of the present-day (about 1°C), with the largest impacts expected in the tropics and the Southern Hemisphere sub-tropics (limited evidence, low confidence). At 2°C substantially lower economic growth is projected for many developed and developing countries (limited evidence, medium confidence), with the potential to also limit economic damages at 1.5°C of global warming." to "Risks to global aggregated economic growth due to climate change impacts are projected to be lower at 1.5°C than at 2°C by the end of this century (medium confidence). This excludes the costs of mitigation, adaptation investments and the benefits of adaptation. Countries in the tropics and Southern Hemisphere sub-tropics are projected to experience the largest impacts on economic..."
growth due to climate change should global warming increase from 1.5°C to 2 °C (medium confidence)."

Change "Some regions are projected to experience multiple compound climate-related risks at 1.5°C that will increase with warming of 2°C and higher (high confidence). Some regions are projected to be affected by collocated and/or concomitant changes in several types of hazards. Multi-sector risks are projected to overlap spatially and temporally, creating new (and exacerbating current) hazards, exposures, and vulnerabilities that will affect increasing numbers of people and regions with additional warming." to "Exposure to multiple and compound climate-related risks increases between 1.5°C and 2°C of global warming, with greater proportions of people both exposed and susceptible to poverty in Africa and Asia (high confidence). For global warming from 1.5°C to 2°C, risks across energy, food, and water sectors could overlap spatially and temporally, creating new and exacerbating current hazards, exposures, and vulnerabilities that could affect increasing numbers of people and regions (medium confidence)."

Reword ES statement and subsection summary on permafrost to include projected range; amend range given in on 3.5.2.5 RFC1 as well as in Table 3.7 (p 3-151).

The ES FGD text used to read 'Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (high confidence). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot. The size and duration of an overshoot will also affect future impacts (e.g. loss of ecosystems, medium confidence). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity {Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter}.' in ES. In the SPM, the statement A3.2 reads A3.2. Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (high confidence). Some impacts may be long-lasting or irreversible, such as the loss of some ecosystems (high confidence). (3.2, 3.4.4, 3.6.3, Cross-Chapter Box 8)." To make the ES consistent, the statement should be edited to read "Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (high confidence). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot (high confidence). The size and duration of an overshoot will also affect future impacts (e.g. irreversible loss of some ecosystems, high confidence). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity (Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter)."

Edit ES statement to make the confidence levels consistent with the SPM and specify the exact numbers as in the SPM. This means to edit from "Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (medium confidence). The number of species projected to lose over half of their
climatically determined geographic range (about 18% of insects, 16% of plants, 8% of vertebrates) is reduced by 50% (plants, vertebrates) or 66% (insects) at 1.5°C versus 2°C of warming (high confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services (3.4.3.2, 3.5.2). Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (high confidence). The number of species projected to lose over half of their climatically determined geographic range at 2°C warming (18% of insects, 16% of plants, 8% of vertebrates) is projected to be reduced to 6% of insects, 8% of plants and 4% of vertebrates at 1.5°C warming (medium confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services (3.4.3.2, 3.5.2). It will also be important to ensure that the confidence levels in the underlying text also match this.

A3.2

For consistency with A2, in the ES the statement 'Overshooting poses large risks for natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of many ecosystems (high confidence).' should be edited to read 'Overshooting poses large risks for natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of some ecosystems (high confidence).’ Also check underlying text.
The ES FGD text used to read "Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (high confidence). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot. The size and duration of an overshoot will also affect future impacts (e.g. loss of ecosystems, medium confidence). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity (Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter)." in ES. In the SPM, the statement A3.2 reads A3.2. Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (high confidence). Some impacts may be long-lasting or irreversible, such as the loss of some ecosystems (high confidence). (3.2, 3.4.4, 3.6.3, Cross-Chapter Box 8)." To make the ES consistent, the statement should be edited to read "Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (high confidence). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilize at 1.5°C without an overshoot (high confidence). The size and duration of an overshoot will also affect future impacts (e.g. irreversible loss of some ecosystems, high confidence). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity (Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter).".

It will also be important to ensure that the confidence levels in the underlying text also match this.

| A3.2 | 3 |
| Edit ES statement to make the confidence levels consistent with the SPM and specify the exact numbers as in the SPM. This means to edit from "Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (medium confidence). The number of species projected to lose over half of their climatically determined geographic range (about 18% of insects, 16% of plants, 8% of vertebrates) is reduced by 50% (plants, vertebrates) or 66% (insects) at 1.5°C versus 2°C of warming (high confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services (3.4.3.2, 3.5.2)." to "Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (high confidence). The number of species projected to lose over half of their climatically determined geographic range at 2°C warming (18% of insects, 16% of plants, 8% of vertebrates) is projected to be reduced to 6% of insects, 8% of plants and 4% of vertebrates at 1.5°C warming (medium confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services (3.4.3.2, 3.5.2).". It will also be important to ensure that the confidence levels in the underlying text also match this.

B3 and B3.1 | 3 |
| Edit ES statement to make the confidence levels consistent with the SPM and specify the exact numbers as in the SPM. This means to edit from "Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (medium confidence). The number of species projected to lose over half of their climatically determined geographic range (about 18% of insects, 16% of plants, 8% of vertebrates) is reduced by 50% (plants, vertebrates) or 66% (insects) at 1.5°C versus 2°C of warming (high confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services (3.4.3.2, 3.5.2)." to "Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (high confidence). The number of species projected to lose over half of their climatically determined geographic range at 2°C warming (18% of insects, 16% of plants, 8% of vertebrates) is projected to be reduced to 6% of insects, 8% of plants and 4% of vertebrates at 1.5°C warming (medium confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services (3.4.3.2, 3.5.2).". It will also be important to ensure that the confidence levels in the underlying text also match this.
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### B3.2 3

The SPM wording is B3.2. "Approximately 4% (interquartile range 2–7%) of the global terrestrial land area is projected to undergo a transformation of ecosystems from one type to another at 1°C of global warming, compared with 13% (interquartile range 8–20%) at 2°C (medium confidence). This indicates that the area at risk is projected to be approximately 50% lower at 1.5°C compared to 2°C (medium confidence), (3.4.3.1, 3.4.3.5)” and the FGD ES wording was 'The terrestrial area affected by ecosystem transformation (13%) at 2°C, which is approximately halved at 1.5°C global warming (high confidence)’. In the ES, this latter sentence needs to be edited to read "The global terrestrial land area projected to be affected by ecosystem transformation (13%, interquartile range 8–20%) at 2°C, is approximately halved at 1.5°C global warming to 4% (interquartile range 2–7%) (medium confidence).”

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The ES FGD text used to read "Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (high confidence). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot. The size and duration of an overshoot will also affect future impacts (e.g. loss of ecosystems, medium confidence). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity (Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter).’ in ES. In the SPM, the statement A3.2 reads A3.2. Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (high confidence). Some impacts may be long-lasting or irreversible, such as
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<table>
<thead>
<tr>
<th>B3 and B3.1</th>
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<tbody>
<tr>
<td>Edit ES statement to make the confidence levels consistent with the SPM and specify the exact numbers as in the SPM. This means to edit from &quot;Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (medium confidence). The number of species projected to lose over half of their climatically determined geographic range (about 18% of insects, 16% of plants, 8% of vertebrates) is reduced by 50% (plants, vertebrates) or 66% (insects) at 1.5°C versus 2°C of warming (high confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services (3.4.3.2, 3.5.2).&quot; to &quot;Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (high confidence). The number of species projected to lose over half of their climatically determined geographic range at 2°C warming (18% of insects, 16% of plants, 8% of vertebrates) is projected to be reduced to 6% of insects, 8% of plants and 4% of vertebrates at 1.5°C warming (medium confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services (3.4.3.2, 3.5.2).&quot;. It will also be important to ensure that the confidence levels in the underlying text also match this.</td>
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</table>

<table>
<thead>
<tr>
<th>A3.2</th>
<th>3</th>
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<tr>
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| B3.2 | 3 | The SPM wording is B3.2. "Approximately 4% (interquartile range 2–7%) of the global terrestrial land area is projected to undergo a transformation of ecosystems from one type to another at 1°C of global warming, compared with 13% (interquartile range 8–20%) at 2°C (medium confidence). This indicates that the area at risk is projected to be approximately 50% lower at 1.5°C compared to 2°C (medium confidence). (3.4.3.1, 3.4.3.5) and the FGD ES wording was "The terrestrial area affected by ecosystem transformation (13%) at 2°C, which is approximately halved at 1.5°C global warming (high confidence)". In the ES, this latter sentence needs to be edited to read "The global terrestrial land area projected to be affected by ecosystem transformation (13%, interquartile range 8–20%) at 2°C, is approximately halved at 1.5°C global warming to 4% (interquartile range 2–7%) (medium confidence)."

| B3.3 | 3 | In ES add B3.3, add and will proceed with further warming’ after "High-latitude tundra and boreal forests are particularly at risk of climate change-induced degradation and loss, with woody shrubs already encroaching into the tundra (high confidence)".

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</thead>
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<tr>
<td>B5.7</td>
<td>3</td>
<td>In ES the text read ‘There are multiple lines of evidence that there has been a substantial increase since AR5 in the levels of risk associated with four of the five Reasons for Concern (RFCs) for global warming levels of up to 2°C (high confidence). The word ‘assessed’ should be inserted before ‘risk’</td>
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<td>B5.7</td>
<td>3</td>
<td>Replace RFC text with text in SPM</td>
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<td>4</td>
<td>Replace ‘&gt;70%’ with ‘to between 75 and 90% (interquartile range)’</td>
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<td>SPM3b</td>
<td>4</td>
<td>Update Table 4.1: update numbers to be consistent with SPM</td>
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<tr>
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<td>4</td>
<td>Update Table 4.1 for pathway classification used in SPM</td>
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<td>5</td>
<td>15:17-18</td>
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<tr>
<td>SPM4</td>
<td>5</td>
<td>Update Figure 5.2: red coloured circle segment corresponding to SDG9 in, circle Trade-offs (negative interaction) energy demand options, to be replaced by white</td>
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<td>25:22</td>
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<td>Glossary</td>
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[FOOTNOTE]
FOOTNOTE: Past IPCC reports, reflecting the literature, have used a variety of approximately equivalent metrics of GMST change.
Cumulative emissions of CO\textsubscript{2} and future non-CO\textsubscript{2} radiative forcing determine the probability of limiting warming to 1.5°C

a) Observed global temperature change and modeled responses to stylized anthropogenic emission and forcing pathways

Global warming relative to 1850-1900 (°C)

b) Stylized net global CO\textsubscript{2} emission pathways
Billion tonnes CO\textsubscript{2} per year (GtCO\textsubscript{2}/yr)

Faster immediate CO\textsubscript{2} emission reductions limit cumulative CO\textsubscript{2} emissions shown in panel (c).

Source: IPCC Special Report on Global Warming of 1.5°C
How the level of global warming affects impacts and/or risks associated with the Reasons for Concern (RFCs) and selected natural, managed and human systems

Five Reasons For Concern (RFCs) illustrate the impacts and risks of different levels of global warming for people, economies and ecosystems across sectors and regions.

Impacts and risks associated with the Reasons for Concern (RFCs)

<table>
<thead>
<tr>
<th>RFC1</th>
<th>RFC2</th>
<th>RFC3</th>
<th>RFC4</th>
<th>RFC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unique and threatened systems</td>
<td>Extreme weather events</td>
<td>Distribution of impacts</td>
<td>Global aggregate impacts</td>
<td>Large scale singular events</td>
</tr>
</tbody>
</table>

Level of additional impact/risk due to climate change

- **Purple** indicates very high risks of severe impacts/risks and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks.
- **Red** indicates severe and widespread impacts/risks.
- **Yellow** indicates that impacts/risks are detectable and attributable to climate change with at least medium confidence.
- **White** indicates that no impacts are detectable and attributable to climate change.

Impacts and risks for selected natural, managed and human systems

Confidence level for transition: L=Low, M=Medium, H=High and VH=Very high

Source: IPCC Special Report on Global Warming of 1.5°C
Global emissions pathway characteristics

General characteristics of the evolution of anthropogenic net emissions of CO₂, and total emissions of methane, black carbon, and nitrous oxide in model pathways that limit global warming to 1.5°C with no or limited overshoot. Net emissions are defined as anthropogenic emissions reduced by anthropogenic removals. Reductions in net emissions can be achieved through different portfolios of mitigation measures illustrated in Figure SPM3B.

Global total net CO₂ emissions

Billion tonnes of CO₂/yr

In pathways limiting global warming to 1.5°C with no or limited overshoot as well as in pathways with a high overshoot, CO₂ emissions are reduced to net zero globally around 2050.

Non-CO₂ emissions relative to 2010

Emissions of non-CO₂ forcers are also reduced or limited in pathways limiting global warming to 1.5°C with no or limited overshoot, but they do not reach zero globally.

Methane emissions

Black carbon emissions

Nitrous oxide emissions

Source: IPCC Special Report on Global Warming of 1.5°C
Characteristics of four illustrative model pathways

Different mitigation strategies can achieve the net emissions reductions that would be required to follow a pathway that limit global warming to 1.5°C with no or limited overshoot. All pathways use Carbon Dioxide Removal (CDR), but the amount varies across pathways, as do the relative contributions of Bioenergy with Carbon Capture and Storage (BECCS) and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sector. This has implications for the emissions and several other pathway characteristics.

Breakdown of contributions to global net CO₂ emissions in four illustrative model pathways

<table>
<thead>
<tr>
<th>Global indicators</th>
<th>P1: A scenario in which social, business, and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A down-sized energy system enables rapid decarbonisation of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.</th>
<th>P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.</th>
<th>P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.</th>
<th>P4: A resource and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathway classification</td>
<td>CO₂ emission change in 2030 (% rel to 2010)</td>
<td>CO₂ emission change in 2030 (% rel to 2010)</td>
<td>CO₂ emission change in 2030 (% rel to 2010)</td>
<td>CO₂ emission change in 2030 (% rel to 2010)</td>
</tr>
<tr>
<td>Pathway classification</td>
<td>CO₂ emission change in 2050 (% rel to 2010)</td>
<td>CO₂ emission change in 2050 (% rel to 2010)</td>
<td>CO₂ emission change in 2050 (% rel to 2010)</td>
<td>CO₂ emission change in 2050 (% rel to 2010)</td>
</tr>
<tr>
<td>Pathway classification</td>
<td>Kyoto-GHG emissions** in 2030 (% rel to 2010)</td>
<td>Kyoto-GHG emissions** in 2030 (% rel to 2010)</td>
<td>Kyoto-GHG emissions** in 2030 (% rel to 2010)</td>
<td>Kyoto-GHG emissions** in 2030 (% rel to 2010)</td>
</tr>
<tr>
<td>Pathway classification</td>
<td>Final energy demand*** in 2030 (% rel to 2010)</td>
<td>Final energy demand*** in 2030 (% rel to 2010)</td>
<td>Final energy demand*** in 2030 (% rel to 2010)</td>
<td>Final energy demand*** in 2030 (% rel to 2010)</td>
</tr>
<tr>
<td>Pathway classification</td>
<td>Renewable share in electricity in 2030 (%)</td>
<td>Renewable share in electricity in 2030 (%)</td>
<td>Renewable share in electricity in 2030 (%)</td>
<td>Renewable share in electricity in 2030 (%)</td>
</tr>
<tr>
<td>Pathway classification</td>
<td>Primary energy from coal in 2030 (% rel to 2010)</td>
<td>Primary energy from coal in 2030 (% rel to 2010)</td>
<td>Primary energy from coal in 2030 (% rel to 2010)</td>
<td>Primary energy from coal in 2030 (% rel to 2010)</td>
</tr>
<tr>
<td>Pathway classification</td>
<td>Primary energy from coal in 2050 (% rel to 2010)</td>
<td>Primary energy from coal in 2050 (% rel to 2010)</td>
<td>Primary energy from coal in 2050 (% rel to 2010)</td>
<td>Primary energy from coal in 2050 (% rel to 2010)</td>
</tr>
<tr>
<td>Pathway classification</td>
<td>from oil in 2030 (% rel to 2010)</td>
<td>from oil in 2030 (% rel to 2010)</td>
<td>from oil in 2030 (% rel to 2010)</td>
<td>from oil in 2030 (% rel to 2010)</td>
</tr>
<tr>
<td>Pathway classification</td>
<td>from gas in 2030 (% rel to 2010)</td>
<td>from gas in 2030 (% rel to 2010)</td>
<td>from gas in 2030 (% rel to 2010)</td>
<td>from gas in 2030 (% rel to 2010)</td>
</tr>
<tr>
<td>Pathway classification</td>
<td>from nuclear in 2030 (% rel to 2010)</td>
<td>from nuclear in 2030 (% rel to 2010)</td>
<td>from nuclear in 2030 (% rel to 2010)</td>
<td>from nuclear in 2030 (% rel to 2010)</td>
</tr>
<tr>
<td>Pathway classification</td>
<td>from biomass in 2030 (% rel to 2010)</td>
<td>from biomass in 2030 (% rel to 2010)</td>
<td>from biomass in 2030 (% rel to 2010)</td>
<td>from biomass in 2030 (% rel to 2010)</td>
</tr>
<tr>
<td>Pathway classification</td>
<td>from non-biomass renewables in 2030 (% rel to 2010)</td>
<td>from non-biomass renewables in 2030 (% rel to 2010)</td>
<td>from non-biomass renewables in 2030 (% rel to 2010)</td>
<td>from non-biomass renewables in 2030 (% rel to 2010)</td>
</tr>
<tr>
<td>Pathway classification</td>
<td>Cumulative CCS until 2100 (GtCO₂)</td>
<td>Cumulative CCS until 2100 (GtCO₂)</td>
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<td>Cumulative CCS until 2100 (GtCO₂)</td>
</tr>
<tr>
<td>Pathway classification</td>
<td>Land area of bioenergy crops in 2050 (million hectare)</td>
<td>Land area of bioenergy crops in 2050 (million hectare)</td>
<td>Land area of bioenergy crops in 2050 (million hectare)</td>
<td>Land area of bioenergy crops in 2050 (million hectare)</td>
</tr>
</tbody>
</table>

NOTE: Indicators have been selected to show global trends identified by the Chapter 2 assessment.
National and sectoral characteristics can differ substantially from the global trends shown above.

Source: IPCC Special Report on Global Warming of 1.5°C

* Kyoto-gas emissions are based on SAR GWP-100
** Changes in energy demand are associated with improvements in energy efficiency and behaviour change
Indicative linkages between mitigation options and sustainable development using SDGs (The linkages do not show costs and benefits)

Mitigation options deployed in each sector can be associated with potential positive effects (synergies) or negative effects (trade-offs) with the Sustainable Development Goals (SDGs). The degree to which this potential is realized will depend on the selected portfolio of mitigation options, mitigation policy design, and local circumstances and context. Particularly in the energy-demand sector, the potential for synergies is larger than for trade-offs. The bars group individually assessed options by level of confidence and take into account the relative strength of the assessed mitigation-SDG connections.

Length shows strength of connection

Shades show level of confidence

The overall size of the coloured bars depict the relative for synergies and trade-offs between the sectoral mitigation options and the SDGs.

The shades depict the level of confidence of the assessed potential for Trade-offs/Synergies.

Energy-supply

Energy-demand

Land

SDG1 No Poverty
SDG2 Zero Hunger
SDG3 Good Health and Well-being
SDG4 Quality Education
SDG5 Gender Equality
SDG6 Clean Water and Sanitation
SDG7 Affordable and Clean Energy
SDG8 Decent Work and Economic Growth
SDG9 Industry, Innovation and Infrastructure
SDG10 Reduced Inequality
SDG11 Sustainable Cities and Communities
SDG12 Responsible Consumption and Production
SDG13 Life Below Water
SDG14 Life on Land
SDG15 Peace and Justice Strong Institutions
SDG16 Partnerships for the Goals

Source: IPCC Special Report on Global Warming of 1.5°C