## Executive Summary

**Limiting warming to 1.5°C above pre-industrial levels would require transformative systemic change, integrated with sustainable development. Such change would require the upscaling and acceleration of the implementation of far-reaching, multilevel 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 (*medium evidence, high agreement*) {Chapter 2, Chapter 3, 4.2.1, 4.4.5, 4.5}.** 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 9 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 utilize 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 mobilized (*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 multilevel 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 11 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 above pre-industrial conditions 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, utilization and storage (CCUS) would lead to the deep emissions reductions required in energy-intensive industries 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 helps enable industrial system transitions but would have to be complemented with greenhouse gas (GHG)-neutral processes or carbon dioxide removal (CDR) to make energy-intensive industries consistent with 1.5°C (*high confidence*). {4.3.1, 4.3.4}

**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 6 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 behaviours and water-efficient practices rather than through large-scale infrastructural interventions (*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}

**Shifts in 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 changing dietary behaviour could result in mitigation and adaptation (*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 consistent with limiting warming to 1.5°C. 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 decarbonizing energy supply in the built environment, especially in buildings. Other rapid changes needed in urban environments include demotorization and decarbonization 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, for example, 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, 4.4.3, 4.4.4}

**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 than other adaptation options 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 attempting 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 $CO_2$ 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 above pre-industrial levels. 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 $CO_2$, 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, which differ between options, limiting the potential for any single option to sustainably achieve the large-scale deployment required in the 1.5°C-consistent pathways described 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 neutralize emissions that are expensive to avoid, or to draw down $CO_2$ 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 of $CO_2$ removed is higher for AR than for BECCS, but given the low levels of 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 absence of economic incentives were to be resolved (*high agreement, medium evidence*). The large potential of afforestation and the co-benefits if implemented appropriately (e.g., on biodiversity and 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 feasibility and cost-effectiveness at the global scale 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, legitimize, 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 10 in this chapter}

### Enabling Rapid and Far-Reaching Change

**The speed of transitions and of technological change required to limit warming to 1.5°C above pre-industrial levels 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 multilevel 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; addressing 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 these actions 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 limit warming 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 capacity to adapt to climate risks would require large increases of investments in low-emission infrastructure and buildings, along with a redirection of financial flows towards low-emission investments (*robust evidence, high agreement*).** An estimated mean annual incremental investment of around 1.5% of global gross fixed capital formation (GFCF) for the energy sector is indicated between 2016 and 2035, as well as about 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 fully substitute for these investments. {2.5.2, 4.2.1, 4.4.5}

**Enabling this investment requires the mobilization 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. These 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 incentive levels needed to trigger system transitions (*robust evidence, medium agreement*). But, embedded in consistent policy packages, they can help mobilize 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 for limiting warming to 1.5°C {4.4.5, 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 mobilization 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 (*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

[1] Annual capital revenues are paid interests plus an increase of asset value.

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promote a portfolio shift towards long-term low-emission assets that would help redirect capital away from potentially stranded assets (*medium evidence, medium agreement*). {4.4.5}

## Knowledge Gaps

**Knowledge gaps around implementing and strengthening the global response to climate change would need to be urgently resolved if the transition to a 1.5°C world is to become reality.** Remaining questions include: how much can be realistically expected from innovation and behavioural and systemic political and economic changes 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 would limiting warming to 1.5°C require a harmonization of macro-financial and fiscal policies, which 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, 4.3.7, 4.4.1, 4.4.5, 4.6}

## 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 above pre-industrial levels. In the context of systemic transitions, the chapter assesses adaptation and mitigation options, including carbon dioxide removal (CDR), and potential solar radiation modification (SRM) remediative measures (Section 4.3), as well as the enabling conditions that would be required for implementing the rapid and far-reaching global response of limiting warming to 1.5°C (Section 4.4), and render the options more or less feasible (Section 4.5).

The impacts of a 1.5°C-warmer world, 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 decarbonization.

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 DESA, 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. However, these trends 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 in 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 affects 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, and 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 mobilization of new, traditional and indigenous knowledge.

The convergence of short-term development co-benefits from 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 impacts (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 urbanization is achieved in developing countries (Revi, 2016), or without reforms in the global financial intermediation system.

Unless affordable and environmentally and socially acceptable CDR becomes feasible and available at scale well before 2050, 1.5°C-consistent pathways will be difficult to realize, 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 (Grubb et al., 2014; Winkler and Dubash, 2015; Campiglio, 2016).

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 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, and 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 organized 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, 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 4.5. A wide range of 1.5°C-consistent pathways from integrated assessment modelling (IAM), supplemented by other literature, are assessed in 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 is particularly significant for the supply mix and electrification (Table 4.1). Individual, sectoral studies may show higher rates of change compared to IAMs (Figueres et al., 2017; Rockström et al., 2017; WBCSD, 2017; Kuramochi et al., 2018). 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 several other studies reviewed in Chapter 2 that assess mitigation transitions consistent with limiting warming to 1.5°C. Values for '1.5°C-no or -low-OS' and '1.5C-high-OS' indicate the median and the interquartile ranges for 1.5°C scenarios. If a number in square brackets is indicated, this is the number of scenarios for this indicator. S1, S2, S5 and LED represent the four illustrative pathway archetypes selected for this assessment (see Chapter 2, Section 2.1 and Supplementary Material 4.SM.1 for detailed description).

| Pathways | | Number of scenarios | Energy | | Buildings | Transport | | Industry |
|---|---|---|---|---|---|---|---|---|
| | | | Share of renewables in primary energy [%] | Share of renewables in electricity [%] | Change in energy demand for buildings (2010 baseline) [%] | Share of low-carbon fuels (electricity, hydrogen and biofuel) in transport [%] | Share of electricity in transport [%] | Industrial emissions reductions (2010 baseline) [%] |
| IAM Pathways 2030 | 1.5°C-no or low-OS | 50 | 29 (37; 26) | 54 (65; 47) | 0 (7; −7) [42] | 12 (18; 9) [29] | 5 (7; 3) [49] | 42 (55; 34) [42] |
| | 1.5°C-high-OS | 35 | 24 (27; 20) | 43 (54; 37) | −17 (−12; −20) [29] | 7 (8; 6) [23] | 3 (5; 3) | 18 (28; −13) [29] |
| | S1 | | 29 | 58 | −8 | | 4 | 49 |
| | S2 | | 29 | 48 | −14 | 5 | 4 | 19 |
| | S5 | | 14 | 25 | | 3 | 1 | |
| | LED | | 37 | 60 | 30 | | 21 | 42 |
| Other Studies 2030 | Löffler et al. (2017) | | 46 | 79 | | | | |
| | IEA (2017c) (ETP) | | 31 | 47 | 2 | 14 | 5 | 22 |
| | IEA (2017g) (WEM) | | 27 | 50 | −6 | 17 | 6 | 15 |
| IAM Pathways 2050 | 1.5°C-no or low-OS | 50 | 60 (67; 52) | 77 (86; 69) | −17 (3; −36) [42] | 55 (66; 35) [29] | 23 (29; 17) [49] | 79 (91; 67) [42] |
| | 1.5°C-high-OS | 35 | 62 (68; 47) | 82 (88; 64) | −37 (−13; −51) [29] | 38 (44; 27) [23] | 18 (23; 14) | 68 (81; 54) [29] |
| | S1 | | 58 | 81 | −21 | | 34 | 74 |
| | S2 | | 53 | 63 | −25 | 26 | 23 | 73 |
| | S5 | | 67 | 70 | | 53 | 10 | |
| | LED | | 73 | 77 | 45 | | 59 | 91 |
| Other Studies 2050 | Löffler et al. (2017) | | 100 | 100 | | | | |
| | IEA (2017c) (ETP) | | 58 | 74 | 5 | 55 | 30 | 57 |
| | IEA (2017g) (WEM) | | 47 | 69 | −5 | 58 | 32 | 55 |

#### 4.2.1.1 Challenges and Opportunities for Mitigation Along the Reviewed Pathways

**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 $yr^{-1}$ globally with an average of about 3.5 trillion USD $yr^{-1}$ over 2016–2050 (see Figure 2.27). This can be compared to an average of about 3.0 trillion USD $yr^{-1}$ over the same period for 2°C-consistent pathways (also in Figure 2.27).

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 would overtake fossil fuel investments globally by 2025 in 1.5°C-consistent pathways (Chapter 2, 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 (Chapter 2, 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).

**Greater policy design and decision-making implications.** The 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. These policies and responses would 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 decarbonization of energy supply, electrification, fuel switching, energy efficiency, land-use change, and lifestyles (Chapter 2, Section 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 utilization 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 3–4 times by 2050 under a 1.5°C-consistent pathway compared to a 2°C-consistent pathway (Chapter 2, 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).

**Greater sustainable development implications.** Few studies address the relations between the Shared Socio-Economic Pathways (SSPs) and the Sustainable Developments 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 (Chapter 2, Section 2.5.3, Chapter 5, Section 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 (Chapter 2, Sections 2.4.3, 2.5.3). Strengthening the institutional and policy responses to deal with these challenges is 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 (Chapter 3, 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 (Chapter 3, 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 Chapter 3, 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 (Chapter 3, 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

Realizing 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 $CO_2$ 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 normalized to gross domestic product (GDP; as opposed to other normalization 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 Sluisveld 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°-consistent pathways, but may be more optimistic about the systemic ability to realize 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 shift 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 strategies and associated price declines in photovoltaic technologies, particularly in China (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 (Azeiteiro and Leal Filho, 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 for rapid and transformational change (Cole, 2015; Geels et al., 2016b; Hallegatte and Mach, 2016). 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 (Termeer et al., 2017) or large-scale disruptions, is seldom an insular or discrete process (Sterling et al., 2017). This finding informs the multidimensional 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 emphasizes 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 emphasizes 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 transitions. The feasibility of individual options as well as the potential for synergies and reducing trade-offs will vary according to context and the local enabling conditions. These are explored at a high level in Section 4.5. 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. 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 and 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 (IEA, 2017c; IRENA, 2017b; REN21, 2017).

The largest growth driver for renewable energy since AR5 has been the dramatic reduction in the cost of solar photovoltaics (PV) (REN21, 2017). This has made rooftop solar competitive in sunny areas between 45° north and south latitude (Green and Newman, 2017b), though IRENA (2018) suggests it is cost effective in many other places too. Solar PV with batteries has 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 northwest 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 (Ghorbani et al., 2017; REN21, 2017). Several countries have adopted targets of 100% renewable electricity (IEA, 2017c) as this meets multiple social, economic and environmental goals and contributes to mitigation of climate change (REN21, 2017).

#### 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 67–310 (median 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 Chapter 2, Section 2.3.4.2 and Section 4.3.7 for a discussion of BECCS). Detailed assessments indicate that deployment is similar for pathways limiting global warming to below 2°C (Chum et al., 2011; P. Smith et al., 2014; Creutzig et al., 2015b). 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 such 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), and 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; Mouratiadou 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 $CO_2$ emissions (Jaiswal et al., 2017).

The carbon intensity of bioenergy, key for both bioenergy as an emission-neutral energy option and BECCS as a 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., 2012; Harris et al., 2015; Repo et al., 2015; DeCicco et al., 2016; Qin et al., 2016)[2]; the feedstock considered; and time frame (Zanchi et al., 2012; Daioglou et al., 2017; Booth, 2018; Sterman et al., 2018), as well as the availability of coordinated policies and management to minimize negative side effects and trade-offs, particularly those around food security (Stevanović et al., 2017) and livelihood and equity considerations (Creutzig et al., 2013; Calvin et al., 2014) .

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 decarbonization (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 realized 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 scalability and speed of scaling of nuclear plants have historically 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 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 standardization and series effects (Grubler, 2010). What the costs of nuclear power are and have been is debated in the literature (Lovering et al., 2016; Koomey et al., 2017). Countries with liberalized 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 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)(Blaabjerg et al., 2004; IRENA, 2013; IEA, 2017d; Majzoobi and Khodaei, 2017), though how variable renewables can be balanced without hydro or natural gas-based power back-up at a larger scale would still need demonstration. 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, 2017). 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).

[2] 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; Zilberman, 2017)

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 electricity 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, emphasize the need for redundancy (Liu et al., 2017). The implementation of controllable and islandable microgrids, including the use of residential batteries, 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 Chapter 2, Section 2.4.2, assign significant emission reductions over the course of this century to $CO_2$ 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 discusses bioenergy with CCS (BECCS). Section 2.4.2 puts the cumulative $CO_2$ stored from fossil-fuelled power at 410 (199–470 interquartile range) $GtCO_2$ 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 relies on climate policy incentives for its business case and economic feasibility. Since 2017, two CCS projects in the power sector capture 2.4 $MtCO_2$ annually, while 30 $MtCO_2$ is captured annually in all CCS projects (Global CCS Institute, 2017).

The technological maturity of $CO_2$ 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 $GtCO_2$ 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). $CO_2$ retention in the storage reservoir was recently assessed as 98% over 10,000 years for well-managed reservoirs, and 78% for poorly regulated ones (Alcalde 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 $CO_2$ 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 realized 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 the two full-scale projects in the power sector mentioned above, 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 $CO_2$ to mobilize more oil out of depleting oil fields, leading to additional $CO_2$ emissions by combusting the additionally recovered oil (Cooney et al., 2015).

### 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, Southeast 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 $CO_2$ 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 $CO_2$ 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 $CO_2$, 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. Such options 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)** is a soil management approach 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 when used independently, may 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 $CO_2$ from the atmosphere (Aguilera et al., 2013; Poeplau and Don, 2015; Vicente-Vicente et al., 2016). 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; H. Smith et al., 2017).

**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 $GtCO_2$ per year, 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).

4

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 the security of food supplies (Gerber et al., 2013; FAO and NZAGRC, 2017a, b, c). 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 (Havlik 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 Mha 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 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, 2018). 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. Also, increasing irrigation efficiency may foster higher dependency on irrigation, resulting in a heightened sensitivity to climate that 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, 2018; 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; 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 employed at the 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 – the 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 $GtCO_2$-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 Cas9; 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, elevated $CO_2$, 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 $CO_2$, 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 $GtCO_2$ (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 forest degradation) as an institutional mechanism. However, restoration and management activities need not be limited to REDD+, and locally adapted implementation may keep costs low, capitalize 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/$tCO_2$; and a third of the cost-effective potential at <10 USD/$tCO_2$ (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 constrains 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). Forest restoration and conservation are compatible with biodiversity (Rey Benayas et al., 2009; Jantke et al., 2016) and available 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 et al., 2015), or reinforce them through carbon fertilization (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 limits (Well and Carrapatoso, 2017). While there are indications that land tenure has a positive impact (Sunderlin et al., 2014), 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 Chapter 3, 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 a 1.5°C warmer world, 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 with 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 middle part of this century (UN DESA, 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 urbanization and economic and infrastructure development could account for an additional 226 $GtCO_2$ by 2050 (Bai et al. 2018). However, urban systems can harness the mega-trends of urbanization, digitalization, financialization 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 (SDSN, 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 (Solecki et al., 2013; Ahern et al., 2014; Floater et al., 2014; Revi et al., 2014a; Villarroel Walker et al., 2014; Kennedy et al., 2015; Rodríguez, 2015; McGranahan et al., 2016; Dodman et al., 2017a; Newman et al., 2017; UN-Habitat, 2017; Westphal et al., 2017).

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 Chapter 3, Section 3.3) (Dodman et al., 2017a; Satterthwaite and Bartlett, 2017). Unless adaptation and mitigation efforts are designed around the need to decarbonize 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 those 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, 2018).

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. (2018) 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).

Based on the IEA-ETP (IEA, 2017g), Chapter 2 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 energy embodied in building materials provides further energy and GHG savings (Cabeza et al., 2013; Oliver and Morecroft, 2014; Koezjakov et al., 2018), in particular through increased use of bio-based materials (Lupíšek et al., 2015) and wood construction (Ramage et al., 2017). The United Nations Environment Programme (UNEP[3]) estimates that improving embodied energy, thermal performance, and direct energy use of buildings can reduce emissions by 1.9 $GtCO_2e\ yr^{-1}$ (UNEP, 2017b), with an additional reduction of 3 $GtCO_2e\ yr^{-1}$ 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, offers opportunities to accelerate energy efficiency in buildings and cities (Moreno-Cruz and Keith, 2013; Hoy, 2016) (see also Section 4.4.4). Some cities in developing countries 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).

[3] Currently called UN Environment.

#### 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 Pietrostefani, 2017). Significant reductions in car use are associated with dense, pedestrianized 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 (Schiller and Kenworthy, 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 (Rode et al., 2017; Ahlfeldt and Pietrostefani, 2017) and enable combinations of cleaner fuel feedstocks and urban smart grids, in which vehicles form part of the storage capacity (Oldenbroek et al., 2017). Similarly, the spatial organization 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 depend on a roughly 15% reduction in final energy use by the transport sector by 2050 relative to 2015 (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., 2018). 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 urbanizing and re-urbanizing in ways that coordinate 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 4.7 $GtCO_2e$ $yr^{-1}$ (4.1–5.3) by 2030. This is significantly more than is predicted by integrated assessment models (UNEP, 2017b). Such a transition depends on cities that enable modal shifts and avoided journeys and that provide incentives for uptake of improved fuel efficiency and changes in urban design that encourage walkable cities, non-motorized transport and shorter commuter distances (IEA, 2016a; Mittal et al., 2016; Zhang et al., 2016; Li and Loo, 2017). In at least 4 African cities, 43 Asian cities and 54 Latin American cities, transit-oriented development (TOD), has emerged as an organizing principle for urban growth and spatial planning (Colenbrander et al., 2017; Lwasa, 2017; BRTData, 2018). This trend is important to counter the rising demand for private cars in developing-country cities (AfDB/OECD/UNDP, 2016). 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 realizing 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; Schiller and Kenworthy, 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

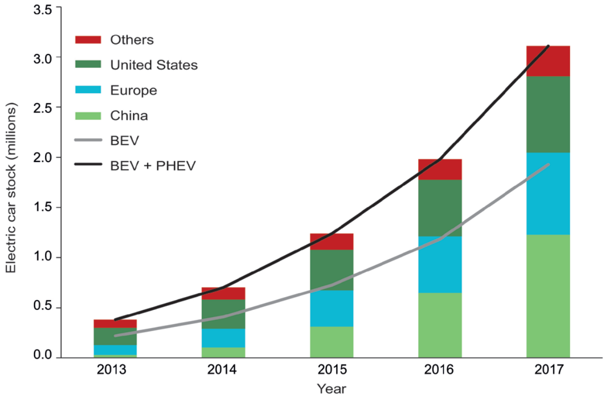


**Figure 4.1 | Increase of the global electric car stock by country (2013–2017).** The grey line is battery electric vehicles (BEV) only while the black line includes both BEV and plug-in hybrid vehicles (PHEV). Source: (IEA, 2018). Based on IEA data from Global EV Outlook 2018 © OECD/IEA 2018, IEA Publishing.

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 electric bicycles 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, 2018). 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 intercity 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 decarbonizing 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 $CO_2$, has gained momentum but has not yet demonstrated benefits on a scale consistent with 1.5°C pathways (Ezeji, 2017; Fasihi et al., 2017). Decarbonizing the fuel used by the world's 60,000 large ocean 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 to do this (Carter et al., 2015; Dhar and Khirfan, 2017; Siders, 2017; Stults and Woodruff, 2017). Adaptation plans can reduce exposure to urban flood risk (which, in a 1.5°C world, could double relative to 1976–2005; Alfieri et al., 2017), heat stress (Chapter 3, Section 3.5.5.8), fire risk (Chapter 3, Section 3.4.3.4) and sea level rise (Chapter 3, 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). In cases where adaptation planning may further marginalize poor citizens, either through limited local control over adaptation priorities or by displacing impacts onto poorer communities, successful urban risk management would need to consider factors such as justice, equity, and inclusive participation, as well as recognize 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, and water features) into city planning can be difficult (Leck et al., 2015) but increases urban resilience to impacts of 1.5°C warming (Table 4.2) in ways that can be more cost-effective than conventional infrastructure (Cartwright et al., 2013; Culwick and Bobbins, 2016).

Realizing 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 runoff and flooding during intense rainfall (Skougaard Kaspersen et al., 2015), but urban design in many cities now seeks to mediate runoff, 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 of 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 the increase in global mean temperature is to remain under 1.5°C, modelling indicates that industry cannot emit more than 2 $GtCO_2$ in 2050, corresponding to a reduction of between 67 and 91% (interquartile range) in GHG emissions compared to 2010 (see Chapter 2, Figures 2.20 and 2.21, and Table 4.1). Moreover, the consequences of warming 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 has 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

**Table 4.2 |** Green urban infrastructure and benefits

| Green Infrastructure | Adaptation Benefits | Mitigation Benefits | References |
|---|---|---|---|
| Urban tree planting, urban parks | Reduced heat island effect, psychological benefits | Less cement, reduced air-conditioning use | Demuzere et al., 2014; Mullaney et al., 2015; Soderlund and Newman, 2015; Beaudoin and Gosselin, 2016; Green et al., 2016; Lin et al., 2017 |
| Permeable surfaces | Water recharge | Less cement in city, some bio-sequestration, less water pumping | 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 |
| Forest retention, urban agricultural land | Flood mediation, healthy lifestyles | Reduced air pollution | 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; R. White et al., 2017 |
| Wetland restoration, riparian buffer zones | Reduced urban flooding, low-skilled local work, sense of place | Some bio-sequestration, less energy spent on water treatment | Cartwright et al., 2013; Elmqvist et al., 2015; Brown and McGranahan, 2016; Camps-Calvet et al., 2016; Culwick and Bobbins, 2016; McPhearson et al., 2016; Ziervogel et al., 2016b; Collas et al., 2017; F. Li et al., 2017 |
| Biodiverse urban habitat | Psychological benefits, inner-city recreation | Carbon sequestration | Beatley, 2011; Elmqvist et al., 2015; Brown and McGranahan, 2016; Camps-Calvet et al., 2016; McPhearson et al., 2016; Collas et al., 2017; F. Li et al., 2017 |

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 $CO_2$ 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, (utilization) 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.

#### 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, 2018). 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: (i) motor systems (for example electric motors, variable speed drives, pumps, compressors and fans), responsible for about 10% of worldwide industrial energy consumption, with a global energy efficiency improvement potential of around 20–25% (Napp et al., 2014); and (ii) 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 organizational 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 rate of, for example, buildings (Haas et al., 2015). Material substitution and $CO_2$ 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 $CO_2$ (Arnold et al., 2018).

#### 4.3.4.3 Bio-based feedstocks

Bio-based feedstock processes could be seen as part of the circular materials economy (see section above). In several sectors, bio-based

**Table 4.3 |** Overview of different mitigation options potentially consistent with limiting warming to 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).

| Industrial mitigation option | Iron/Steel | Cement | Refineries and Petrochemicals | Chemicals |
|---|---|---|---|---|
| Process and Energy Efficiency | Can make a difference of between 10% and 50%, depending on the plant. Relevant but not enough for 1.5°C | | | |
| Bio-based | Coke can be made from biomass instead of coal | Partial (only energy-related emissions) | Biomass can replace fossil feedstocks | |
| Circularity & Substitution | More recycling and replacement by low-emission materials, including alternative chemistries for cement | | Limited potential | |
| Electrification & Hydrogen | Direct reduction with hydrogen<br>Heat generation through electricity | Partial (only electrified heat generation) | Electrified heat and hydrogen generation | |
| Carbon dioxide capture, utilization and storage | Possible for process emissions and energy. Reduces emissions by 80–95%, and net emissions can become negative when combined with biofuel | | Can be applied to energy emissions and different stacks but not on emissions of products in the use phase (e.g., gasoline) | |

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 life cycle, both upstream and downstream, could be significant (Wesseling et al., 2017). Bio-based feedstocks may put pressure on natural resources by increasing land demand by 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 would entail 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 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).

#### 4.3.4.5 $CO_2$ capture, utilization and storage in industry

$CO_2$ 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 (>1MtCO$_2$ yr$^{-1}$) CCS projects capture $CO_2$ from industrial sources, including the Sleipner project in Norway, which has been injecting $CO_2$ 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 $CO_2$ as inherent process emissions and can therefore not reduce emissions to zero without CC(U)S. $CO_2$ stacks in some industries have a high economic and technical feasibility for $CO_2$ capture as the $CO_2$ concentration in the exhaust gases is relatively high (IPCC, 2005b; 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 $CO_2$ capture through amine solvents (for solvent regeneration) can decrease by around 60%, from 5 GJ tCO$_2^{-1}$ in 2005 to 2 GJ tCO$_2^{-1}$ in the best-performing current 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 incentivize industrial CCS (Mikunda et al., 2014), and may decrease institutional feasibility.

Whether carbon dioxide utilization (CCU) can contribute to limiting warming to 1.5°C depends on the origin of the $CO_2$ (fossil, biogenic or atmospheric), the source of electricity for converting the $CO_2$ or regenerating catalysts, and the lifetime of the product. Review studies indicate that $CO_2$ utilization in industry has a small role to play in limiting warming to 1.5°C because of the limited potential of reusing $CO_2$ with currently available technologies and the re-emission of $CO_2$ when used as a fuel (IPCC, 2005b; Mac Dowell et al., 2017). However, new developments could make CCU more feasible, in particular in $CO_2$ use as a feedstock for carbon-based materials that would isolate $CO_2$ from the atmosphere for a long time, and in low-cost, low-emission electricity that would make the energy use of $CO_2$ capture more sustainable. The conversion of $CO_2$ to fuels using zero-emission electricity has a lower technical, economic and environmental feasibility than direct $CO_2$ 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 –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 (Chapter 3, Section 3.4) may 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 impacts 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 mechanisms for learning and knowledge sharing 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

Climate change will exacerbate existing health challenges (Chapter 3, Section 3.4.7). Options for enhancing current health services include 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). Indigenous knowledge is threatened by acculturation, dispossession of land rights and land grabbing, rapid environmental changes, colonization and social change, resulting in 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 (Chapter 3, Section 3.4.10.2). There is *medium evidence* and *low agreement* as to whether migration is adaptive, in relation to cost effectiveness concerns (Grecequet et al., 2017) and scalability (Brzoska and Fröhlich, 2016; Gemenne and Blocher, 2017; Grecequet et al., 2017). 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; Kumari Rigaud et al., 2018) 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 (Briley et al., 2015; WMO, 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.SM.2.

| Option | Enabling Conditions | Examples |
|---|---|---|
| **Disaster risk management (DRM)** | Governance and institutional capacity: supports post-disaster recovery and reconstruction (Kelman et al., 2015; Kull et al., 2016). | 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). |
| **Risk sharing and spreading: insurance** | Institutional capacity and finance: 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). | 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). |
| **Social safety nets** | 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). | 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). |
| **Education and learning** | 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). | 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). |
| **Population health and health system** | 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. | Heatwave 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). |
| **Indigenous knowledge** | 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). | 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). |
| **Human migration** | 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). | 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). |
| **Climate services** | Technological innovation: rapid technical development (due to increased financial inputs and growing demand) is improving quality of climate information provided (Rogers and Tsirkunov, 2010; Clements et al., 2013; Perrels et al., 2013; Gasc et al., 2014; WMO, 2015; Roudier et al., 2016). | Climate services are seeing wide application in sectors such as agriculture, health, disaster management and insurance (Lourenço et al., 2016; Vaughan et al., 2018), with implications for adaptation decision-making (Singh et al., 2017). |

4

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

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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 generalize 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 of global warming relative to pre-industrial levels, chances of an ice-free Arctic during summer are substantially higher than at 1.5°C (see Chapter 3, 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; Ng et al., 2018).

*Cross Chapter Box 9 (continued)*

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., 2015b; 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 Chapter 5, Box 5.3). In Alaska, the cumulative economic impacts of climate change on public infrastructure are projected at 4.2 billion USD to 5.5 billion USD from 2015 to 2099, with adaptation efforts halving these estimates (Melvin et al., 2017). Marginalization, colonization, 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 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). Utilizing 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 Small Island Developing States (SIDS) and Territories**

Extreme weather, linked to tropical storms and hurricanes, represent one of the largest risks facing Caribbean island nations (Chapter 3, 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; Chapter 3, Section 3.3.6; Box 3.5) are a significant cause for concern, making adaptation a matter of survival (Mycoo and Donovan, 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 mobilization 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 Overseas 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 composed of representatives from multiple stakeholders (Osei, 2007). Most initiatives are primarily funded through a mix of multilateral and bilateral 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).

*Cross Chapter Box 9 (continued)*

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 (Chapter 5, 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) (Chapter 3, 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 socio-economic development (Pinho et al., 2014); and high levels of climate vulnerability (Darela et al., 2016). Limiting global 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) (Chapter 5, 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 (Chapter 5, Section 5.2.3).

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**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 being 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 (Georgeson 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 (Georgeson et al., 2016; Reckien et al., 2017).

**New York, United States:** Adaptation plans are undertaken across government levels, sectors and departments (NYC Parks, 2010; Vision 2020 Project Team, 2011; PlaNYC, 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 (HSRTF, 2013). In 2013 the Mayor's office, in response to Hurricane Sandy, published the city's adaptation strategy (PlaNYC, 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 (ORR, 2018). 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, Uganda:** Kampala Capital City Authority (KCCA) 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 recognizes the need to adapt to uniquely local solutions (Evans et al., 2018).

*Cross Chapter Box 9 (continued)*

**Rotterdam, The Netherlands:** The Rotterdam Climate Initiative (RCI) was launched to reduce greenhouse gas 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 the Rotterdam Climate Proof programme and the 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 focusing 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 can potentially overcome these barriers in Rotterdam (Hölscher et al., 2018).

### 4.3.6 Short-Lived Climate Forcers

The main short-lived climate forcer (SLCF) emissions that cause warming are methane ($CH_4$), 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 ($SO_2$) and organic carbon (OC). Nitrogen oxides (NOx) can have both warming and cooling effects, by affecting ozone ($O_3$) and $CH_4$, depending on time scale 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 $CO_2$ and $CH_4$, and that non-$CO_2$ climate forcers reduce carbon budgets by about 2200 $GtCO_2$ per degree of warming attributed to them (see the Supplementary Material to Chapter 2).

Reducing non-$CO_2$ 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 $CO_2$ emissions. $CO_2$ 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 $CO_2$ emissions to net zero would not limit global warming, even if SLCFs are reduced, due to accumulating $CO_2$-induced warming that overwhelms SLCFs' mitigation benefits in a couple of decades (Shindell et al., 2012; Schmale et al., 2014) (and see Chapter 2, Section 2.3.3.2).

Mitigation options for warming SLCFs often overlap with other mitigation options, especially since many warming SLCFs are co-emitted with $CO_2$. 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). The benefits of such strategies depend greatly upon the assumed level of progression of access to modern energy for the poorest populations who still rely on biomass fuels, as this affects the reference level of BC emissions (Rogelj 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 $CO_2$ warming (Smith and Mizrahi, 2013; Pierrehumbert, 2014). Reducing fossil fuel combustion will reduce aerosols levels, and thereby cause warming from removal of aerosol cooling effects (Myhre et al., 2013; Xu and Ramanathan, 2017; Samset et al., 2018). While some studies have found a lower temperature effect from BC mitigation, 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), other models and observationally constrained estimates suggest that these widely-used models do not fully capture observed effects of BC and co-emissions on climate (e.g., Bond et al., 2013; Cui et al., 2016; Peng et al., 2016).

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.

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., 2017a).

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., 2017b) 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 Chapter 5, Section 5.4.2.1). Limited interagency co-ordination, poor science-policy interactions (Zusman et al., 2015), and weak policy and

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**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).

| SLCF Compound | Atmospheric Lifetime | Annual Global Emission | Main Anthropogenic Emission Sources | Examples of Options to Reduce Emissions Consistent with 1.5°C | Examples of Co-Benefits Based on Haines et al. (2017) Unless Specified Otherwise |
|---|---|---|---|---|---|
| **Methane** | On the order of 10 years | 0.3 $GtCH_4$ (2010) (Pierrehumbert, 2014) | Fossil fuel extraction and transportation; Land-use change; Livestock and rice cultivation; Waste and wastewater | Managing manure from livestock; Intermittent irrigation of rice; Capture and usage of fugitive methane; Dietary change; For more: see Section 4.3.2 | Reduction of tropospheric ozone (Shindell et al., 2017a); Health benefits of dietary changes; Increased crop yields; Improved access to drinking water |
| **HFCs** | Months to decades, depending on the gas | 0.35 $GtCO_2$-eq (2010) (Velders et al., 2015) | Air conditioning; Refrigeration; Construction material | Alternatives to HFCs in air-conditioning and refrigeration applications | Greater energy efficiency (Mota-Babiloni et al., 2017) |
| **Black Carbon** | Days | ~7 Mt (2010) (Klimont et al., 2017) | Incomplete combustion of fossil fuels or biomass in vehicles (esp. diesel), cook stoves or kerosene lamps; Field and biomass burning | Fewer and cleaner vehicles; Reducing agricultural biomass burning; Cleaner cook stoves, gas-based or electric cooking; Replacing brick and coke ovens; Solar lamps; For more see Section 4.3.3 | Health benefits of better air quality; Increased education opportunities; Reduced coal consumption for modern brick kilns; Reduced deforestation |

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 organization of supply chains (Jeuland et al., 2015). Similar feasibility considerations emerge in switching from kerosene wick lamps for lighting 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 (e.g., Anenberg et al., 2012) and crop yields (e.g., Shindell et al., 2012), energy access, gender equality and poverty eradication (e.g., 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 to developing policies for addressing SLCF emissions (Venkataraman et al., 2016). The incentives for reducing SLCFs are particularly strong for small groups of countries, and such collaborations could increase the 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 and, in most cases, achieve net negative emissions to return to 1.5°C from an overshoot. See Cross-Chapter Box 7 in Chapter 3 for a synthesis of land-based CDR options. Cross-cutting issues and uncertainties are summarized in Table 4.6.

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

BECCS has been assessed in previous IPCC reports (IPCC, 2005b, 2014b; P. Smith et al., 2014; Minx et al., 2017) and has been incorporated into integrated assessment models (Clarke et al., 2014), but also 1.5°C-consistent pathways without BECCS have emerged (Bauer et al., 2018; Grubler et al., 2018; Mousavi and Blesl, 2018; van Vuuren et al., 2018). Still, the overall set of pathways limiting global warming to 1.5°C with limited or no overshoot indicates that 0–1, 0–8, and 0–16 $GtCO_2$ $yr^{-1}$ would be removed by BECCS by 2030, 2050 and 2100, respectively (Chapter 2, Section 2.3.4). BECCS is constrained by sustainable bioenergy potentials (Section 4.3.1.2, Chapter 5, Section 5.4.1.3 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 $GtCO_2$[4]. Fuss et al.

[4] 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 4.SM.3 Table 1.

(2018) narrow this range to 0.5–5 $GtCO_2$ $yr^{-1}$ (*medium agreement, high evidence*) (Figure 4.3), meaning that BECCS mitigation potentials are not necessarily sufficient for 1.5°C-consistent 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 $GtCO_2$-eq $yr^{-1}$ by 2100, considered as a conservative deployment estimate for BECCS-accepting pathways consistent with 1.5°C), Smith et al. (2016b) estimate a land-use intensity of 0.3–0.5 ha $tCO_2$-$eq^{-1}$ $yr^{-1}$ using forest residues, 0.16 ha $CO_2$-$eq^{-1}$ $yr^{-1}$ for agricultural residues, and 0.03–0.1 ha $tCO_2$-$eq^{-1}$ $yr^{-1}$ 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, for example, 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 designing 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 and land and water footprints show wide ranges in bottom-up assessments due to differences in technology, feedstock and other parameters (–1–150 EJ $yr^{-1}$ of energy, 109–990 Mha, 6–79 MtN, 218–4758 $km^3$ $yr^{-1}$ of water per $GtCO_2$ $yr^{-1}$; 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 (Nemet et al., 2018). 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 $MtCO_2$ 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 $tCO_2^{-1}$ (Figure 4.2), 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 $yr^{-1}$, 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 modelled mitigation costs (Kriegler et al., 2013; Bauer et al., 2018).

#### 4.3.7.2 Afforestation and reforestation (AR)

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 $GtCO_2$ $yr^{-1}$ for decades. The full literature range gives 2050 potentials of 1–7 $GtCO_2$ $yr^{-1}$ (*low evidence, medium agreement*), narrowed down to 0.5–3.6 $GtCO_2$ $yr^{-1}$ 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 $tCO_2$-$eq^{-1}$ (*robust evidence, high agreement*). Yet, realizing 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 $GtCO_2$ $yr^{-1}$ for reforestation with significant co-benefits (Cross-Chapter Box 7 in Chapter 3).

Biogenic storage is not as permanent as emission reductions by 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 $CO_2$ 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 these challenges 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 can 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 (Grubler et al., 2018). Such land-sparing strategies could also benefit other land-based CDR options.

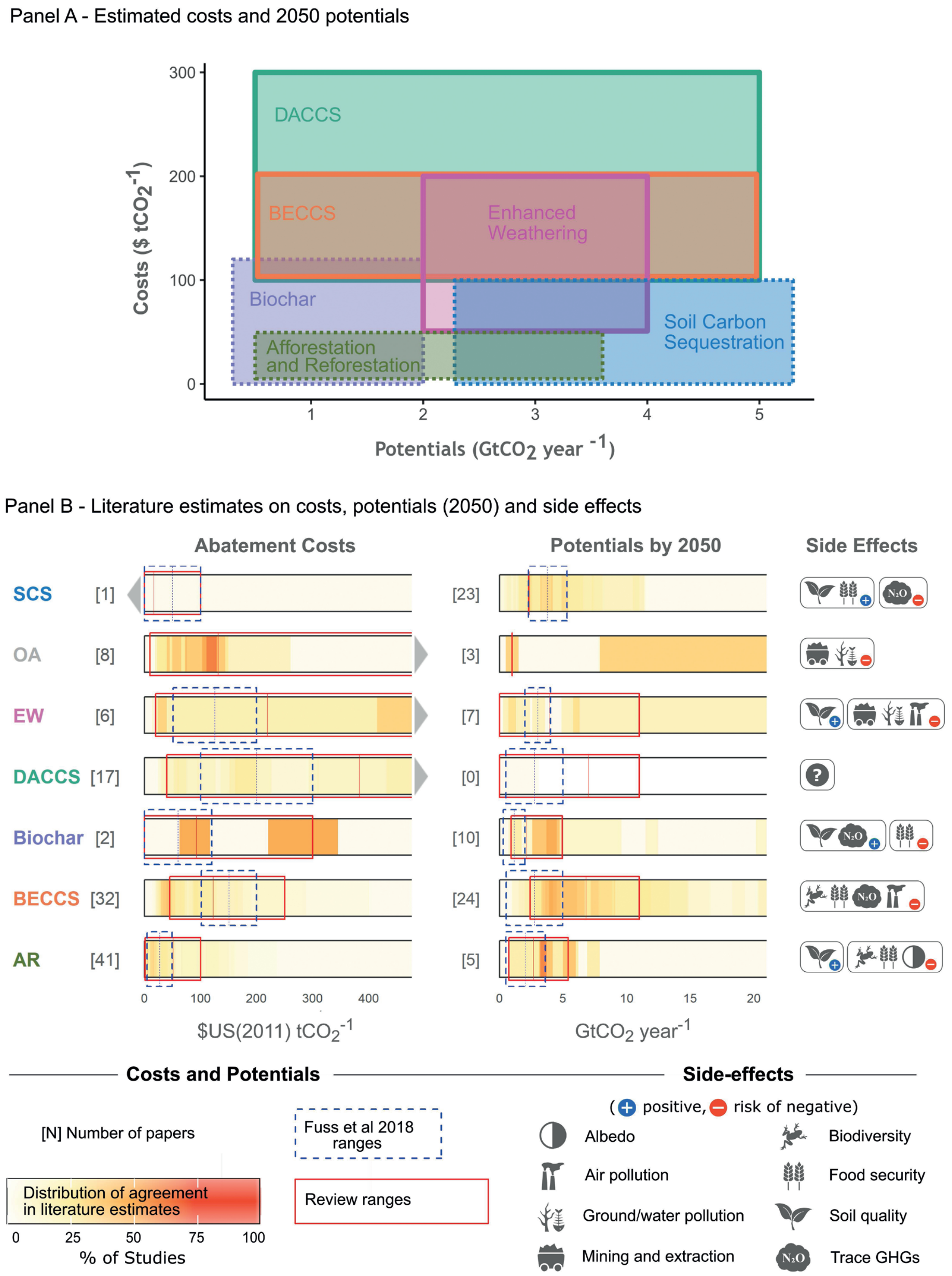


**Figure 4.2 | Evidence on carbon dioxide removal (CDR) abatement costs, 2050 deployment potentials, and key side effects.** Panel A presents estimates based on a systematic review of the bottom up literature (Fuss et al., 2018), corresponding to dashed blue boxes in Panel B. Dashed lines represent saturation 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 included (as early as 2030, older estimates are excluded if they lack a base year and thus cannot be made comparable). Ranges have been trimmed to show detail (see Fuss et al., 2018 for the full range). Costs refer only to abatement costs. Icons for side-effects are allocated only if a critical mass of papers corroborates their occurrence

*Notes: For references please see Supplementary Material Table 4.SM.3. Direct air carbon dioxide capture and storage (DACCS) is theoretically only constrained by geological storage capacity, estimates presented are considering upscaling and cost challenges* (Nemet et al., 2018). *BECCS potential estimates are based on bioenergy estimates in the literature (EJ yr$^{-1}$), converted to GtCO$_2$ following footnote 4. Potentials cannot be added up, as CDR options would compete for resources (e.g., land). SCS - soil carbon sequestration; OA - ocean alkalinization; EW- enhanced weathering; DACCS - direct air carbon dioxide capture and storage; BECCS - bioenergy with carbon capture and storage; AR - afforestation.*

#### 4.3.7.3 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 –45–100 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 at between 0.5 and 11 $GtCO_2$ $yr^{-1}$, narrowed down to 2.3–5.3 $GtCO_2$ $yr^{-1}$ 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.[5] Looking at the full literature range, the global potential in 2050 lies between 1 and 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 $N_2O$ 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 sequestrated in plants and soil at higher temperatures (Wang et al., 2013).

#### 4.3.7.4 Enhanced weathering (EW) and ocean alkalinization

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, 2005a). 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 alkalinization 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 $GtCO_2$ $yr^{-1}$ (*low evidence, low agreement*) (Hartmann and Kempe, 2008; Köhler et al., 2010; Hartmann et al., 2013; Taylor et al., 2016; Strefler et al., 2018a). Marine application of ground minerals is limited by feasible rates of mineral extraction, grinding and delivery, with estimates of 1–6 $GtCO_2$ $yr^{-1}$ (*low evidence, low agreement*) (Köhler et al., 2013; Hauck et al., 2016; Renforth and Henderson, 2017). 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 challenges, with deployment at scale potentially requiring decades (NRC, 2015a), considerable costs in transport and disposal (Hangx and Spiers, 2009; Strefler et al., 2018a) and mining (NRC, 2015a; Strefler et al., 2018a)[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), and range from 15–40 USD $tCO_2^{-1}$ to 3,460 USD $tCO_2^{-1}$ (*limited evidence, low agreement*; Figure 4.2) (Schuiling and Krijgsman, 2006; Köhler et al., 2010; Taylor et al., 2016). The evidence base for costs of ocean alkalinization and marine enhanced weathering is sparser than the land applications. The ocean alkalinization 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); utilization 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

[5] 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)

[6] 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., 2013; Lu et al., 2015). However, these techniques have not been proven at large scale either (Renforth and Henderson, 2017).

4

of marine EW and ocean alkalinization 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 alkalinization 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., 2016b, 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). There is lower agreement and a smaller evidence base at the lower end of the cost range. Fuss et al. (2018) narrow this range to 100–300 USD $tCO_2^{-1}$.

Research and efforts by small-scale commercialization projects focus on utilization of captured $CO_2$ (Wilcox et al., 2017). Given that only a few IAM scenarios incorporate DACCS (e.g., Chen and Tavoni, 2013; Strefler et al., 2018b) its possible role in cost-optimized 1.5°C scenarios is not yet fully explored. Given the technology's early stage of development (McLaren, 2012; NRC, 2015a; Nemet 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 fertilization

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 decarbonization (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 from 15.2 $ktCO_2$ $yr^{-1}$ (Bakker et al., 2001) for a spatially constrained field experiment up to 44 $GtCO_2$ $yr^{-1}$ (Sarmiento and Orr, 1991) following a modelling approach, but Fuss et al. (2018) 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 (Zeebe, 2005; Aumont and Bopp, 2006; Zahariev et al., 2008).

Cost estimates range from 2 USD $tCO_2^{-1}$ (for iron fertilization) (Boyd and Denman, 2008) to 457 USD $tCO_2^{-1}$ (Harrison, 2013). Jones (2014) proposed values greater than 20 USD $tCO_2^{-1}$ for nitrogen fertilization. Fertilization is expected to impact food webs by stimulating its base organisms (Matear, 2004), and extensive algal blooms may cause anoxia (Sarmiento and Orr, 1991; Matear, 2004; Russell et al., 2012) 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 (Matear, 2004; Bertram, 2010) and non-$CO_2$ GHGs may increase (Sarmiento and Orr, 1991; Matear, 2004; Bertram, 2010). 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 fertilization (Strong et al., 2009), which is widely viewed as a de facto moratorium on commercial ocean fertilization activities.

There is *low agreement* in the technical literature on the permanence of $CO_2$ 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 (Zeebe, 2005; Aumont and Bopp, 2006).

[7] This analysis relies on the assessment in Fuss et al. (2018), which provides more detail on saturation and permanence.

**Table 4.6 |** Cross-cutting issues and uncertainties across carbon dioxide removal (CDR) options, aspects and uncertainties

| Area of Uncertainty | Cross-Cutting Issues and Uncertainties |
|---|---|
| **Technology upscaling** | • CDR options are at different stages of technological readiness (McLaren, 2012) and differ with respect to scalability.<br>• Nemet 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 $CO_2$ removals needed in 1.5°C pathways and the long -time periods involved in scaling up novel technologies.<br>• 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, for example, sugar and paper processing facilities (Möllersten et al., 2003), district heating (Kärki et al., 2013; Ericsson and Werner, 2016), and industrial and municipal waste (Sanna et al., 2012). Turner et al. (2018) constrain potential using sustainability considerations and overlap with storage basins to avoid the $CO_2$ transportation challenge, providing a possible, though limited entry point for BECCS.<br>• The impacts on land use, water, nutrients and albedo of BECCS could be alleviated using marine sources of biomass that could include aquacultured micro and macro flora (Hughes et al., 2012; Lenton, 2014).<br>• Regarding captured $CO_2$ as a resource is discussed as an entry point for CDR. However, this does not necessarily lead to carbon removals, particularly if the $CO_2$ is sourced from fossil fuels and/or if the products do not store the $CO_2$ for climate-relevant horizons (von der Assen et al., 2013) (see also Section 4.3.4.5).<br>• Methane[8] is a much more potent GHG than $CO_2$ (Montzka et al., 2011), associated with difficult-to-abate emissions in industry and agriculture and with 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 $CH_4$. There is *low confidence* that existing technologies for $CH_4$ 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.<br>• 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).<br>• An international governance mechanism is only in place for R&D of ocean fertilization within the Convention on Biological Diversity (IMO, 1972, 1996; CBD, 2008, 2010).<br>• Burns and Nicholson (2017) propose a human rights-based approach to protect those potentially adversely impacted by CDR options. |
| **Policy** | • The CDR potentials that can be realized are constrained by the lack of policy portfolios incentivising large-scale CDR (Peters and Geden, 2017).<br>• Near-term opportunities could be supported through modifying existing policy mechanisms (Lomax et al., 2015).<br>• Scott and Geden (2018) sketch three possible routes for limited progress, (i) at EU-level, (ii) at EU Member State level, and (iii) at private sector level, noting the implied paradigm shift this would entail.<br>• EU may struggle to adopt policies for CDR deployment on the scale or time-frame envisioned by IAMs (Geden et al., 2018).<br>• 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)<br>• 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 Chapter 2, Section 2.2.2.2. |

### 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 Chapter 1, Section 1.4.1 and Glossary).

Table 4.7 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 also 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.

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) and be multilateral because of the risk of termination, and risks that implementation or unilateral action by one country or organization will produce negative precipitation or extreme weather effects across borders (Lempert and

[8] Current work (e.g., de Richter et al., 2017) examines other technologies considering non-$CO_2$ GHGs like $N_2O$.

**Table 4.7 |** Overview of the main characteristics of the most-studied SRM methods.

| SRM indicator | Stratospheric Aerosol injection (SAI) | Marine Cloud Brightening (MCB) | Cirrus Cloud Thinning (CCT) | Ground-Based Albedo Modification (GBAM) |
|---|---|---|---|---|
| **Description of SRM method** | Injection of a gas in the stratosphere, which then converts to aerosols. Injection of other particles also considered. | Spraying sea salt or other particles into marine clouds, making them more reflective. | Seeding to promote nucleation, reducing optical thickness and cloud lifetime, to allow more outgoing longwave radiation to escape into space. | 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). |
| **Radiative forcing efficiencies** | 1–4 TgS $W^{-1}$ $m^2$ $yr^{-1}$ | 100–295 Tg dry sea salt $W^{-1}$ $m^2$ $yr^{-1}$ | Not known | Small on global scale, up to 1°C–3°C on regional scale |
| **Amount needed for 1°C overshoot** | 2–8 TgS $yr^{-1}$ | 70 Tg dry sea salt $yr^{-1}$ | Not known | 0.04–0.1 albedo change in agricultural and urban areas |
| **SRM specific impacts on climate variables** | 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 | Regional rainfall responses; reduction in hurricane intensity | Low-level cloud changes; tropospheric drying; intensification of the hydrological cycle | Impacts on precipitation in monsoon areas; could target hot extremes |
| **SRM specific impacts on human/ natural systems** | In case of $SO_2$ injection, stratospheric ozone loss (which could also have a positive effect – a net reduction in global mortality due to competing health impact pathways) and significant increase of surface UV | Reduction in the number of mild crop failures | Not known | Not known |
| **Maturity of science** | Volcanic analogues; *high agreement* amongst simulations; *robust evidence* on ethical, governance and sustainable development limitations | Observed in ships tracks; several simulations confirm mechanism; regionally limited | No clear physical mechanism; *limited evidence* and *low agreement*; several simulations | Natural and land-use analogues; several simulations confirm mechanism; *high agreement* to influence on regional temperature; land use costly |
| **Key references** | Robock et al., 2008; Heckendorn et al., 2009; Tilmes et al., 2012, 2016; Pitari et al., 2014; Crook et al., 2015; C.J. Smith et al., 2017; Visioni et al., 2017a, b; Eastham et al., 2018; Plazzotta et al., 2018 | Salter et al., 2008; Alterskjær et al., 2012; Jones and Haywood, 2012; Latham et al., 2012, 2013; Kravitz et al., 2013; Crook et al., 2015; Parkes et al., 2015; Ahlm et al., 2017 | Storelvmo et al., 2014; Kristjánsson et al., 2015; Jackson et al., 2016; Kärcher, 2017; Lohmann and Gasparini, 2017 | Irvine et al., 2011; Akbari et al., 2012; Jacobson and Ten Hoeve, 2012; Davin et al., 2014; Crook et al., 2015, 2016; Seneviratne et al., 2018 |

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 (Szerszynski 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). Reasons for states to join an international governance framework for SRM include having a voice in SRM diplomacy, prevention of unilateral action by others and benefits from research collaboration (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 organizations 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' (CBD, 2010).

### 4.3.8.2 Economic and technological feasibility

The literature on the engineering costs of SRM is limited and may be unreliable in the absence of testing or deployment. There is *high agreement* that costs 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 could, after some modifications, inject millions of tons of $SO_2$ in the lower stratosphere (at approximately 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, privatization 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). SRM might motivate individuals (as opposed to policymakers) to reduce their GHG emissions, but even a subtle difference in the articulation of information about SRM can influence subsequent judgements of favourability (Merk et al., 2016). The argument that SRM research increases the likelihood of deployment (the 'slippery slope' argument), is also made (Quaas et al., 2017), but some also found an opposite effect (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 characterized as oblivious to 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 that seek to limit global warming (see Chapter 1, Section 1.4.1). Most methods involve reducing the amount of incoming solar radiation reaching the surface, but others also act on the longwave radiation budget by reducing optical thickness and cloud lifetime (see Table 4.7). In the context of this report, SRM is assessed in terms of its potential to limit 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 summarized in Table 4.7. 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 supplemental measure to large-scale carbon dioxide removal (Chapter 2, 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 rise exceeds 1.5°C compared to pre-industrial level by mid-century and returns below 1.5°C before 2100 with a 66% likelihood (see Chapter 2). In all such limited adaptive deployment scenarios, deployment of SRM only

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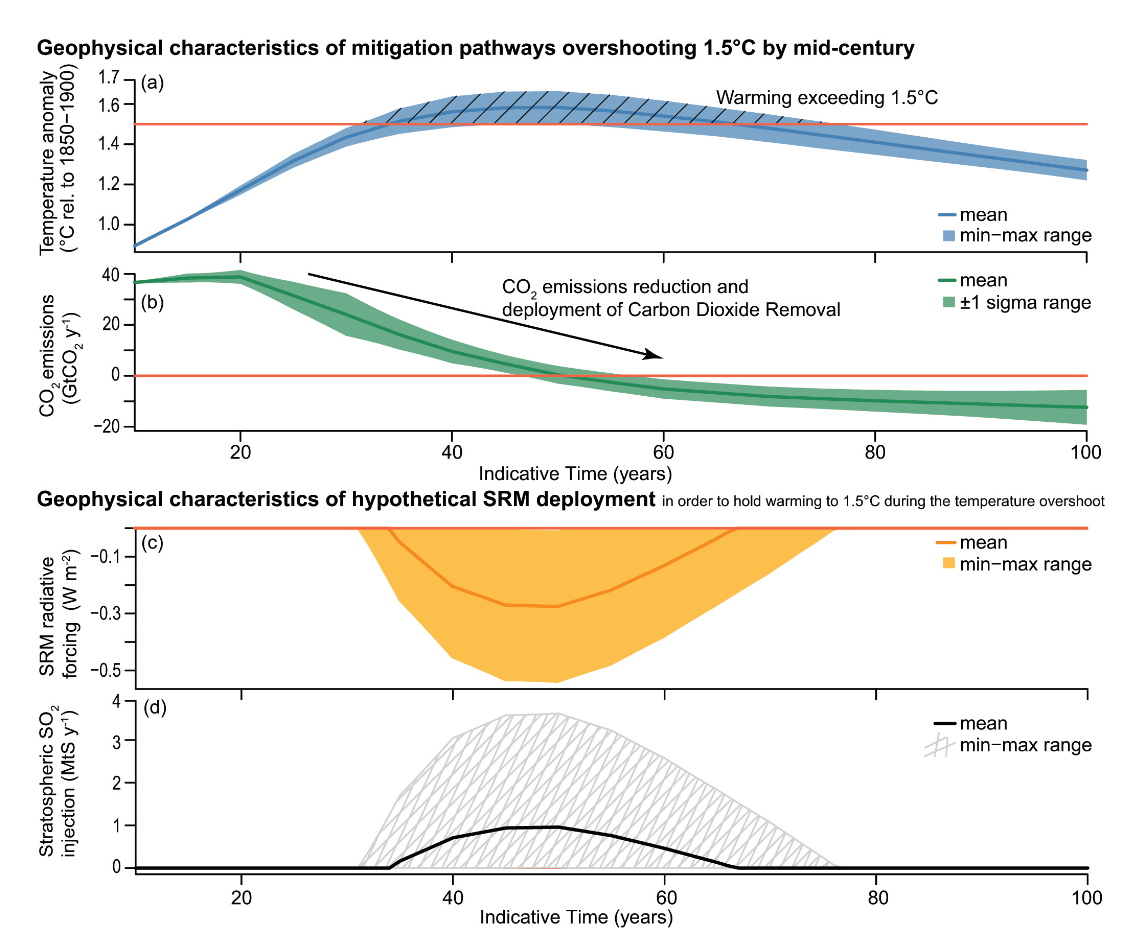
*Cross Chapter Box 10 (continued)*

commences under conditions in which $CO_2$ 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 $MtSO_2\ yr^{-1}$ (panel c) (Robock et al., 2008; Heckendorn et al., 2009).




**Cross-Chapter Box 10, Figure 1 | Evolution of hypothetical SRM deployment (based on stratospheric aerosols injection, or SAI) in the context of 1.5°C-consistent pathways.** (a) Range of median temperature outcomes as simulated by MAGICC (see in Chapter 2, Section 2.2) given the range of $CO_2$ emissions and (b) 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 (c) the magnitude of radiative forcing and (d) the amount of stratospheric $SO_2$ injection 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– m$^2$) of Plazzotta et al. (2018). Magnitude and timing of $SO_2$ 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 $SO_2$ injection, however, is uncertain and varies depending on the model parametrization 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.

*Cross Chapter Box 10 (continued)*

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 and land-cover change 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 would 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 consequences 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 could 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), 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 multimodel mean of this response suggests an increase of the RCP4.5 carbon budget of about 150 $GtCO_2$ after 50 years of $SO_2$ injection with a rate of 4 TgS $yr^{-1}$, which represents about 4 years of $CO_2$ emissions at the current rate (36 $GtCO_2$ $yr^{-1}$). 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

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*Cross Chapter Box 10 (continued)*

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 (see Section 4.3.8) (Boyd, 2016; Preston, 2016; Asayama et al., 2017; Sugiyama et al., 2017b; Svoboda, 2017; McKinnon, 2018; Talberg et al., 2018). 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.

## 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 scaled 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 in Boxes 4.1 to 4.10 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 the feasibility of 1.5°C-consistent pathways and adapting to the consequences. This includes better alignment across governance scales (OECD, 2015a; Geels et al., 2017), enabling multilevel governance (Cheshmehzangi, 2016; Revi, 2017; Tait and Euston-Brown, 2017) and nested institutions (Abbott, 2012). It also includes interdisciplinary 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 realization of co-benefits for sustained rapid change (Blanchet, 2015; Ziervogel et al., 2016a).

### 4.4.1 Enhancing Multilevel Governance

Addressing climate change and implementing responses to 1.5°C-consistent pathways would require engagement between 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) recognize 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 emphasized 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 organized via many mechanisms, including international organizations, 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 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 it is now recognized to be a multi-scaled, multi-actor process that transcends scales from local and sub-national to national and international (Mimura et al., 2014; UNEP, 2017a). National governments provide a central pivot for coordination, planning, determining policy 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 operationalized 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) organized around a diverse set of instruments: (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 the 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; BASIC experts, 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 should 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 be more effective in securing trust (Dagnet et al., 2016) and 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 Kuyper, 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 Nationally 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 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 emphasize different governance approaches to implement the Paris Agreement. Through the new proposed sustainable development mechanism in Article 6, the Paris Agreement allows the space to harness the lowest cost mitigation options worldwide. This may incentivize policymakers to enhance mitigation ambition by speeding up climate action as part of a '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).

COP 16 in Cancun was also the first time in the UNFCCC that adaptation was recognized to have similar priority as mitigation. The Paris Agreement recognizes the importance of adaptation action and cooperation to enhance such action. Chung Tiam Fook (2017) and 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 therefore 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 multilevel 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 organized across hydrological as well as political units.

#### 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 or by 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 urbanization and weaker government regulation (Sarmiento and Tilly, 2018). It remains to be seen how the possibilities and consequences of alternative urban governance models will be managed for large, complex problems and for addressing inequality and urban adaptation (Amin and Cirolia, 2018; Bai et al., 2018; Sarmiento and Tilly, 2018).

Expanding networks of cities are sharing experiences on coping with climate change and drawing economic and development benefits from climate change responses – a recent institutional innovation. This could be complemented by efforts of national governments to enhance local climate action through national urban policies (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 for over 100 of such mitigation initiatives.

#### 4.4.1.4 Interactions and processes for multilevel governance

Literature has proposed multilevel 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 and sectors and across institutional types at the same level (Romero-Lankao et al., 2018), with multilevel reinforcement and the mobilization of economic interests at different levels of governance (Jänicke 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) found good governance to be the one of the strongest predictors of national adaptation policy. An analysis of the climate responses of 200 large and medium-sized cities across eleven European countries found that factors such as membership of climate networks, population size, gross domestic 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, 2016; Magnan and Ribera, 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 (Cross-Chapter Box 11 in this Chapter) (Magnan et al., 2015; Kato and Ellis, 2016; Peters et al., 2017).

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, which could include elements describing policies and measures needed to achieve transition, the human and financial resources needed, milestones, and appropriate measurement and verification processes (Azevedo and Leal, 2017). Discussing the plan with stakeholders and civil society, including citizens and allowing for participation for minorities, and having them provide input and endorse it, has been 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 also need to be addressed 'in politically unstable contexts, where power and politics shape adaptation outcomes'.

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 transnational engagement of sub- and non-state actors (Andonova et al., 2017). Local initiatives are complementary with higher level policies and can be integrated in the multilevel 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) organizations, to strengthen adaptation responses (Donner et al., 2016; Adenle et al., 2017). National governments or international organizations 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 the adaptation policies of early adapters in Quito, Ecuador, and Durban, and 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 4.1 | Multilevel 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 $CO_2$ emission reduction. The participation of small municipalities has been facilitated by the development and testing of a new multilevel governance model involving Covenant Territorial Coordinators (CTCs), i.e., provinces and regions, which commit to providing strategic guidance and financial and technical support to municipalities in their territories. Results from the 315 monitoring inventories submitted show an achievement of 23% reduction in emissions (compared to an average year 2005) for 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. The local Chamber of Commerce also had a key role 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 multilevel 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 multilevel 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 Chapter 5, 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. Another insight is the finding that incremental voluntary changes are amplified through community networking, polycentric governance (Dorsch and Flachsland, 2017), 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).

### Box 4.2 | Watershed Management in a 1.5°C World

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

**Response to drought and El Niño–Southern Oscillation (ENSO) in southern Guatemala**
Hydro-meteorological events, including 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 transition (Wang et al., 2017). 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 organizations, established dialogue tables for different watersheds to discuss water usage amongst stakeholders and plans to mitigate the effects of drought, alleviate 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 composed of working groups that assess water use and sustainability, decide national level distribution of water access, and support 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 limited institutional capacity 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, although ICPDR also works on governance, basin planning, monitoring, and IWRM, indicating its 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).

Box 4.2 exemplifies how multilevel governance has been used for watershed management in different basins, given the impacts on water sources (Chapter 3, Section 3.4.2).

## Cross-Chapter Box 11 | Consistency Between Nationally Determined Contributions and 1.5°C Scenarios

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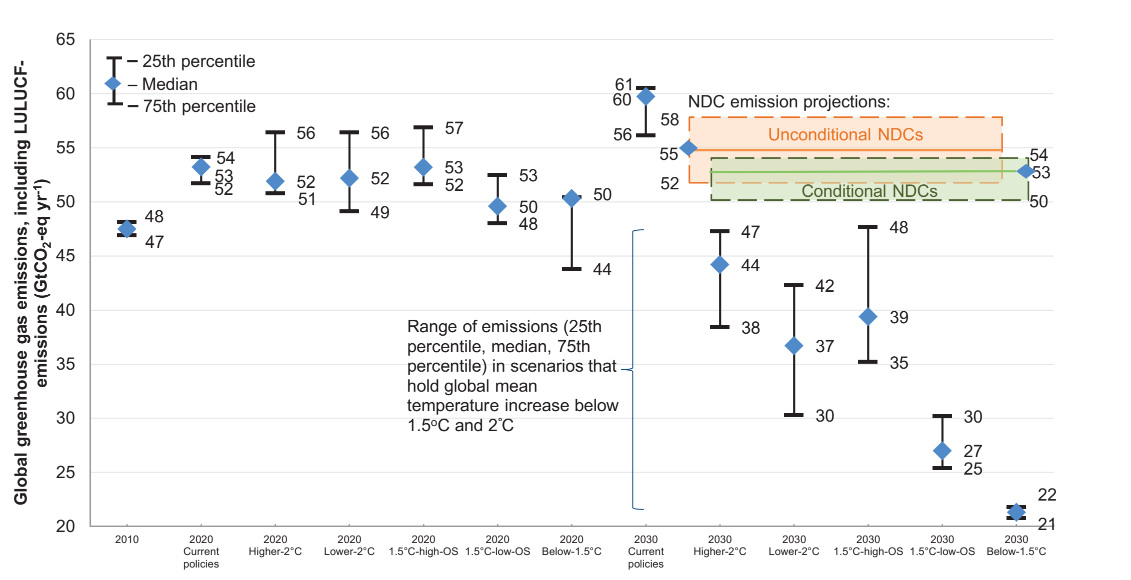
### Mitigation

*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 projections 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; UNEP, 2017b; Kuramochi et al., 2018).

*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) $GtCO_2$-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 $CO_2$-equivalence computed with 100-year global warming potentials (GWPs) reported in IPCC SAR, while the emissions for 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°C–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

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*Cross Chapter Box 11 (continued)*

of 690 to 850 $GtCO_2$ for the period 2011–2030 if the NDCs are successfully implemented. The carbon budget for post-2010 till 2100 compatible with staying below 1.5°C with a 50–66% probability was estimated at 550–600 $GtCO_2$ (Clarke et al., 2014; Rogelj et al., 2016), which will be well exceeded by 2030 at full implementation of the NDCs (Chapter 2, 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) and 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 emissions 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) $GtCO_2$-eq (Cross-Chapter Box 11, Figure 1 above).

Studies indicate important trade-offs of delaying global emissions reductions (Chapter 2, 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 $GtCO_2$-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 the need for 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-consistent pathways (Luderer et al., 2016; Rogelj et al., 2017), indicating that if emissions through 2030 are at NDC levels, the resulting post-2030 reductions required to remain within a 1.5°C-consistent carbon budget during the 21st century (Chapter 2, Section 2.2) are not within the feasible operating space of IAMs. This indicates that the chances of 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 reductions than current NDCs would imply action towards levels identified in Chapter 2, 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 socio-economic conditions (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 (Forsell 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).

*6. 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/fulfilment 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 assessments (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 and Sundqvist, 2017; Lahn, 2018).

*Cross Chapter Box 11 (continued)*

**Adaptation**

The Paris Agreement recognizes 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 achieving a temperature goal would determine the level of adaptation ambition required to deal with the 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%), health (54%), and biodiversity/ecosystems (50%) (Pauw et al., 2016b, 2018).

### 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 characterization 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, 2018). 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 (see Chapter 5, Section 5.5) (UNEP, 2005).

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 (Chapter 5, Section 5.5.1) (Pasquini et al., 2015).

Given the scale of change needed to limit warming to 1.5°C, strengthening the response capacity of relevant institutions is best addressed in ways that take advantage of existing decision-making processes in local and regional governments and within cities and

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communities (Romero-Lankao et al., 2013), and draws 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 decision-making are provided in Box 4.3 and Box 4.4.

Implementing 1.5°C-consistent 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 urbanization 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 20 km 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), and Article 15 on compliance (UNFCCC, 2016).

### Box 4.3 | Indigenous Knowledge and Community Adaptation

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 (López 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 by involving local communities in monitoring and discussing the implications of indigenous knowledge and meteorological forecasts (Shaffer, 2014), and creating local forecasts by utilizing 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 utilizing 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 westernization 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., prioritizing 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).

### Box 4.4 | Manizales, Colombia: Supportive National Government and Localized 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 decentralized 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 recognized 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 programme that trains women and keeps records of vulnerable households. Planning also looks to include mitigation opportunities and enhance local capacity through participatory engagement (Hardoy and Velásquez Barrero, 2016).

Manizales' mayors were identified as important champions for much of these early integration and innovation efforts. Their role may have been enabled by Colombia's history of decentralized approaches to planning and policy formulation, including establishing environmental observatories (for continuous environmental assessment) and participatory tracking of environmental indicators. Multi-stakeholder involvement has both enabled and driven progress, and has enabled the integration of climate risks in development planning (Hardoy and Velásquez Barrero, 2016).

#### 4.4.2.2 Monitoring, reporting, and review institutions

One of the novel features of the new climate governance architecture emerging from the 2015 Paris Agreement is the transparency framework in Article 13 committing countries, based on capacity, to provide regular progress reports on national pledges to address climate change (UNFCCC, 2016). Many countries will rely on public policies and existing national reporting channels to deliver on their NDCs under the Paris Agreement. Scaling up the mitigation and adaptation efforts in these countries to be consistent with 1.5°C would put significant pressure on the need to develop, enhance and streamline local, national and international climate change reporting and monitoring methodologies and institutional capacity in relation to mitigation, adaptation, finance, and GHG inventories (Ford et al., 2015b; Lesnikowski et al., 2015; Schoenefeld et al., 2016). Consistent with this direction, the provision of the information to the stocktake under Article 14 of the Paris Agreement would contribute to enhancing reporting and transparency (UNFCCC, 2016). Nonetheless, approaches, reporting procedures, reference points, and data sources to assess progress on implementation across and within nations are still largely underdeveloped (Ford et al., 2015b; Araos et al., 2016b; Magnan and Ribera, 2016; Lesnikowski et al., 2017). The availability of independent private and public reporting and statistical institutions are integral to oversight, effective monitoring, reporting and review. The creation and enhancement of these institutions would be an important contribution to an effective transition to a low-emission world.

#### 4.4.2.3 Financial institutions

IPCC AR5 assessed that in order to enable a transition to a 2°C pathway, the volume of climate investments would need to be transformed along with changes in the pattern of general investment behaviour towards low emissions. The report argued that, compared to 2012, annually up to a trillion dollars in additional investment in low-emission energy and energy efficiency measures may be required until 2050 (Blanco et al., 2014; IEA, 2014a). Financing of 1.5°C would present an even greater challenge, addressing financing of both existing and new assets, which would require significant transitions to the type and structure of financial institutions as well as to the method of financing (Cochrani et al., 2014; Ma, 2014). Both public and private financial institutions would be needed to contribute to the large resource mobilization needed for 1.5°C, yet, in the ordinary course of business, these transitions may not be expected. On the one hand, private financial institutions could face scale-up risk, for example, the risks associated with commercialization and scaling up of renewable technologies to accelerate mitigation (Wilson, 2012; Hartley and Medlock, 2013) and/or price risk, such as carbon price volatility that carbon markets could face. In contrast, traditional public financial institutions are limited by both structure and instruments, while concessional financing would require taxpayer support for subsidization. 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) discussed 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 cooperative institutions and social safety nets may help address energy access and 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. Explanations for this situation include 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-organ¬ised institutional settings, where equipment and resource systems are commonly owned and managed, can poten¬tially 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 responding 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 asses 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 by 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).

Various policy approaches and strategies can encourage and enable climate actions by individuals and organizations. Policy approaches would be more effective when they address key contextual and psycho-

**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)

| Climate action | Type of action | Examples |
|---|---|---|
| Mitigation | Implementing resource efficiency in buildings | Insulation<br>Low-carbon building materials |
| | Adopting low-emission innovations | Electric vehicles<br>Heat pumps, district heating and cooling |
| | Adopting energy efficient appliances | Energy-efficient heating or cooling<br>Energy-efficient appliances |
| | Energy-saving behaviour | Walking or cycling rather than drive short distances<br>Using mass transit rather than flying<br>Lower temperature for space heating<br>Line drying of laundry<br>Reducing food waste |
| | Buying products and materials with low GHG emissions during production and transport | Reducing meat and dairy consumption<br>Buying local, seasonal food<br>Replacing aluminium products by low-GHG alternatives |
| | Organisational behaviour | Designing low-emission products and procedures<br>Replacing business travel by videoconferencing |

*Table 4.8 (continued)*

| Climate action | Type of action | Examples |
|---|---|---|
| Adaptation | Growing different crops and raising different animal varieties | Using crops with higher tolerance for higher temperatures or $CO_2$ elevation |
| | Flood protective behaviour | Elevating barriers between rooms<br>Building elevated storage spaces<br>Building drainage channels outside the home |
| | Heat protective behaviour | Staying hydrated<br>Moving to cooler places<br>Installing green roofs |
| | Efficient water use during water shortage crisis | Rationing water<br>Constructing wells or rainwater tanks |
| Mitigation & adaptation | Adoption of renewable energy sources | Solar PV<br>Solar water heaters |
| | Citizenship behaviour | Engage through civic channels to encourage or support planning for low-carbon climate-resilient development |

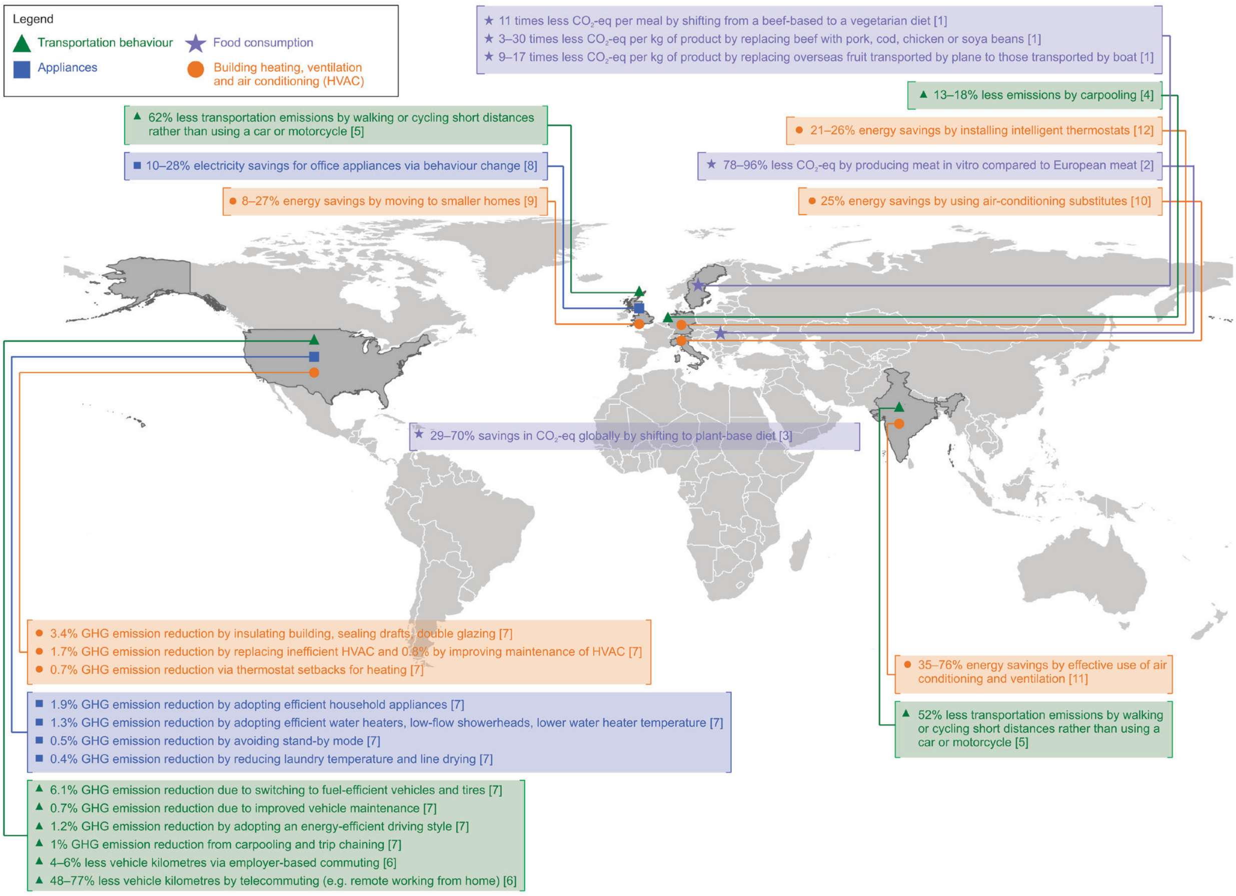


**Figure 4.3 | Examples of mitigation behaviour and their GHG emission reduction potential. Mitigation potential assessments are printed in different units.** Based on [1] Carlsson-Kanyama and González (2009); [2] Tuomisto and Teixeira de Mattos (2011); [3] Springmann et al. (2016); [4] Nijland and Meerkerk (2017); [5] Woodcock et al. (2009); [6] Salon et al. (2012); [7] Dietz et al. (2009); [8] Mulville et al. (2017); [9] Huebner and Shipworth (2017); [10] Jaboyedoff et al. (2004); [11] Pellegrino et al. (2016); [12] Nägele et al. (2017).

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 United States 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 (EU), 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.

**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 $CO_2$ 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 of 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 emphasize 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).

**Motivation to engage in climate action.** Climate actions are more strongly related to motivational factors than to knowledge, reflecting individuals' reasons for actions, such as values, ideology and worldviews (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 impacts 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). Decentralized renewable energy systems are evaluated most favourably when they guarantee independence, autonomy, control and supply security (Ecker et al., 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; Dóci 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 Preisendörfer, 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; Chatrchyan 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 their actions and think that 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 realize they have 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).

**Habits, heuristics and biases.** Decisions are often not based on weighing costs and benefits, but on habit or automaticity, both of individuals (Aarts and Dijksterhuis, 2000; Kloeckner et al., 2003) and within organizations (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 (Maréchal, 2010). Habits are mostly only reconsidered when the situation changed significantly (Fujii and Kitamura, 2003; Maréchal, 2010; Verplanken and Roy, 2016). Hence, strategies that create the opportunity for reflection and encourage active decisions can break habits (Steg et al., 2018).

Individuals can follow heuristics, or 'rules of thumb', in making inferences, which demand less cognitive resources, knowledge and time than thinking through all implications of actions (Preston et al., 2013; Frederiks et al., 2015; Gillingham and Palmer, 2017). For example, people tend to think that larger and more 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).

Biases also 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 emphasize 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). In addition, pursuing small financial gains is perceived to be less worth the effort than pursuing equivalent $CO_2$ 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 organization sponsoring incentive programmes (Mundaca, 2007) or when it takes too much effort to receive the incentive (Stern et al., 2016a).

### 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 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 incentivizes purchases of low-emission vehicles via a feebate system. As a result, per capita transport emissions (approximately 1.25 $tCO_2yr^{-1}$) 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 over time despite economic and population growth (Eliasson, 2014). $CO_2$ 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 buses 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 the scheme gained support of about two-thirds of the population and all political parties after it was implemented (Eliasson, 2014), which may be related to the fact that the revenues were earmarked for 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 $CO_2$ emissions from road traffic reduced by 20% (Santos, 2008).

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 organizations (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 for promoting 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; Hornsey et al., 2016). Also, tailored information can remove barriers to receive and interpret information faced by vulnerable groups, such as the elderly during heatwaves (Vandentorren et al., 2006; Keim, 2008). Further, prompts can be effective when they serve as reminders to perform a planned action (Osbaldiston 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), visualization 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 emphasize 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 (Osbaldiston 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).

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-related 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 (Adger et al., 2003). Change can be initiated by governments at various levels, but also by individuals, communities, profit-making organizations, trade organizations, 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 the 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 and 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

### 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, organizations, 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).



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 have already done their part (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 (see Box 4.8).

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 organizations (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 well-being when such actions involve more costs, effort or discomfort. Yet some climate actions enhance well-being, such as technology that improves daily comfort and nature-based solutions for climate adaptation (Wamsler and Brink, 2014b). Further, climate action may enhance well-being (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 1.5°C, and how innovation can contribute to strengthening implementation to move towards or to adapt to 1.5°C 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 better understand climate, agriculture, and material sciences, 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, for example, in the form of applications such as smart lighting systems, more efficient drilling techniques that make 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 the internet of things (IoT), nanotechnologies, biotechnologies, robotics, and so forth (WEF, 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 microelectromechanical systems. The latter GPTs are not usually categorized as climate technologies, but they can impact GHG emissions.

Progress of GPT could help reduce 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,

**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.

| Sector | Examples of Mitigation/Adaptation Technological Innovation | Enabling GPT |
|---|---|---|
| Buildings | Energy and $CO_2$ efficiency of logistics, warehouse and shops (GeSI, 2015; IEA, 2017a) | IoT, AI |
| | Smart lighting and air conditioning (IEA, 2016b, 2017a) | IoT, AI |
| Industry | Energy efficiency improvement by industrial process optimization (IEA, 2017a) | Robots, IoT |
| | Bio-based plastic production by biorefinery (OECD, 2017c) | Biotechnology |
| | New materials from biorefineries (Fornell et al., 2013; McKay et al., 2016) | ICT, biotechnology |
| Transport | Electric vehicles, car sharing, automation (Greenblatt and Saxena, 2015; Fulton et al., 2017) | Biotechnology |
| | Bio-based diesel fuel by biorefinery (OECD, 2017c) | ICT, biotechnology |
| | Second generation bioethanol potentially coupled to carbon capture systems (De Souza et al., 2014; Rochedo et al., 2016) | Biotechnology |
| | Logistical optimization, and electrification of trucks by overhead line (IEA, 2017e) | ICT, biotechnology |
| | Reduction of transport needs by remote education, health and other services (GeSI, 2015; IEA, 2017a) | Biotechnology |
| | Energy saving by lightweight aircraft components (Beyer, 2014; Faludi et al., 2015; Verhoef et al., 2018) | Additive manufacturing (3D printing) |
| Electricity | Solar PV manufacturing (Nemet, 2014) | Nanotechnology |
| | Smart grids and grid flexibility to accommodate intermittent renewables (Heard et al., 2017) | IoT, AI |
| | Plasma confinement for nuclear fusion (Baltz et al., 2017) | AI |
| Agriculture | Precision agriculture (improvement of energy and resource efficiency including reduction of fertilizer use and $N_2O$ emissions) (Pierpaoli et al., 2013; Brown et al., 2016; Schimmelpfennig and Ebel, 2016) | Biotechnology ICT, AI |
| | Methane inhibitors (and methane-suppressing vaccines) that reduce livestock emissions from enteric fermentation (Wedlock et al. 2013; Hristov et al. 2015; Wollenberg et al. 2016) | Biotechnology |
| | Engineering C3 into C4 photosynthesis to improve agricultural production and productivity (Schuler et al., 2016) | Biotechnology |
| | Genome editing using CRISPR to improve/adapt crops to a changing climate (Gao, 2018) | Biotechnology |
| Disaster Reduction and Adaptation | Weather forecasting and early warning systems, in combination with user knowledge (Hewitt et al., 2012; Lourenço et al., 2016) | ICT |
| | Climate risk reduction (Upadhyay and Bijalwan, 2015) | ICT |
| | Rapid assessment of disaster damage (Kryvasheyeu et al., 2016) | ICT |



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 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.

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 research and development (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 (Edler and Fagerberg, 2017). 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).

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 being 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 these 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 recognized as an enabler of both mitigation and adaptation in Article 10 in the Paris Agreement (UNFCCC, 2016) as well as in Article 4.5 of the original text of the UNFCCC (UNFCCC, 1992). As previous sections have focused 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).

### 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 both 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 $CO_2$ emissions (Macedo et al., 2008). Examples of innovations include: (i) the development of environmentally well-adapted varieties of sugarcane; (ii) the development and scaling up of sugar fermentation in a non-sterile environment, and (iii) the development of adaptations of car engines to use ethanol as a fuel in isolation 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 $CO_2$ 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; Paraiso 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 for political and economic stability of the donor country (Brazil) and the necessity for 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).

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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 organizations. 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 innovation initiative called the 'Breakthrough Energy Coalition'.

Most technology transfer is driven by through markets by the interests of technology seekers and technology holders, particularly 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, 2016). 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 the 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, which 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 estimate by seven models of annual investment needs in the energy system is around 2.38 trillion USD2010 (1.38 to 3.25) between 2016 and 2035. This represents between 2.53% (1.6–4%) 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 (WEF, 2013) and the Global Commission on the Economy and Climate (GCEC, 2014) confirm these orders of magnitude of investment.

The average increase of investment in the energy sector resulting from Box 4.8 represents a mean value of 1.5% of the total world investment compared with the baselines scenario in MER and a little over 1% in PPP. Including infrastructure investments would raise this to 2.5% and 1.7% respectively.[9]

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 a 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 infrastructure would not be an incremental cost in terms of development and welfare (IMF, 2014; Gurara et al., 2017)

[9] 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.

## Box 4.8 | Investment Needs and the Financial Challenge of Limiting Warming to 1.5°C

Peer-reviewed literature that estimates the investment needs over the next two decades to scale up the response to limit warming to 1.5°C is very limited (see Section 4.6). This box attempts to bring together available estimates of the order of magnitude of these investments, after consultation with the makers of those estimates, to provide the context for global and national financial mobilization 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 harmonizing their metrics): an ensemble of four integrated assessment models (here denoted IAM, see Chapter 2), an Organization for Economic Co-operation and Development (OECD) scenario for a 2°C limit (OECD, 2017a) and scenarios from the International Energy Agency (IEA, 2016c). All three sources provide estimates for the energy sector for various mitigation scenarios. They give a mean value of 2.38 trillion USD of yearly investments in the energy sector over the period, with minimum and maximum values of 1.38 and 3.25 respectively. We also report the OECD estimate for 2°C because it also covers transportation and other infrastructure (water, sanitation, and telecommunication), which are essential to deliver the Sustainable Development Goals (SDGs), including SDG 7 on clean energy access, and enhance the adaptive capacity to climate change.

**Box 4.8, Table 1 |** Estimated annualized world mitigation investment needed to limit global warming to 2°C or 1.5°C (2015–2035 in trillions of USD at market exchange rates) from different sources. The top four lines indicate the results of Integrated Assessment Models (IAMs) as reported in Chapter 2 for their Baseline, Nationally Determined Contributions (NDC), 2°C- and 1.5°C-consistent pathways. These numbers only cover the energy sector and the second row includes energy efficiency in all sectors. The final two rows indicate the mitigation investment needs for the energy, transport and other infrastructure according to the Organization for Economic Co-operation and Development (OECD) for a Baseline pathway and a 2°C-consistent pathway. Sources: IEA, 2016c; OECD, 2017a.

| | Energy Investments | Of which Demand Side | Transport | Other Infra-structures | Total | Ratio to MER GDP |
|---|---|---|---|---|---|---|
| IAM Baseline (mean) | 1.96 | 0.24 | | | 1.96 | 1.8% |
| IAM NDC (mean) | 2.04 | 0.28 | | | 2.04 | 1.9% |
| IAM 2°C (mean) | 2.19 | 0.38 | | | 2.19 | 2.1% |
| IAM 1.5°C (mean) | 2.32 | 0.45 | | | 2.32 | 2.2% |
| IEA NDC | 2.40 | 0.72 | | | 2.40 | 2.3% |
| IEA 1.5°C | 2.76 | 1.13 | | | 2.76 | 2.7% |
| **Mean IAM-IEA, 1.5°C** | **2.38** | **0.54** | | | **2.38** | **2.53%** |
| Min IAM-IEA, 1.5°C | 1.38 | 0.38 | | | 1.38 | 1.6% |
| Max IAM-IEA, 1.5°C | 3.25 | 1.13 | | | 3.25 | 4.0% |
| OECD Baseline | | | | | 5.74 | 5.4% |
| OECD 2°C | 2.13 | 0.40 | 2.73 | 1.52 | 6.38 | 6.0% |

The mean incremental share of annual energy investments to stay well below 2°C is 0.36% (between 0.2–1%) of global GDP between 2016 and 2035. Since total world investment (also called 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. As the higher ends of these ranges reflect pessimistic assumptions in 1.5°C-consistent pathways on technological change, the implementation of policies to accelerate technical change (see the remainder of Section 4.4.5) could lower the probability of higher incremental investment.

If we assume the amounts of investments given by the OECD for transportation and other infrastructure for warming of 2°C to be a lower limit for an 1.5°C pathway, then total incremental investments for all sectors for a 1.5°C-consistent pathway would be estimated at 2.4% of total world investments. This total incremental investment reaches 2.53% if the investments in transportation are scaled up proportionally with the investments in the energy sector and if all other investments are kept constant. Comparing this 2.4% or 2.53% number for all sectors to the 1.5% number for energy only (see previous paragraph) suggests that the investments in sectors other than energy contribute significantly to incremental world investments, even though a comprehensive study or estimate of these investments for a 1.5°C limit is not available.

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

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*Box 4.8 (continued)*

reduction would be 0.8% if we account for the investment needs of all infrastructure sectors. Assuming conversely a constant savings ratio, this would necessitate 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 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 (World Bank, 2018b), 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 and 7% on equity, leading to a weighted mean return on 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 yearly 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 limit 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).



Investments in other (non-energy system) infrastructure to meet development and poverty-reduction goals can strengthen the adaptive capacity to address climate change, and are 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 mobilization 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 between 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 realizing 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 trigger a new growth cycle (Stern, 2013, 2015). In this case, a massive mobilization of low-emission investments would 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 envelope of worldwide marginal abatement costs for 1.5°C-consistent pathways reported in Chapter 2 is 135–5500 USD2010 $tCO_2^{-1}$ in 2030 and 245–13000 USD2010 $tCO_2^{-1}$ in 2050, which is between three to four 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 (see Section 4.3.1) (OECD, 2017c). Yet there are multiple constraints to a system-wide energy transition. Lower costs of some supply- and demand-side options do 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, the inertia of market structures, cultural habits and 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 and amplify overall production costs. During the early stage of a low-emission transition, an increase in the prices of non-energy goods could reduce consumer purchasing power and final demand. A rise in energy prices has a proportionally greater impact in developing countries that are in a catch-up phase, as they have a stronger 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, in remote areas, and in 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 (Baumgärtner et al., 2017).

A second matter of concern is the distortion of international competition and employment implications in the 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, 2015a; 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 about 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) minimizing 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 maximizing 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 strengths and weaknesses, from a 1.5°C perspective, policy tools would have to be both scaled up and better coordinated in packages in a synergistic manner.

#### 4.4.5.2 Carbon pricing: necessity and constraints

Economic literature has long argued that climate and energy policy grounded only 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).

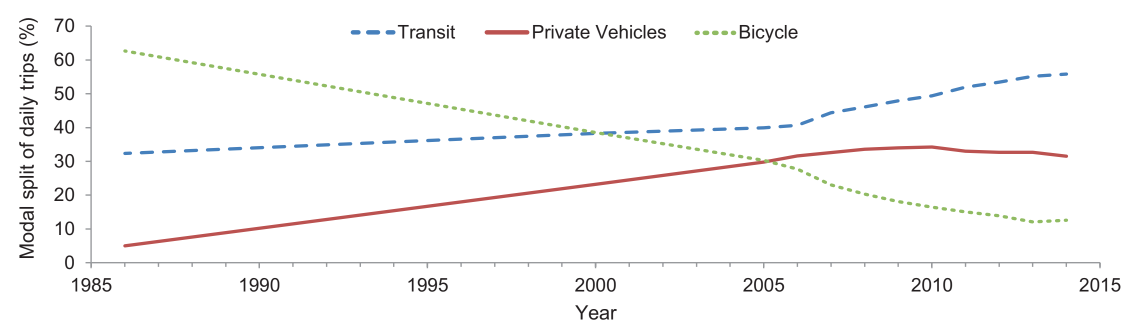
In a frictionless world, a uniform world carbon price could minimize the social costs of the low-carbon transition by equating the marginal costs of abatement across all sources of emissions. This implies that investors will be able to make the right choices under perfect foresight and that domestic and international compensatory transfers offset the adverse distributional impacts of higher energy prices and their consequences on economic activity. In the absence of such transfers, carbon prices would have to be differentiated by jurisdiction (Chichilnisky and Heal, 2000; Sheeran, 2006; Böhringer et al., 2009; Böhringer and Alexeeva-Talebi, 2013). This differentiation could in turn raise concerns of distortions in international competition (Hourcade et al., 2001; Stavins et al., 2014).

Obstacles to enforcing a uniform world carbon price in the short run would not necessarily crowd out explicit national carbon pricing, for three reasons. First, a uniform carbon price would limit an emissions rebound resulting from 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 would compensate for 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

## Box 4.9 | Emerging Cities and 'Peak Car Use': Evidence of Decoupling in Beijing

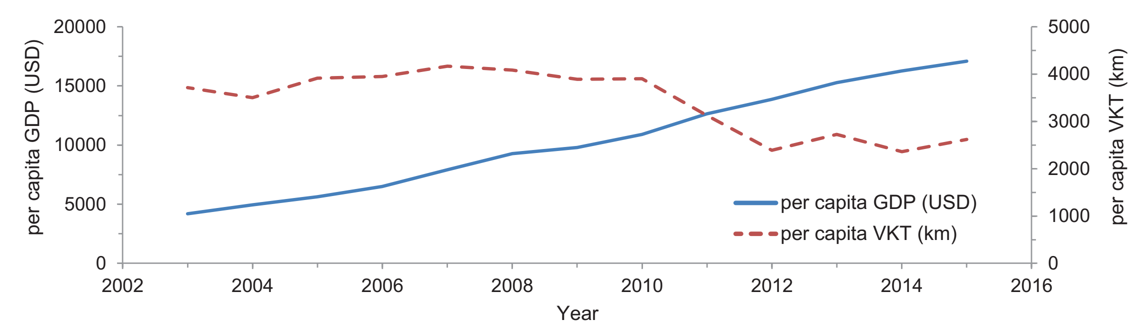
The phenomenon of 'peak car use', or reductions in per capita car use, provides hope for continuing reductions in greenhouse gases from oil consumption (Millard-Ball and Schipper, 2011; Newman and Kenworthy, 2011; Goodwin and Van Dender, 2013). The phenomenon has been mostly associated with developed 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 motorization was a result of strong economic growth, fast urban development and the prosperity of the Chinese automobile industry (Gao et al., 2015). However, recent data (Gao and Newman, 2018) (expressed as a percentage of daily trips) suggest the first signs of a break in the growth of car use along with the growth in mass transit, primarily the expansion of Metro systems (see Box 4.9, Figure 1).




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

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 the growth in vehicle kilometres of travel (VKT) has decoupled absolutely from GDP as shown in Box 4.9, Figure 2 below.




**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).

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 (Combet, 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 incentivizing low-carbon behaviour and mitigating the adverse distributional consequences of higher energy prices (Combet 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 specifically critical in the context of the 1.5°C limit (Michaelowa et al., 2018). 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 $tCO_2^{-1}$ (World Bank, 2016). This is too low to outweigh the 'noise' from the volatility of oil markets (in the range of 100 USD $tCO_2^{-1}$ 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), these subsidies represent 25–30% of government expenditures 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 remain a necessary condition of ambitious climate policies, and some authors highlight the potential benefit brought by coordination among groups of countries (Weischer et al., 2012; Hermwille et al., 2017; Keohane et al., 2017). They could take the form of carbon pricing corridors (Bhattacharya et al., 2015). They are a necessary 'lubricant' through fiscal reforms or direct compensating transfers 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' (Drèze 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., the USA, Japan, Korea, Australia, the EU) and, more recently, in developing countries (M.J. Scott et al., 2015; Brown et al., 2017). Such instruments include 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 per gallon or level of $CO_2$ emission per kilometre) have been used in the transport sector, for light- and heavy-duty vehicles, which have spillovers for the global car industry. In the EU (Ajanovic and Haas, 2017) and the USA (Sen et al., 2017), vehicle manufacturers need to meet an annual $CO_2$ 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 locking rapidly urbanizing countries into 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 incentivize 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 coordination 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-Álvarez 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 implemented 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 Río, 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 (e.g., for cars), have had a neutral impact on public budgets by incentivizing low-emission products and penalizing 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 of 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 globalization (Krugman, 2009; Rajan, 2011) and the chronic underinvestment 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, which was qualified by the Governor of the Bank of England as a 'tragedy of the horizon' (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 155 billion USD (BNEF, 2018). 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 question 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 (CISL, 2015; Schoenmaker and van Tilburg, 2016).

The readiness of financial actors to reduce investments in fossil fuels is a real trend (Platinga and Scholtens, 2016; Ayling and Gunningham, 2017), but they may not resist the attractiveness of carbon-intensive investments in many regions. Hence, decarbonizing 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 other sectors (10 to 15) (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 with uncertain future revenues due to volatility of fossil fuel prices (Roques et al., 2008; Gross et al., 2010) as well as uncertainty around regulatory policies. This inhibits low-emission investments by corporations functioning under a 'shareholder value business regime' (Berle and Means, 1932; Roe, 1996; Froud et al., 2000) and actors with restricted access to capital (e.g. cities, local authorities, SMEs and households).

De-risking policy instruments to enable low-emission investment encompasses 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 increase the leverage effect of public financing on private financing. Such de-risking instruments imply indeed 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 (Bellassen 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' recognized by the COP 21 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.

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

[10] One prototype is the World Bank's Pilot Auction Facility on Methane and Climate Change

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, which 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 context 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 focused 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 (UNEP/Climate Analytics, 2015) they would be higher than the UNEP estimate of 22.5 billion USD of bilateral and multilateral funding for climate change adaptation in 2014. Currently, 18–25% of climate finance flows to adaptation in developing countries (OECD, 2015b, 2016; 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 SDGs 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 sharing 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; Adenle 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 synergistically 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 the combination of policy instruments that address three domains of action: behavioural changes, economic optimization and 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).

4

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 (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 banks (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 the 4.5–5.4 trillion USD $yr^{-1}$ 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, and 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 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 part of global systems under transition that make up 1.5°C-consistent pathways.

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), overarching adaptation options (Section 4.3.5) and carbon dioxide removal (CDR) options (Section 4.3.7). This is done to assess the multidimensional 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 categorized as 'resilience of power infrastructure'.

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

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 of 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 4.SM.4.2 and 4.SM.4.3. 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 4.SM.4.1 for the averaging and weighing guidance).

The results are summarized 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 mixed or moderate but still existent barriers, and light shading indicates that multiple barriers, in this dimension, may block implementation.

A three-step process of independent validation and discussion by authors was undertaken to make this assessment as robust as possible within the scope of this Special Report. It must, however, be recognized 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. Some contextual factors are indicated in the rightmost column in Tables 4.11 and 4.12.

**Table 4.10 |** Sets of indicators against which the feasibility of adaptation and mitigation options are assessed for each feasibility dimension. The options are discussed in Sections 4.3.1-4.3.5 and 4.3.7.

| Feasibility Dimensions | Adaptation Indicators | Mitigation Indicators |
|---|---|---|
| **Economic** | Microeconomic viability<br>Macroeconomic viability<br>Socio-economic vulnerability reduction potential<br>Employment & productivity enhancement potential | Cost-effectiveness<br>Absence of distributional effects<br>Employment & productivity enhancement potential |
| **Technological** | Technical resource availability<br>Risks mitigation potential | Technical scalability<br>Maturity<br>Simplicity<br>Absence of risk |
| **Institutional** | Political acceptability<br>Legal & regulatory feasibility<br>Institutional capacity & administrative feasibility<br>Transparency & accountability potential | Political acceptability<br>Legal & administrative feasibility<br>Institutional capacity<br>Transparency & accountability potential |
| **Socio-cultural** | Social co-benefits (health, education)<br>Socio-cultural acceptability<br>Social & regional inclusiveness<br>Intergenerational equity | Social co-benefits (health, education)<br>Public acceptance<br>Social & regional inclusiveness<br>Intergenerational equity<br>Human capabilities |
| **Environmental/Ecological** | Ecological capacity<br>Adaptive capacity/ resilience building potential | Reduction of air pollution<br>Reduction of toxic waste<br>Reduction of water use<br>Improved biodiversity |
| **Geophysical** | Physical feasibility<br>Land use change enhancement potential<br>Hazard risk reduction potential | Physical feasibility (physical potentials)<br>Limited use of land<br>Limited use of scarce (geo)physical resources<br>Global spread |

### 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 synthesizes the assessment of the enabling conditions in Section 4.4.

#### 4.5.2.1 Assessing 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 summarized in Table 4.11. An explanation of the approach is given in Section 4.5.1 and in supplementary material 4.SM.4.1. 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 4.SM.4.2.

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. This Special Report did not have the mandate, space or the literature base to undertake a regionally specific assessment. Hence the assessment is caveated as providing a broad indication of the likely global barriers, ignoring significant regional diversity. Regional and context-specific literature is also just emerging as is noted in the knowledge gaps section (Section 4.6). Nevertheless, in Table 4.11, an indicative attempt has been made to capture relevant contextual information. The 'context' column indicates which 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 energy, so solar irradiation is mentioned in this column.

#### 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 actions relate to people's values. This section synthesizes 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 multilevel and engaging different actors, while being efficient, and choosing the form 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

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**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 indicating that, on average, the dimension does not have a positive or negative effect on the feasibility of the option, or the evidence is mixed, and faint shading the presence of potentially blocking barriers. No shading means that the literature found was not sufficient to make an 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 were different. For the methodology and literature basis, see supplementary material 4.SM.4.1 and 4.SM.4.2.
Abbreviations used: Ec: Economic - Tec: Technological - Inst: Institutional - Soc: Socio-cultural - Env: Environmental/Ecological - Geo: Geophysical

| System | Mitigation Option | Evidence | Agreement | Ec | Tec | Inst | Soc | Env | Geo | Context |
|---|---|---|---|---|---|---|---|---|---|---|
| Energy System Transitions | Wind energy (on-shore & off-shore) | Robust | Medium | | | | | | | Wind regime, economic status, space for wind farms, and the existence of a legal framework for independent power producers affect uptake; cost-effectiveness affected by incentive regime |
| | Solar PV | Robust | High | | | | | | | Cost-effectiveness affected by solar irradiation and incentive regime. Also enhanced by legal framework for independent power producers, which affects uptake |
| | Bioenergy | Robust | Medium | | | | | | | Depends on availability of biomass and land and the capability to manage sustainable land use. Distributional effects depend on the agrarian (or other) system used to produce feedstock |
| | Electricity storage | Robust | High | | | | | | | Batteries universal, but grid-flexible resources vary with area's level of development |
| | Power sector carbon dioxide capture and storage | Robust | High | | | | | | | Varies with local $CO_2$ storage capacity, presence of legal framework, level of development and quality of public engagement |
| | Nuclear energy | Robust | High | | | | | | | Electricity market organization, legal framework, standardization & know-how, country's 'democratic fabric', institutional and technical capacity, and safety culture of public and private institutions |
| Land & Ecosystem Transitions | Reduced food wastage & efficient food production | Robust | High | | | | | | | Will depend on the combination of individual and institutional behaviour |
| | Dietary shifts | Medium | High | | | | | | | Depends on individual behaviour, education, cultural factors and institutional support |
| | Sustainable intensification of agriculture | Medium | High | | | | | | | Depends on development and deployment of new technologies |
| | Ecosystems restoration | Medium | High | | | | | | | Depends on location and institutional factors |
| Urban & Infra structure System Transitions | Land-use & urban planning | Robust | Medium | | | | | | | Varies with urban fabric, not geography or economy; requires capacitated local government and legitimate tenure system |
| | Electric cars and buses | Medium | High | | | | | | | Varies with degree of government intervention; requires capacity to retrofit "fuelling" stations |
| | Sharing schemes | Limited | Medium | | | | | | | Historic schemes universal, but new ones depend on ICT status; undermined by high crime and low levels of law enforcement |
| | Public transport | Robust | Medium | | | | | | | 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 |
| | Non-motorized transport | Robust | High | | | | | | | Viability rests on linkages with public transport, cultural factors, climate and geography |
| | Aviation & shipping | Medium | Medium | | | | | | | Varies with technology, governance and accountability |
| | Smart grids | Medium | Medium | | | | | | | Varies with economic status and presence or quality of existing grid |
| | Efficient appliances | Medium | High | | | | | | | Adoption varies with economic status and policy framework |
| | Low/zero-energy buildings | Medium | High | | | | | | | Depends on size of existing building stock and growth of building stock |

*Table 4.11 (continued)*

| System | Mitigation Option | Evidence | Agreement | Ec | Tec | Inst | Soc | Env | Geo | Context |
|---|---|---|---|---|---|---|---|---|---|---|
| Industrial System Transitions | Energy efficiency | Robust | High | | | | | | | Potential and adoption depend on existing efficiency, energy prices and interest rates, as well as government incentives |
| | Bio-based & circularity | Medium | Medium | | | | | | | Faces barriers in terms of pressure on natural resources and biodiversity. Product substitution depends on market organization and government incentivization |
| | Electrification & hydrogen | Medium | High | | | | | | | Depends on availability of large-scale, cheap, emission-free electricity (electrification, hydrogen) or $CO_2$ storage nearby (hydrogen). Manufacturers' appetite to embrace disruptive innovations |
| | Industrial carbon dioxide capture, utilization and storage | Robust | High | | | | | | | High concentration of $CO_2$ in exhaust gas improve economic and technical feasibility of CCUS in industry. $CO_2$ storage or reuse possibilities |
| Carbon Dioxide Removal | Bioenergy and carbon dioxide capture and storage | Robust | Medium | | | | | | | Depends on biomass availability, $CO_2$ storage capacity, legal framework, economic status and social acceptance |
| | Direct air carbon dioxide capture and storage | Medium | Medium | | | | | | | Depends on $CO_2$-free energy, $CO_2$ storage capacity, legal framework, economic status and social acceptance |
| | Afforestation & reforestation | Robust | High | | | | | | | Depends on location, mode of implementation, and economic and institutional factors |
| | Soil carbon sequestration & biochar | Robust | High | | | | | | | Depends on location, soil properties, time span |
| | Enhanced weathering | Medium | Low | | | | | | | Depends on $CO_2$-free energy, economic status and social acceptance |

to applying general-purpose technologies to mitigation purposes. If this is not managed, some reduction in emissions 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 create innovation capabilities in all countries that allow them to operate, maintain, adapt and regulate a portfolio of mitigation technologies. Case studies in the various subsections highlight the opportunities and challenges of doing this in practice. They indicate that it can be done in specific circumstances, which can be created.

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

Governments could benefit from enhanced carbon prices, as a price and innovation incentive and also a source of additional revenue to correct distributional effects and subsidize 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 incentivize 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, regulatory financial institutions, such as central banks, could intervene.

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, 2016). 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).

Operationalizing 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)

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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 summarizes 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 4.SM.4.3 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 prioritization. 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 generalizing these findings.

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

Table 4.12 summarizes 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).

When considered jointly, the description of adaptation options (Section 4.3), the feasibility assessment (summarized 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 such energy system transitions 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 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 multilevel governance that focuses on resilience components can help secure these transitions (Exner et al., 2016).

For land and ecosystem transitions, the options of 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 having *medium evidence* and *high agreement* to face scaling barriers. Scaling community-based adaptation may require structural changes, implying the need for transformational adaptation in some regions. This would involve enhanced multilevel 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

**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 indicating that, on average, the dimension does not have a positive or negative effect on the feasibility of the option, or the evidence is mixed, and light shading indicating the presence of potentially blocking barriers. No shading means that sufficient literature could not 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 4.SM.4.
Abbreviations used: Ec: Economic - Tec: Technological - Inst: Institutional - Soc: Socio-cultural - Env: Environmental/Ecological - Geo: Geophysical

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

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), and necessitates a focus on governance structures and the inclusion of equity and justice concerns (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 (Rosenzweig and Solecki, 2014; Radhakrishnan et al., 2018), for example, urban adaptation pathways were implemented in the aftermath of Superstorm 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 trade-offs (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 sharing 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 organizations, 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 (Reckien et al., 2014; Araos et al., 2016a, b; Austin et al., 2016; Heidrich et al., 2016; Lesnikowski et al., 2016; Robinson, 2017). In response to a need for global, regional and local adaptation, the development of indicators and standardized approaches to evaluate and compare adaptation over time and across regions, countries, and sectors would enhance comparability and learning. A number of constraints continue to hamper progress on adaptation M&E, including a debate on what actually constitutes adaptation for the purposes of assessing progress (Dupuis and Biesbroek, 2013; Biesbroek et al., 2015), an absence of comprehensive and systematically collected data on adaptation to support longitudinal assessment and comparison (Ford et al., 2015b; Lesnikowski et al., 2016), a lack of agreement on indicators to measure (Brooks et al., 2013; Bours et al., 2015; Lesnikowski et al., 2015), and challenges of attributing altered vulnerability to adaptation actions (Ford et al., 2013; Bours et al., 2015; UNEP, 2017a).

### 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 4.SM.5.1 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 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 4.SM.5.2 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 can 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 them.

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, multilevel 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 nexus 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 (Villarroel 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; 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 maximizing 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).

### 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), improving its economic growth (gross domestic product, GDP) and maintaining its 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 & GNH, 2016). Like most emerging countries, Bhutan wants to increase its wealth and become a middle-income country (RGoB, 2013, 2016), while remaining carbon-neutral – a goal which has been in place since 2009 at COP15 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 its resilience and adaptation strategy.

Nevertheless, Bhutan faces rising GHG emissions. Transport and industry are the largest growth areas (NEC, 2011). Bhutan's carbon-neutral status would be threatened by 2044 with 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 GNHI (Michaelowa et al., 2018) through synthesizing all three goals and improving its adaptive capacity.

## 4.6 Knowledge Gaps and Key Uncertainties

The global response to limiting warming to 1.5°C is a new knowledge area, which has emerged after the Paris Agreement. This section 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 trade-offs. Illustrative questions that emerge synthesizing the more comprehensive Table 4.13 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 organized within a global governance framework and financial system, based on principles of justice and ethics (CBDR-RC), reciprocity and partnership? To what extent would limiting warming to 1.5°C require a harmonization of macro-financial and fiscal policies, which 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.

4

**Table 4.13 |** Knowledge gaps and uncertainties

| Knowledge Area | | Mitigation | Adaptation | Reference |
|---|---|---|---|---|
| 1.5°C Pathways and Ensuing Change | | • Lack of literature specific to 1.5°C on investment costs with detailed breakdown by technology<br>• Lack of literature specific to 1.5°C on mitigation costs in terms of GDP and welfare<br>• Lack of literature on distributional implications of 1.5°C compared to 2°C or business-as-usual at sectoral and regional levels<br>• Limited 1.5°C-specific case studies for mitigation<br>• 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<br>• Lack of literature on what overshoot means for adaptation<br>• Lack of knowledge on avoided adaptation investments associated with limiting warming to 1.5°C, 2°C or business-as-usual<br>• Limited 1.5°C-specific case studies for adaptation<br>• Scant literature examining current or future adaptation options, or examining what different climate pathways mean for adaptation success<br>• Need for transformational adaptation at 1.5°C and beyond remains largely unexplored | 4.2 |
| Options to Achieve and Adapt to 1.5°C | Energy Systems | • The shift to variable renewables that many countries are implementing is just reaching a level where large-scale storage systems or other grid 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<br>• 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<br>• 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 | • Relatively little literature on individual adaptation options since AR5<br>• No evidence on socio-cultural acceptability of adaptation options<br>• Lack of regional research on the implementation of adaptation options | 4.3.1 |
| | Land & ecosystems | • More knowledge would be needed on how land-based mitigation can be reconciled with land demands for adaptation and development<br>• While there is now more literature on the underlying mechanisms of land transitions, data is often insufficient to draw robust conclusions, and there is uncertainty about land availability<br>• The lack of data on social and institutional information (largest knowledge gap indicated for ecosystems restoration in Table 4.11), which are therefore not widely integrated in land use modelling<br>• 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<br>• There is relatively little scientific literature on the effects of dietary shifts and reduction of food wastage on mitigation, especially regarding the institutional, technical and environmental concerns | • Regional information on some options does not exist, especially in the case of land-use transitions<br>• Limited research examining socio-cultural perspectives and impacts of adaptation options, especially for efficient irrigation, coastal defence and hardening, agroforestry and biodiversity management<br>• Lack of longitudinal, regional studies assessing the impacts of certain adaptation options, such as conservation agriculture and shifting to efficient livestock systems<br>• 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, or on employment and productivity enhancement potential for biodiversity management and coastal defence and hardening.<br>• More knowledge is needed on risk mitigation and the potential of biodiversity management<br>• Lack of evidence of the political acceptability of efficient livestock systems<br>• *Limited evidence* on legal and regulatory feasibility of conservation agriculture and no evidence on coastal defence and hardening<br>• For transparency and accountability potential, there is *limited evidence* for conservation agriculture and no evidence for biodiversity management, coastal defence and hardening and sustainable aquaculture<br>• No evidence on hazard risk reduction potential of conservation agriculture and biodiversity management | 4.3.2 |
| | Urban & infrastructure systems | • *Limited evidence* of effective land-use planning in low-income cities where tenure and land zoning are contested, and the risks of trying to implement land-use planning under communal tenure<br>• *Limited evidence* on the governance of public transport from an accountability and transparency perspective | • Regional and sectoral adaptation cost assessments are missing, particularly in the context of welfare losses of households, across time and space<br>• 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 | 4.3.3 |

*Table 4.13 (continued)*

| Knowledge Area | | Mitigation | Adaptation | Reference |
|---|---|---|---|---|
| Options to Achieve and Adapt to 1.5°C | Urban & infrastructure systems | • *Limited evidence* on relationship between toxic waste and public transport<br>• *Limited evidence* on the impacts of electric vehicles and non-motorized urban transport, as most schemes are too new<br>• As changes in shipping and aviation have been limited to date, limited evidence of social impacts<br>• Knowledge about how to facilitate disruptive, demand-based innovations that may be transformative in urban systems, is needed<br>• Understanding of the urban form implications of combined changes from electric, autonomous and shared/public mobility systems, is needed<br>• Considering distributional consequences of climate responses is an on-going need<br>• 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<br>• The potential for leapfrog technologies to be applied to slums and new urban developments in developing countries is weak. | • More evidence would be needed on hot-spots, for example the growth of peri-urban areas populated by large informal settlements<br>• Major uncertainties emanate from the lack of knowledge on the integration of climate adaptation and mitigation, disaster risk management, and urban poverty alleviation<br>• There is *limited evidence* on the institutional, technological and economic feasibility of green infrastructure and environmental services and for socio-cultural and environmental feasibility of codes and standards<br>• In general, there is no evidence for the employment and productivity enhancement potential of most adaptation options.<br>• There is *limited evidence* on the economic feasibility of sustainable water management | 4.3.3 |
| | Industrial systems | • Lack of knowledge on potential for scaling up and global diffusion of zero- and low-emission technologies in industry<br>• 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<br>• 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<br>• Life-cycle assessment-based comparative analyses of CCUS options are missing, as well as life-cycle information on electrification and hydrogen<br>• Impacts of industrial system transitions are not well understood, especially on employment, identity and well-being, in particular in the case of substitution of conventional, high-carbon industrial products with lower-carbon alternatives, as well as electrification and use of hydrogen | • *Very limited evidence* on how industry would adapt to the consequences of 1.5°C or 2°C temperature increases, in particular large and immobile industrial clusters in low-lying areas as well as availability of transportation and (cooling) water resources and infrastructure<br>• There is *limited evidence* on the economic, institutional and socio-cultural feasibility of adaptation options available to industry | 4.3.4 |
| | Overarching adaptation options | • There is no evidence on technical and institutional feasibility of educational options<br>• There is *limited evidence* on employment and productivity enforcement potential of climate services<br>• There is *limited evidence* on socio-cultural acceptability of social safety nets<br>• There is a small but growing literature on human migration as an adaptation strategy. Scant literature on the cost-effectiveness of migration | | 4.3.5 |
| | Short-lived climate forcers | • *Limited evidence* of co-benefits and trade-offs of SLCF reduction (e.g., better health outcomes, agricultural productivity improvements)<br>• 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 | | 4.3.6 |

*Table 4.13 (continued)*

| Knowledge Area | | Mitigation | Adaptation | Reference |
|---|---|---|---|---|
| Options to Achieve and Adapt to 1.5°C | Carbon dioxide removal | • A bottom-up analysis of CDR options indicates that there are still key uncertainties around the individual technologies. Ocean-based options will be assessed in depth in the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)<br>• Assessments of environmental aspects are missing, especially for 'newer' options like enhanced weathering or direct air carbon capture<br>• 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 modelling of 1.5°C pathways<br>• 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 incentivization<br>• Knowledge gaps on integrated systems of renewable energy and CDR technologies such as enhanced weathering and DACCS<br>• Knowledge gaps on under which conditions the use of captured $CO_2$ is generating negative emissions and would qualify as a mitigation option | | 4.3.7 |
| Solar radiation modification (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 measures but also concerning ethical issues<br>• We do not know how to govern SRM in order to avoid unilateral action and how to prevent possible reductions in mitigation ('moral hazard') | | 4.3.8 |
| Enabling Conditions | Governance | • As technological changes have begun to accelerate, there is a lack of knowledge on new mechanisms that can enable private enterprise to mainstream this activity, and reasons for success and failure need to be researched<br>• Research is thin on effective multilevel governance, in particular in developing countries, including participation by civil society, women and minorities<br>• Gaps in knowledge remain pertaining to partnerships within local governance arrangements that may act as mediators and drivers for achieving global ambition and local action<br>• Methods for assessing contribution and aggregation of non-state actors in limiting warming to 1.5°C<br>• Knowledge gap on an enhanced framework for assessment of the ambition of NDCs | • 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<br>• Limited empirical assessment of how governance affects adaptation across cases<br>• Focus on 'success' stories and leading adaptors overlooks lessons from situations where no or unsuccessful adaptation is taking place | 4.4.1 |
| | Institutions | • Lack of 1.5°C-specific literature<br>• Role of regulatory financial institutions and their capacity to guarantee financial stability of economies when investments potentially face risks, both because of climate impacts and because of the systems transitions if lower temperature scenarios are pursued<br>• Knowledge gaps on how to build capabilities across all countries and regions globally to implement, maintain, manage, govern and further develop mitigation options for 1.5°C.<br>• While importance of indigenous and local knowledge is recognized, the ability to scale up beyond the local remains challenging and little examined<br>• There is a lack of monitoring and evaluation (M&E) of adaptation measures, with most studies enumerating M&E challenges and emphasising the importance of context and social learning. Very few studies evaluate 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 modelling. Adaptation M&E is additionally challenged by limited understanding on what indicators to measure and how to attribute altered vulnerability to adaptation actions | | 4.4.2 |
| | 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<br>• Limited knowledge on GHG emissions reduction potential of diverse mitigation behaviour across the world<br>• 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 is typically on enabling individual behaviour change, far less on enabling change in organizations and political systems | • Knowledge gaps on factors enabling adaptation behaviour, except for behaviour in agriculture.<br>• Little is known about cognitive and motivational factors promoting adaptive behaviour.<br>• Little is known about how potential adaptation actions might affect behaviour to influence vulnerability outcomes | 4.4.3 |

*Table 4.13 (continued)*

<table>
<tr><th colspan="2">Knowledge Area</th><th>Mitigation</th><th>Adaptation</th><th>Reference</th></tr>
<tr><td rowspan="5">Enabling Conditions</td><td rowspan="2">Lifestyle and behavioural change</td><td colspan="2">• Limited understanding and treatment of behavioural change and the potential effects of related policies in ambitious mitigation pathways, e.g., in Integrated Assessment Models</td><td rowspan="2">4.4.3</td></tr>
<tr><td colspan="2">Lack of insight on what can enable changes in adaptation and mitigation behaviour in organizations and political systems</td></tr>
<tr><td>Technological innovation</td><td colspan="2">• 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<br>• Evidence on the role of international organizations, including the UNFCCC, in building capabilities and enhancing technological innovation for 1.5°C, except for some parts of the transport sector<br>• Technology transfer trials to enable leapfrog applications in developing countries have limited evidence</td><td>4.4.4</td></tr>
<tr><td>Policy</td><td>• More empirical research would be needed to derive robust conclusions on effectiveness of policies for enabling transitions to 1.5°C and on which factors aid decision-makers seeking to ratchet up their NDCs</td><td>• Understanding of what policies work (and do not work) is limited for adaptation in general and for 1.5°C in particular, beyond specific case studies</td><td>4.4.5</td></tr>
<tr><td>Finance</td><td colspan="2">Knowledge gaps persist with respect to the instruments to match finance to its most effective use in mitigation and adaptation</td><td>4.4.5</td></tr>
<tr><td colspan="2">Synergies and Trade-Offs Between Adaptation and Mitigation</td><td colspan="2">• 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<br>• Water–energy conservation relationships of individual conservation measures in industries other than the water and energy sectors have not been investigated in detail<br>• There is no evidence on synergies with adaptation of CCS in the power sector and of enhanced weathering under carbon dioxide removal<br>• 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<br>• There is no evidence of synergies or trade-offs with mitigation of CbA<br>• There is no evidence of trade-offs with mitigation of the built environment, on adaptation options for industrial energy, and climate services</td><td>4.5.4</td></tr>
</table>

4

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 pre-industrial 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 with adapting to the consequences.*

There are actions across all sectors that 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 mobilize investment), but also on social/cultural conditions (e.g., awareness and acceptability) and institutional conditions (e.g., political support and understanding).



To limit warming to1.5°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*);

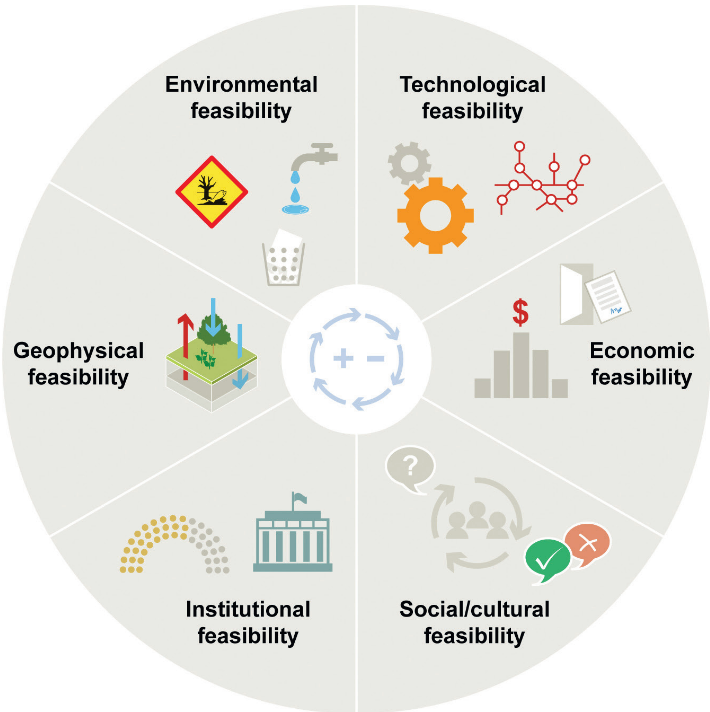
*FAQ 4.1 (continued)*

(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: **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 4.1, Figure 1 | The different dimensions to consider when assessing the 'feasibility' of adaptation and mitigation options or actions within each system that can help to limit warming to 1.5°C.** These are: (i) the environmental feasibility; (ii) the technological feasibility; (iii) the economic feasibility; (iv) the social/cultural feasibility; (v) the institutional feasibility; and (vi) the geophysical feasibility.

4

Frequently Asked Questions

## FAQ 4.2 | What are Carbon Dioxide Removal and Negative Emissions?

***Summary:*** *Carbon dioxide removal (CDR) refers to the process of removing $CO_2$ from the atmosphere. Since this is the opposite of emissions, practices or technologies that remove $CO_2$ 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 $CO_2$. 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 $CO_2$ directly from the ambient air and store it elsewhere (e.g., 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 pre-industrial 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 $CO_2$ 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 decarbonize, 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 $CO_2$ to bring global temperature back down. To achieve this temperature reduction, the amount of $CO_2$ 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 stabilizing atmospheric $CO_2$ concentration – and, therefore, global temperature – at a certain level. The larger and longer an overshoot, the greater the reliance on practices that remove $CO_2$ from the atmosphere.

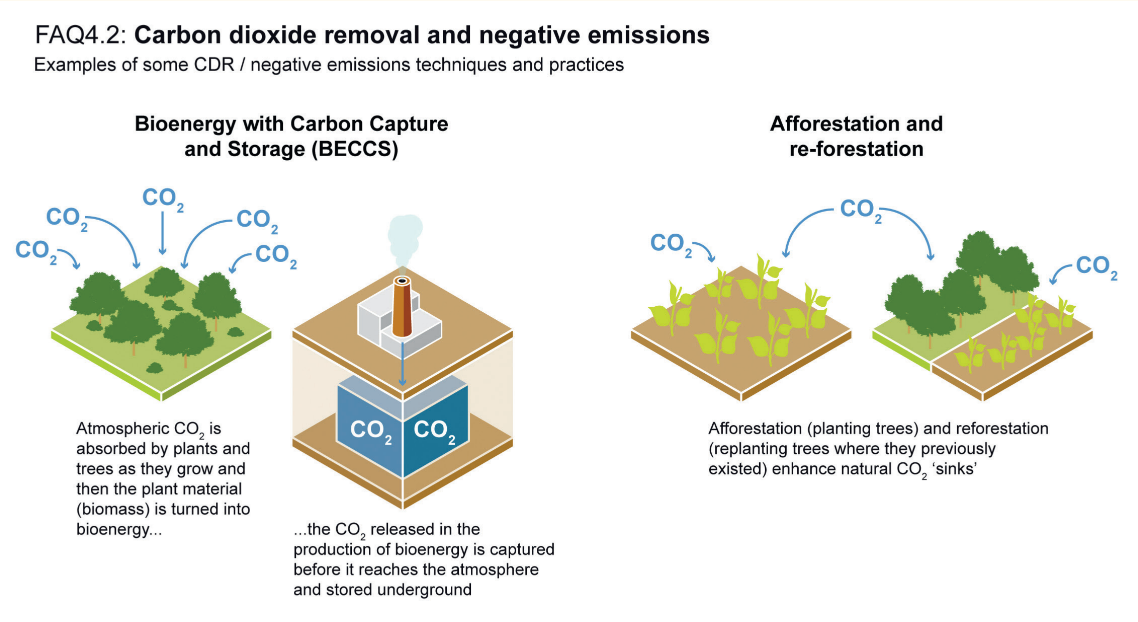
There are a number of CDR methods, each with different potentials for achieving negative emissions, as well as different associated costs and side effects. They are also at differing levels of development, with some more conceptual than others. One example of a CDR method in the demonstration phase is a process known as bioenergy with carbon capture and storage (BECCS), in which atmospheric $CO_2$ is absorbed by plants and trees as they grow, and then the plant material (biomass) is burned to produce bioenergy. The $CO_2$ released in the production of bioenergy is captured before it reaches the atmosphere and stored in geological formations deep underground on very long time scales. Since the plants absorb $CO_2$ as they grow and the process does not emit $CO_2$, the overall effect can be to reduce atmospheric $CO_2$.



Afforestation (planting new trees) and reforestation (replanting trees where they previously existed) are also considered forms of CDR because they enhance natural $CO_2$ 'sinks'. Another category of CDR techniques uses chemical processes to capture $CO_2$ from the air and store it away on very long time scales. In a process known as direct air carbon capture and storage (DACCS), $CO_2$ 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 $CO_2$ 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 $CO_2$ from the air requires considerable energy.

*FAQ 4.2 (continued)*




**FAQ 4.2, 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.

Frequently Asked Questions

## FAQ 4.3 | Why is Adaptation Important in a 1.5°C-Warmer World?

***Summary:*** *Adaptation is the process of adjusting 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 the current 1°C above pre-industrial levels to 1.5°C, and beyond, increases the need for adaptation. Therefore, stabilizing global temperatures at 1.5°C above pre-industrial levels would require a smaller adaptation effort than at 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 pre-industrial 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 change 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 by 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 pre-industrial temperatures would increase the need for adaptation. Stabilizing 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, there are 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. However, 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.

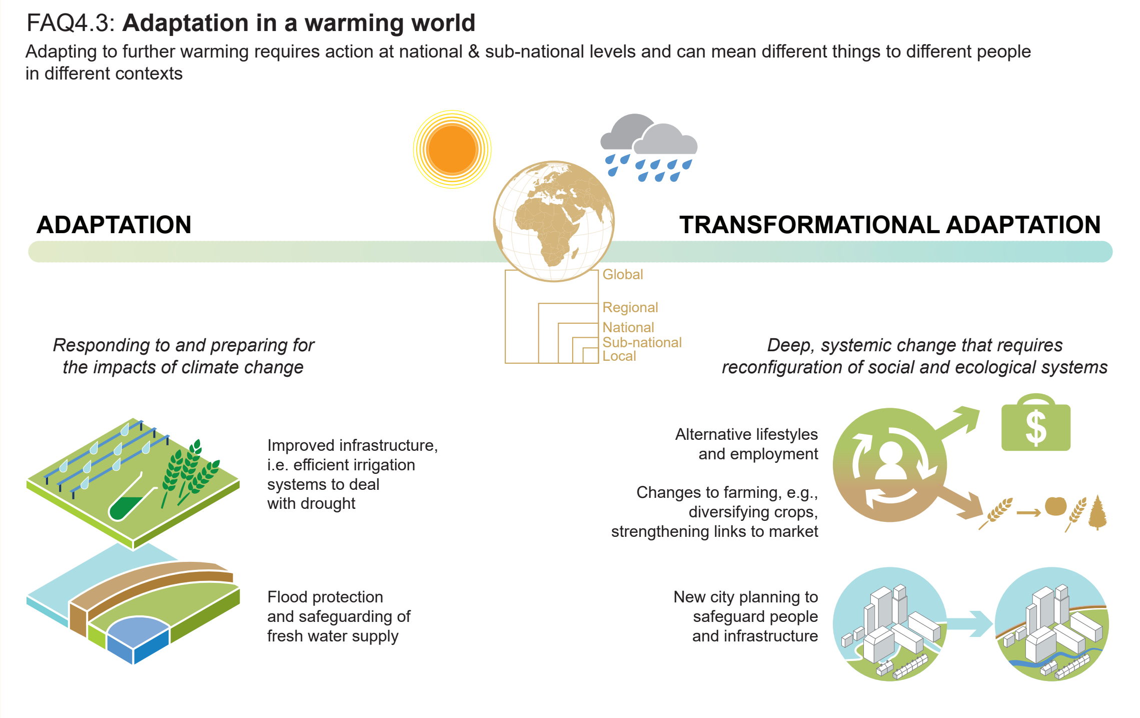


When done successfully, adaptation can allow individuals to adjust to the impacts of climate change in ways that minimize negative consequences and to maintain their livelihoods. This could involve, for example, a farmer switching to drought-tolerant crops to deal with increasing occurrences of heatwaves. 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 rise 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 would not 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 are 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).

*FAQ 4.3 (continued)*

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.




**FAQ 4.3, Figure 1 | Why is adaptation important in a world with global warming of 1.5°C?** Examples of adaptation and transformational adaptation. Adapting to further warming requires action at national and sub-national levels and can mean different things to different people in different contexts. While transformational adaptation would not 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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