Chapter 4: Strengthening and implementing the global response

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Executive Summary

The transition and adaptation to a 1.5°C world would require upscaling and accelerating the implementation of far-reaching, multi-level and cross-sectoral climate mitigation and adaptation actions, integrated with sustainable development initiatives {Chapter 2; 4.2.1} (*high agreement, medium evidence*)**.** While transitional change in energy efficiency, carbon intensity of fuels, electrification and land use change is underway, it will require a greater scale and pace to be transformational. Current national pledges on mitigation and adaptation are inadequate to stay below the Paris Agreement temperature limits and achieve its adaptation goals {Cross-Chapter Box 4.1}.

Multiple examples from around the world illustrate that climate-resilient, inclusive, prosperous and healthy societies are possible. At the same time, very few cities, regions, countries, businesses or communities are truly in line with 1.5°C pathways at scale (*medium agreement, medium evidence*)**.** Increased ambition, greater awareness of adaptation needs, better insights in synergies and trade-offs between adaptation and mitigation options via value chains, and enhanced capabilities are all integral for 1.5ºC. Necessary institutional arrangements include: robust legal and regulatory frameworks, trustworthy and equity-enhancing financial institutions, alignment of government and business institutions, transparent and accountable monitoring processes, and collaborative transnational networks across scales and regions. {Case studies in 4.4; 4.4.1; 4.4.2; 4.4.6}

To strengthen implementation of global responses, all countries would need to significantly raise their level of ambition, shift financial flows, improve coherence in governance, address equity across and between generations and regions, and build capabilities, including in using traditional, Indigenous and local knowledge. All countries face many challenges to this. In many developing countries, particularly amongst poor and vulnerable people, it will require financial, technological and other forms of support to build capacity for effective climate governance and implementation, for which current local, national and international resources are insufficient (*medium agreement, high evidence*) {4.4.1; 4.4.2; 4.4.6}. Public and financial institutional and innovation capabilities are currently falling short of implementing far-reaching measures at scale *(high confidence)*. Multinational networks supporting multi-level climate action are growing, but challenges in scaling-up remain {4.4.2; 4.4.4; case studies in 4.4}.

Adaptation needs will be lower in a 1.5°C as compared to a 2°C world. While transformational adaptation is necessary under current (~1°C) warming conditions in some regions, adaptation limits are expected to be exceeded in multiple systems and regions in a 1.5ºC world, putting large numbers of poor and vulnerable people, systems and regions at risk (*medium evidence)* {Cross-Chapter Box 4.4}. 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 {4.4.6} can help their mainstreaming within sustainable development practices. Preventing maladaptation {Cross-Chapter Box 4.3}, drawing on bottom-up approaches {Box 4.6}, and using Indigenous knowledge {Box 4.3} are examples of adaptation that effectively engage vulnerable communities. While adaptation finance volumes have increased quantitatively, they remain insufficient; and qualitative gaps in distribution, and monitoring mechanisms undermine their potential to reduce impact {Chapter 3; 4.4.6; 4.5.1}.

Rates of change of emissions found in the modelling of emission pathways for remaining below 1.5°C have been observed historically {4.2.2.1}. The geographical and economic scales of the required energy, land, urban and industrial transitions to a 1.5°C world, however, are larger and have no documented historic precedents. Such transitions require more planning, coordination and disruptive innovation across actors and scales of governance than the changes observed in the past (*medium agreement, medium evidence*)**.** Mitigation actions with the potential for staying below 1.5°C and adaptation options that allow for coping with a 1.5°C world are related. Whether the simultaneous systems transitions jointly succeed depends on behaviour and lifestyle changes, faster innovation, effective governance and policies; and innovative fiscal and financing arrangements. {4.2; 4.2.2; 4.4}

Governance compatible with 1.5°C worlds may be able to create an enabling environment for mitigation and adaptation options, behavioural change and innovation, and be aligned with the

political economy of both adaptation and mitigation (*medium agreement, medium evidence*)**.** For 1.5°C action, useful governance elements include: accountable multi-level governance (including non-state actors such as industry, civil society and scientific institutions), coordinated sectoral and cross-sectoral policies to create collaborative multi-stakeholder partnerships, greater public awareness and improved education, monitoring and evaluation systems, reciprocal international agreements that take into account equity and SDGs and financial architecture to enable unhindered access to finance and technology, and address climate-related trade barriers. {4.4; 4.4.1}

Changes in behaviour and lifestyles are essential for a transition to 1.5°C. Policy and finance actors may find their actions more cost-effective and acceptable if multiple factors affecting behaviour are considered (*high agreement, medium evidence*)**.** Behaviour- and lifestyle-related measures have led to limited emission reductions around the world *(high confidence)*. Changing lifestyles and behaviour can result in greater participation in governance for the 1.5°C transition through bottom-up initiatives that, in turn, help gather political and public support for further-reaching mitigation and adaptation, creating a virtuous circle. {4.4.1; 4.4.3, Figure 4.4}

Public and political support for climate policy may be mobilised by aligning it with other policy objectives and with people's core values. Packages of policy instruments, working across governance levels and promoting innovation, are needed to implement a rapid and far-reaching response *(medium agreement, medium evidence).* Policy instruments, both price and non-price, are needed to accelerate the deployment of carbon-neutral technologies as long as the market continues to prefer fossil fuel-based technology for a variety of reasons. Evidence and theory suggests that some form of carbon pricing is a necessary but insufficient part of the mix *(medium agreement).* {4.4.3; 4.4.4; 4.4.5}

1.5°C-compatible worlds are impossible without active involvement of the financial sector, including central and multilateral banks, as front-loading of investments compared to current actions is unavoidable (*medium agreement, medium evidence*)**.** If this is to happen, building institutional capacity to handle both climate and transition risks in the mainstream financial sector in all countries would be needed. Reducing financial risks for low-emission technologies and adaptation actions, and enabling redirection of world savings and other capital away from investment that would become stranded from both an impact and a mitigation perspective, are indispensable for 1.5ºC worlds. Potential instruments that promote low-emission assets and/or adaptation investment include public guarantees and reducing risk-weighted capital costs. {4.4.6}

The energy transition is taking place in many sectors and regions around the world, but follows a slower pace in energy-intensive industry and international transport (*high agreement, medium evidence*)**.** In solar energy, onshore wind energy and energy storage systems, a transformation seems to be underway. The political, economic, social and technical feasibility of solar and onshore wind energy has improved dramatically over the past few years, and electricity storage technologies, relevant for intermittent renewables as well as electric vehicles are rapidly getting more feasible. In industry, the options that lead to deep emissions reductions consistent with 1.5°C are limited by institutional, economic and technical constraints, and pose high financial risks for firms. Efficiency and CCS technologies are less economically risky, closer to implementation for major industrial sectors, and enable significant emission reduction, but in the long run are not sufficient to stay below 1.5ºC. Adaptation measures, including power infrastructure resilience and water management, will be increasingly important for power and energy systems *(high agreement)* {4.3.2; 4.3.5}.

Global and regional land-use and ecosystem transitions to stay below 1.5°C will see impacts on agricultural and natural resource-dependent livelihoods {Chapter 3} but, in combination with changes in behaviour, can enhance future mitigation. However, if not managed carefully, they could be associated with significant changes in agriculture and forest systems that that threaten ecosystem equilibrium, and would lead to critical food, water and livelihood security challenges, which limit their social and environmental feasibility (*medium agreement, medium evidence*)**.** {4.3.3; 4.5.3}

Changing agricultural practices using principles of conservation agriculture, efficient irrigation, and mixed crop-livestock systems are effective adaptation strategies {4.3.3, 4.5.3}. There is *high evidence* to suggest that mixed crop-livestock production systems can be cost effective adaptation strategies, both in developing countries and developed agriculture systems. Improving irrigation efficiency is an effective means of dealing with changing water endowments globally. This might be better realised by farmers adopting efficient irrigation techniques through behavioural change, as opposed to large-scale infrastructure (*medium evidence*) {4.3.3}. Depending upon the context and vulnerability of specific communities, community-based adaptation can be an effective adaptation option and decreasing food waste would be an effective mitigation and adaptation measure (*high confidence*){4.3.3, 4.5.3}. Behavioural change around diets as well as sustainable intensification would reduce emissions and pressure on land {4.4.5; 4.5.2}.

Rapid, systemic transitions in urban areas will be a defining element of an accelerated transition to a 1.5°C world. Such deep, structural changes can be enabled by a rapidly implemented, integrated mix of mitigation and adaptation measures, led by local and regional governments, and supported by national governments, aligned with sustainable and economic development. Various mitigation options, such as accelerating urban electrification and the penetration of renewables, lowering and decarbonising energy use in the built environment (especially buildings); demotorisation and decarbonisation of transportation systems; and deploying efficient appliances, are expanding rapidly across many geographies (*medium evidence, high agreement*). Both technological and social innovations in enabling technologies, including smart grids, energy storage technologies and general-purpose technologies such as ICT and artificial intelligence, can contribute to 1.5ºC pathways when managed to contribute to such a goal. Enabling green infrastructure, water and urban ecosystem services, adapting buildings and land use through regulation and planning are feasible adaptation options (*medium evidence, medium to high agreement*).

Several overarching adaptation options enable synergies across systemic transitions and can be implemented across rural and urban landscapes. Investing in health, social safety nets, and insurance for risk management are cost-effective with high potential to scale up {4.3.6, 4.5.3} (*high agreement*)**.** Disaster risk management and education-based adaptation options have lower prospects of scalability and cost-effectiveness (*high agreement, medium evidence*) but are critical for building adaptive capacity {4.3.6, 4.5.3}.

Combining adaptation and mitigation options can increase cost effectiveness, but multiple trade-offs limit the speed and potential to scale up. Examples of synergistic options include (i) agroforestry, ecosystem-based adaptation, efficient food production, afforestation and reforestation *(medium agreement)*; (ii) land-use planning, urban planning and urban design *(medium agreement)*; (iii) implementing building codes and standards to reduce energy use and manage risk *(high agreement)*; and (iv) alter urban form and reduce urban heat islands {4.3.3; 4.3.4}. Sustainable water management (*high evidence, medium agreement*), and investing in green infrastructure (*medium evidence, high agreement*) to deliver sustainable water and environmental services and support urban agriculture are less cost effective but important to build climate resilience {4.3.4}. However, even when reaping multiple benefits, governance, finance and social and policy support are often challenging when combining multiple objectives as timing also needs to be aligned {4.3.3; 4.4.1; 4.5.2; 4.5.3}.

Options to reduce short-lived climate pollutants (SLCPs), such as methane, black carbon and short-lived HFCs, can provide rapid emission reductions and unrivalled co-benefits such as health due to prevention of air pollution, which enhances political feasibility, but economic and social feasibility are more complex. If the energy, land and urban transitions mentioned above succeed, the emission of SLCPs will be greatly reduced. {4.3.7}

Options that lead to a removal of CO_2 from the atmosphere face multiple feasibility constraints. Therefore, the scale and speed of implementation required in the 1.5°C pathways in Chapter 2 are challenging (*high agreement*)**.** Among the carbon dioxide removal options, bioenergy with carbon capture and storage and afforestation and reforestation – the prominent CDR options in 1.5°C pathways - are technically feasible but face environmental, economic, institutional and social feasibility constraints (*medium agreement, medium evidence*)**.** The energy requirements and costs of direct air capture and storage and Enhanced Weathering are still high (medium agreement, medium evidence). Soil Carbon Sequestration bears important co-benefits (high agreement, high evidence). For other options such as ocean fertilisation there is no robust evidence that significant mitigation potentials can be achieved without severe environmental impacts posing grand challenges for governance.Other options are in early stages of development or need significant upgrading to be effective mitigation options. {4.3.8}

The uncertainties surrounding various solar radiation management measures, hereafter called radiation modification measures (RMMs), including technological immaturity, lack of physical understanding, efficiency to limit global warming, and ability to scale, govern and legitimise, constrain their responsible implementation. Even in the uncertain case that some of the most adverse side effects of RMMs can be avoided, governance issues, ethical implications, public resistance and impacts on sustainable development could render RMMs economically, socially and institutionally infeasible (*low agreement*, *medium evidence*)**.** {4.3.9; Cross-Chapter Box 4.2}.

Gaps in knowledge for implementing and strengthening the global response need to be resolved to facilitate the transition to a 1.5°C world. These include questions of how much can be realistically expected from innovation, behaviour and systemic political and economic changes in improving resilience and reducing emissions; the need for technical breakthroughs in fuels for industry and international transport; whether generalisable and practical principles of climate resilient governance can be identified; and realistic assessments of available land for multiple purposes, including mitigation {4.5.1}. A challenge remains how the convergence of climate and sustainable development policies can be organised within a global governance frame based on justice and ethic (CBDR) principles, reciprocity and partnership, and how different actors and processes in climate governance can reinforce each other to enable this {4.1; 4.4.1}.

4.1 Accelerating the global response to climate change

This chapter discusses opportunities and challenges associated with accelerating the redirection of the world economy and socio-ecological systems towards a 1.5°C world. Expected impacts at 1.5°C pose lesser challenges than those at higher levels of warming (see Chapters 3 and 5) but they are still significant and will have to be alleviated, when possible, by development responses and associated adaptation action. From a mitigation perspective, staying below 1.5°C means that the global response will need to be systemic, far-reaching and rapid. This chapter is about how to strengthen climate policies, enabling conditions and implementation in a synergetic manner with the goals of sustainable development, equity and justice.

Previous IPCC reports, especially AR5, outline measures to maximise economic efficiency and development efficacy while staying below a 2°C target. Many of these conclusions are valid for a 1.5°C target, but more and transformative systemic actions will need to be taken in the short - to medium-term. The social costs and benefits of meeting this temperature limit, depend critically on: (1) mobilizing low-emission technologies, knowledge and R&D to enable a global energy, land and urban transition; (2) enabling the building of adaptive capacity and responses, across key systems and geographies at risk before adaptation limits are crossed; (3) creating enabling global to local, governance, and finance conditions for wide spread institutional and behavioural change; (4) managing the economic impact (*e.g.*, employment, consumptions, savings and investment) of diverting resources towards the decarbonisation of production and consumption and transformative adaptation; and (5) addressing the ‘equity dilemma’ between generations, between the poor and the rich in most regions, and between developed and, emerging and developing economies.

The major difference between a transition to a 2°C world and a 1.5°C world is that the latter leaves almost no temporal flexibility for lags in implementation, unless massive penetration of cheap and environmentally sound carbon dioxide removal technologies becomes feasible and available in time. This implies an acceleration of structural changes from the local- to the global-level in development pathways and institutional systems in order to: (1) accelerate the realization of short-term development co-benefits of mitigation and adaptation action; (2) enhance the adaptive capacity of key systems at risk (*e.g.*, water, energy, food, biodiversity, urban, regional and coastal resources) to climate change impacts; (3) divert investments from current trends to avoid a lock-in into climate-vulnerable and emission-intensive development paths; (4) reinforce innovation processes, changes in lifestyles and spatial dynamics that will allow for deeper reductions in GHG emissions, together with long-term development benefits and universal improvements in quality of life, as envisaged under sustainable development; (5) establish enabling environments that address institutional, market and behavioural barriers to transformative changes.

A challenge posed by severe constraints in temporal flexibility is the need to rapidly reduce of the implementation gap between the stated aspirations of climate policies (*e.g.*, carbon pricing, regulatory measures, financial instruments, R&D, capacity building), their actual level and the level announced in the ‘nationally determined contributions’ (NDCs) at the heart of the Paris Agreement. Reducing this implementation gap cannot be done independent of the current conditions of the world economy, polity and society. 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.

Therefore, a 1.5°C transition needs to be immediately consistent with the universal implementation of the Sustainable Development Goals. This implies a shift in the production possibility frontier of the world economy. The global context since the turn of the century is an increasingly interconnected world, with the human population growing from the current 7.5 billion to over 9 billion by mid-century (United Nations, 2017). There has been a consistent growth of global economic output, wealth and trade with a significant reduction in extreme poverty. These are trends that could continue for the next few decades (Burt et al., 2014), as well as potentially fast developing new, disruptive information, nano- and bio-technologies. However, these trends co-exist with rising inequality, exclusion and social stratification and regions locked in poverty traps (Deaton, 2013; Piketty, 2014).

Moreover the aftermath of the 2008 financial crises generated a challenging environment on which leading economists and institutions have issued repeated alerts about the 'discontents of globalization' (Stiglitz, 2002), 'depression economics' (Krugman, 2009), an excessive reliance of export-led development strategies (Rajan, 2010), rising income inequality (Piketty, 2014), risks of 'secular stagnation' (Summers, 2016), and the 'saving glut' due to the failure of the financial intermediation to bridge the gap between cash balances and long-term assets (Arezki et al., 2016).

The challenge is therefore how to strengthen climate policies, instead of exacerbating, the 'fault lines' of the world economy (Rajan, 2010), by narrowing the current regional and sectoral gap between the 'propensity to save and the propensity to invest' (Summers, 2016). The 1.5°C challenge indicates where future savings could be redirected to: stimulating growth and employment over the short-term; and over the medium-termenhance productive, climate-resilient investments in sustainable infrastructures (Arezki et al., 2016); and improving resources management. They can also do so by aligning climate policy with other public policies (*e.g.*, fiscal, trade, industrial, monetary, urban planning, infrastructure, innovation) and thereby enabling greater access to basic needs and services, defined by the SDGs. This would be a hedge against unstable and dualistic growth, and against a further unsustainable consumption and concentration of wealth (Piketty, 2014).

Finally, reducing the development and climate policy implementation gap depends on an enabling international governance and financial architecture that enables access to finance and technology and helps address trade barriers. As the 1.5°C transition requires accelerated action, in multiple forms, across all world regions almost simultaneously, it cannot be reached with free-riding. Hence, a key governance challenge is how the convergence of voluntary climate and sustainable development policies can be organized thanks to a global 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 (Andonova et al., 2017; Gupta, 2014).

4.2 Pathways compatible with 1.5ºC: Starting points for strengthening implementation

4.2.1 Implications for implementation of pathways consistent with 1.5ºC

The feasibility assessment of mitigation and adaptation options that would play a role in a 1.5°C world (Section 4.3) and insights on strengthening the implementation of pathways towards 1.5°C worlds (Section 4.4) will rely on the 1.5°C pathways assessed in Chapter 2. Most of those pathways are based on the IAM literature (Rogelj et al., 2015, 2017a) although faster and more radical change of innovation and financial systems, lifestyles and behaviour, may be possible and will be discussed in Section 4.4.

The 1.5°C pathways reviewed in Chapter 2 are at or below the emissions pathways of RCP2.6 in AR5, and all feature temperature overshoot. Global emissions will need to move from the current ca. 50 $GtCO_2$-eq yr^{-1} to become net zero by mid-century and net negative thereafter. Additional emissions reductions required to move from a 2°C pathway to a 1.5°C world would largely be achieved by meeting 2050 policy targets in Table 4.1 as well as BECCS, management of land-use transitions and emergent technologies. Non-CO_2 GHGs, including SLCPs, may play a minor role in the additional transition since much of their mitigation potential is already exhausted in most 2°C scenarios, so limited additional emission reduction is possible via them, in 1.5°C pathways.

Current energy demand is 350 EJ yr^{-1}. In no 1.5°C scenario in 2100 does energy demand exceed 450 EJ yr^{-1}, compared to an average of 600 EJ yr^{-1} for 2°C. Hence, in the transition from 2°C to 1.5°C, very little room for growth in global final energy demand exists over the rest of the century (less than 100 EJ yr^{-1}). Human populations are expected to grow from the current 7.6 billion, with over 2.8 billion without clean cooking facilities and 1.1 billion without electricity (IEA, 2017b), to over 11 billion by 2100 (United Nations, 2017).

In terms of policy targets and technologies, the scenarios assessed in Chapter 2 commonly feature 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 (see Table 4.1). In particular, fossil-based electricity generation will be phased out earlier than for 2°C, low-carbon technologies must be ramped up faster, and the share of electricity in final energy rises more rapidly in 1.5°C - consistent scenarios.

Table 4.1: Median global sectoral policy targets consistent with 1.5ºC based on Section 2.4 for 2050. Increase of energy use in end-use sectors are due to higher production and overall demand. The columns "Decrease energy used compared to REF" and "Decrease energy use compared to 2ºC" indicate that considerable cuts in energy use are made compared to the reference scenario and to a 2ºC scenario.

Sector	**Policy target in 2050 in Chapter 2 compared to 2010**	**Decrease energy use compared to REF**	**Decrease energy use compared to 2°C**
Transport	22% increase in final energy use 36% share of low-emission energy (electricity, hydrogen, biofuels)	39%	17%
Buildings	20% reduction in final direct energy use 60% electrification	22%	8%
Industry	16% increase in final energy use 86% reduction coal use 36% electrification 0.8 – 1.8 $GtCO_2$ avoided yr^{-1} by CCS (median: 1.5)	28%	20%
Electricity	Almost zero-emission by 2050 (some coal/gas with CCS still allowed)	n.a.	n.a.
Agriculture	Depends greatly on land pathway Shift from deforestation to reforestation by the same magnitude as currently the case	n.a	n.a.

Two recent studies (IEA, 2017c; Kuramochi et al., 2017) have added more technological detail to the demand sector outcomes in Table 4.1. (IEA, 2017c) finds the greatest direct emission reductions in: industry in energy efficiency as well as innovative processes and CCS; in buildings through energy efficiency in water and space heating and space cooling, as well as appliances and lighting; and in transport in efficiency, modal shift and the increased use of biofuels. Kuramochi et al. (2017) emphasise short-term policy targets like: phasing out of fossil-fuel passenger car sale by 2035 and 2050; and halting net deforestation by 2025. Some scenario studies outside IAMs suggest deep cuts of GHGs by high penetration of solar PV (Creutzig et al., 2017) or 100% wind, water and solar energy by 2050 (Jacobson et al., 2017), although some of this work is contested (Clack et al., 2017).

4.2.1.1 Challenges and opportunities for mitigation along the reviewed pathways

Scale, speed and type of investment

There is high agreement in the literature that staying below 1.5°C would entail significantly greater transformation in terms of energy systems, lifestyles and greater deployment of resources and investments compared to the 2°C target (McCollum et al.). In the context of 2°C pathways, the total investment needed in low-emission energy systems are estimated to be USD 1.7–2.2 trillion yr^{-1}(Riahi et al., 2012). In the context of limiting warming to 1.5°C, the global supply-side investment on energy systems would require a marked upscaling to reach a mean level of 1.4 – 3.8 trillion USD yr^{-1} over 2016–2050 (McCollum et al.).

Not only the level of investment but also the type and speed of sectoral transformation will be impacted by the transition to 1.5°C pathways. The assessment of the IAM literature suggests that for 2010–2030, annual average low-carbon energy investments of USD 60–150 billion are needed for wind and USD 30–120 billion for solar in 1.5°C pathways compared to USD 50–90 billion for wind and USD 30–50 billion for solar in 2°C pathways. For 2030–2050, the annual average low-carbon energy investments are assessed to be USD 100–400 billion for wind and USD 100–600 billion for solar in 1.5°C pathways compared to USD 80–250 billion for wind and USD 90–250 billion for solar in 2°C pathways (Riahi et al., 2017a; Rogelj et al., 2017b).

Greater policy design and decision-making implications

1.5°C pathways raise the bar on the design and coordination of policy responses to effectively deal with the scale and pace of mitigation, finance, distributional implications as well as adaptation to climate impacts. Effective approaches proposed in the literature include: the utilisation of dynamic adaptive policy pathways (Haasnoot et al., 2013) to deal with distributional implications; feedback and transdisciplinary knowledge systems (Bendito and Barrios, 2016) to integrate mitigation with adaptation in the context of sustainable development.

Even with good policy design and effective coordination, the transition to 1.5°C may be associated with considerable costs. Chapter 2 reported (with a probability greater than 50%) that abatement costs, represented in their models by a carbon price, would increase by about three times under 1.5°C compared to 2°C in 2050 (Section 2.5.2: Figure 2.29). Su et al. (2017) showed that achieving 1.5°C will require tripling of carbon prices and doubling mitigation costs from 2030 to 2080 compared to the 2°C case. This does not account for the cost of avoided impacts with lower warming. 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).

Greater sustainable development implications

The literature has few studies on the relations between SSPs (the foundation of the IAM scenarios) and the SDGs (O'Neill et al., 2015; Riahi et al., 2017b), although a literature is emerging. Stechow et al. (2016) assessed the implications of 2°C pathways on key SDG indicators, suggesting that near-term policy choices of low-emission pathways have implications for the synergies and trade-offs across energy related SDGs in the medium and long term. Chapter 5 provides an in-depth assessment of the complexity and interfaces between 1.5°C pathways and sustainable development.

4.2.1.2 Implications for adaptation along the reviewed pathways

It is difficult to discern the implications of 2°C warming compared to 1.5°C warming on climate impacts and avoided adaptation investments at the global level from the IAMs reviewed in Chapter 2, due to uncertainties involved and climate variability in the model comparisons (James et al., 2017; Mitchell et al., 2017). Hence, evidence is limited and case and model specific, mostly from non-IAM literature (see Chapter 3).

Adaptation has limits; not all systems can adapt, and not all impacts can be reversed (see also Cross-Chapter Box 4.4). For example, in a scenario with an end-of-century warming of 2°C, virtually all tropical coral reefs are projected to be at risk of severe degradation due to temperature-induced bleaching from 2050 onwards (Schleussner et al., 2016), which is projected to reduce to about 90% in 2050 and to 70% by 2100 for a 1.5°C scenario (see also Cross-Chapter Box 4.4).

Precipitation-related impacts reveal distinct regional differences and hot-spots of change (Schleussner et al., 2016). Regional reduction in median water availability for the Mediterranean is projected to nearly double from 9% to 17% between 1.5°C and 2°C, while lengthening of regional dry spells would increase from 7 to 11%, which would have negative implications for agricultural yields depending on crop types and world regions. The study also predicts that compared to the year 2000, sea-level would rise by at least 50 cm by 2100 for 2°C scenarios, and about 40 cm for 1.5°C scenarios.

Similarly, a warming from 1.5°C to 2°C would lead to significant increases in temperature and precipitation extremes in most regions (Wang et al., 2017c). However, the projected changes in climate extremes under both warming levels are highly dependent on the emissions pathways, with different GHG/aerosol forcing ratios and GHG levels. Decreased maize yields and runoff, increased long-lasting drought, and more favourable conditions for malaria transmission are greatest over drylands if global warming were to rise from 1.5°C to 2°C (Huang et al., 2017).

4.2.2 Transitions and rates of change

4.2.2.1 Pace of the development and deployment of adaptation and mitigation

This section assesses rates of technological and societal change consistent with pathways to remain below 1.5°C, building on Chapter 2. Literature reveals two basic approaches to the question of whether rates of technological and societal change are realistic: expanding historical trends into the future (in both adaptation and mitigation), and matching historical trends with modelled outcomes (mitigation only). These, and their outcomes, are discussed here.

The first approach is the analysis, evaluation and extrapolation of historical trends into the future. Such studies in the mitigation field sometimes take a narrative approach, collecting, for instance, long-term data on energy use and sources, analysing the drivers of the patterns observed, and applying the results towards understanding the transition to a low-carbon world (Fouquet, 2016). In addition, such extrapolation is done using scenarios and models over relatively long time periods (typically several decades) assuming different growth rates and patterns (Clarke et al., 2014; Lamb and Rao, 2015).

A few studies analyse the closing of the emission gap when ambitious policy targets in single countries are implemented globally (Roelfsema et al.) and references therein. These suggest, consistent with Chapter 2, that there is medium evidence and high agreement that the 1.5ºC temperature limit will be exceeded, if historical patterns continue, including the most ambitious currently implemented policy targets.

In adaptation to a 1.5°C warmer world, transformations have been studied to help avoiding pitfalls (Fazey et al., 2016; Gajjar et al., 2018; Pelling et al., 2015). Such adaptation pathways in the context of sustainable development are discussed in Section 5.3. For implementation questions, adaptation pathways can help identify maladaptive actions (Gajjar et al., 2018; Juhola et al., 2016; Magnan et al., 2016) and encourage social learning approaches across multiple levels of stakeholders in sectors such as marine biodiversity and fresh water supply (Bosomworth et al., 2015; Butler et al., 2015a; van der Brugge and Roosjen, 2015).

The second approach analyses how mitigation technologies have developed over time and contrasts those patterns against quantitative models to understand how new technologies may develop in the future, and whether models are making sound assumptions (Höök et al., 2011). van Sluisveld et al. (2015), based on five Integrated Assessment Models (IAMs), tentatively conclude that when metrics are normalised to GDP (as opposed to other normalisation metrics such as primary energy), modelled rates of change of emissions over the course of the century are broadly consistent with past trends. Yet, this may not be the case for individual technologies, especially on the mid-term, and models are generally more conservative than historic data suggest (Wilson et al., 2013).

A typology of trajectories of technological change, abstracting from the specific speed of change, emphasises the possibility and effects of shocks and other types of discontinuous change (Geels and Schot, 2007). Further, energy transitions are associated with wider socio-economic transformations that are generally not represented in models (Geels et al., 2016a), which gives reason to believe that energy transitions could proceed much faster (Sovacool, 2016). An 'autonomous' rate of change, determined by political will and the willingness to see energy transitions as a 'political, social and cultural project' rather than just a techno-economic one (Kern and Rogge, 2016), gives reason for optimism. Most recently, Creutzig et al. (2017) confirmed this for solar energy.

The two approaches reflect different but complementary views on how the past affects the present and the future, and what is to be learned from history. When extrapolating trends, we assume that we can learn from the past to understand the future direction of technological change. When fitting historical growth patterns into models (the second approach), we assume that time has a cyclic character, that history can repeat itself, and that patterns of change in the past can predict, to some extent, patterns of change in the future. Assessments of the rate of change will vary accordingly, with extrapolating studies emphasising slow, difficult processes of change (Fouquet, 2016) and fitting studies pointing towards the possible high speed of changes (Wilson et al., 2013). Both approaches indicate that the speed of changes in the past have not necessarily been slower than the ones that 1.5°C pathways, including those assessed in Chapter 2, indicate.

4.2.2.2 Disruptive and socio-technical innovation, decoupling and behaviour change

Understanding rates of change requires knowledge of, and preferably modelling of disruptive innovation and the sources of robustness of the socio-technical systems, it disrupts. Disruptive innovations are technological changes that lead to significant system change (Christensen et al., 2015; Green and Newman, 2017a; Seba, 2014) that are very hard to predict by economists and modellers as economic feasibility is a limited predictor of the success of innovations (Geels et al., 2016a; Green and Newman, 2017b). The increase in roof-top solar and energy storage technology supported by digital technology, and the increase in passive housing and Net Zero Emissions buildings, may be disruptive innovations in several countries (Green and Newman, 2017b) that can leave firms and utilities with stranded assets as the transition created by the disruption happens very quickly (IPCC, 2014; Kossoy et al., 2015). Examples are 'unburnable oil' (McGlade and Ekins, 2015) and coal-fired power plant assets (Caldecott, 2017; Farfan and Breyer, 2017).

Technological change, disruptive or not, is associated with social change, such as the adoption of, different business models and governance systems, as well as some areas of cultural change (Freeman and Perez, 2000; Geels and Schot, 2007, 2010, Perez, 2003, 2009a, 2009b). This can explain how energy transitions are happening, showing how significant socio-technical aspects of change are, and will be in driving the transition to 1.5°C (Geels, 2014; Geels et al., 2016b). In addition, strategic niche management (Kemp et al., 1998) and functional approaches through technological innovation systems (Bergek et al., 2008; Hekkert et al., 2007) can help develop policy responses to innovation challenges (Caniëls and Romijn, 2009; Geels et al., 2017c; Kilkis, 2016).

Decoupling (Newman, 2017; von Weizsäcker et al., 2014) suggests that although economic growth has been strongly coupled to the use of fossil fuels, changes in technology and the economy can enable the decoupling of economic growth from a range of environmental issues, including the consumption of fossil fuels. Some argue that it will be a relative decoupling only, due to feedbacks like the rebound effect (Gillingham et al., 2013; Jackson and Senker, 2011).

Data for 2015 and 2016 show that greenhouse emissions decoupled absolutely (IEA, 2017f; Peters et al., 2017b). This has been driven by declines in both coal and oil use, which has been happening since the early 2000s in Europe, in the past seven years in the United States and Australia, and has begun in China (Newman, 2017). In 2017 decoupling reversed due to a drought in China and subsequent increase in the use of coal-fired power (Tollefson, 2017) though this is not expected to continue as China is phasing out coal rapidly (IEA, 2017c). The rate of decoupling depends on increases in efficiency (Dasgupta and Roy, 2017; Qi et al., 2016) as well as socio-technical and disruptive innovations and will need to increase rapidly if the 1.5°C challenge is to be met (Newman et al., 2017) as set out in the new 'sustainable development' scenario of the IEA (IEA, 2017c). Decoupling is also relevant at the city level (Swilling et al., 2013).
Chapter 2 reveals that pathways that are consistent with 1.5°C assume substantial reductions in energy demand and increases in energy efficiency, for which changes in behaviour and lifestyles are critical (Stern et al., 2016a). Moreover, public support affects the feasibility of mitigation and adaptation options as well as the viability of policy and system changes (Clayton et al., 2015; Drews and Bergh, 2016). Section 4.4.3 will elaborate on which behaviour-related climate actions are consistent with a 1.5°C worlds, which factors relate to such climate actions, and assesses which approaches have been effective and acceptable in encouraging climate action.

4.3 Assessment of current and emerging adaptation and mitigation options

4.3.1 Assessing feasibility of options for accelerated transitions

Chapter 2 showed that 1.5°C pathways involve immediate, scaled climate responses to reach zero emissions by 2060–2080. This section assesses the feasibility of the technologies, actions and measures that comprise those pathways. Following the framework developed in Chapter 1, economic and technological; institutional and socio-cultural; and environmental and geophysical feasibility are considered, and applied in Sections 4.3.2–4.3.9 below. Table 4.2: shows the sets of indicators against which the feasibility of individual adaptation and mitigation options is assessed.

Table 4.2: Sets of indicators against which the feasibility of adaptation and mitigation options in Sections 4.3.2–4.3.8 is assessed, for each of the feasibility dimensions. In Section 4.3.9, given the greater uncertainties, the radiation modification measures are only assessed against the characteristics.

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

It is important to consider how these dimensions of feasibility interact and how they are applied.

Responses that meet multiple feasibility dimensions and align adaptation and mitigation interventions with non-climate benefits can accelerate transitions and reduce risks and costs (Bergek et al., 2008; Geels et al., 2016b; Hekkert et al., 2007).Co-benefits such as gender equality and 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 (Hallegatte and Mach, 2016; Steg et al., 2015) and justice (Ziervogel et al., 2017) can enhance the feasibility of climate responses in specific contexts by removing barriers to climate action (Hallegatte and Mach, 2016; Pelling et al., 2018).

Mutually enforcing climate responses across multiple scales (Geels et al., 2017a; Jordan et al., 2015), involving multiple actors can increase competition, experimentation and learning and enhance the flow of information regarding impacts, which can support rapid and transformational change (Cole, 2015a; Geels et al., 2016b; Hallegatte and Mach, 2016; Peters et al., 2017b).

The feasibility of climate responses is dynamic and contingent upon enabling conditions (Adger, 2016; Pelling et al., 2018) (see Section 4.4.1), including geographic context (Lee et al., 2015; Terrapon-Pfaff et al., 2014) and culture (Tàbara and Ilhan, 2008). Since AR5, new estimates for the “emissions budget” associated with 2°C warming (Millar et al., 2017), rapidly changing technology costs (Alstone et al., 2015; Jonas et al., 2014; Kriegler et al., 2014; Peters et al., 2017b; REN21, 2017), new data on global damage functions including detailed studies of specific countries (Carlton and Hsiang, 2016; Hallegatte et al., 2016; Hsiang et al., 2017), new finance options for climate responses (Pauw, 2017) and the emergence of polycentric leadership of climate responses, notably subnational climate networks (Jordan et al., 2015), have enhanced the feasibility of 1.5°C pathways, challenging the assumption that ambitious decarbonisation and climate adaptation will impose additional economic and social costs (Gouldson et al., 2015; OECD, 2017a; Stiglitz et al., 2017).

The urgency implicit in 1.5°C warming pathways necessitates clarity on the readiness of climate responses (Peters et al., 2017b; Sovacool, 2016) and the ease with which they can be applied at scale (Hallegatte et al., 2016).

Feasibility assessments are enhanced where they consider different exposure to climate impacts and differences in attitudes towards the future, that arise from socio-economic status, gender and culture (Cartwright et al., 2013; Giraudet and Guivarch, 2016; Hallegatte et al., 2017; Hof et al., 2014; Kowarsch et al., 2017; Resnick et al., 2012).

In the context of uncertainty, retaining the capacity to respond to a wide range of climate change contingencies represents an important component of feasibility (Daron and Stainforth, 2013; Geels et al., 2017a; Hallegatte et al., 2012; Kalra et al., 2014; Kowarsch et al., 2017; Torvanger and Meadowcroft, 2011).

Systemic and dynamic climate responses introduce analytical complexity that confound standardisation and consensus building (Kowarsch et al., 2017; Markusson et al., 2012; Reyers et al., 2017), but can identify options and ambition beyond IAMs (Battiston et al., 2017; Daron et al., 2015) as well as new risks (Clarke et al., 2014; Sovacool, 2016; Tavoni et al., 2017).

4.3.2 Energy system transitions

This section discusses the feasibility, based on the indicators discussed in Section 4.3.1, of mitigation and adaptation options related to the energy transition. Only options consistent with 1.5°C and with significant changes in their feasibility compared to AR5 are discussed. This means that for options like hydropower and biomass, we refer mostly to AR5 for an assessment of their feasibility though some advances have been made. Demand-side options in the energy sector, including energy efficiency in buildings and transportation, are discussed in Section 4.3.4, and options around energy use in industry are discussed in Section 4.3.5.

4.3.2.1 Renewable energy

Renewable energy options include solar energy, wind energy, hydropower, geothermal energy, tidal and wave energy and osmotic energy. All these options have seen considerable advances over the years since AR5, but solar energy and onshore wind energy have had dramatic growth trajectories and according to the IEA (2017), are on track to contribute significantly to a 2°C pathway to 1.5°C scenarios. Ocean energy, hydropower, concentrated solar power, bio-energy, offshore wind and geothermal energy would all need to show faster growth rates to contribute significantly to a 1.5°C scenario (see Chapter 2).

The largest growth factor since AR5 has been the dramatic reduction in the cost of solar PV (REN21, 2017). Costs have continued to rapidly decrease, leading to costs of rooftop solar in combination with battery storage to be highly competitive in sunny areas such as Australia (Green and Newman, 2017b) and in many rural and developing areas (Szabó et al., 2016). Renewable energy in off-grid or mini-grid systems are becoming a mainstream solution to improve the welfare of people in developing countries, and have already provided many remote communities with electricity independence, allowing them to bypass the need for a transmission network and therefore remove the associated costs of installing and maintaining a network (Jiménez, 2017; Pueyo and Hanna, 2015). Small-scale distributed energy projects are now being implemented around the world (Aguiar et al., 2016) as well as in developed cities where residential and commercial rooftops offer high potential, for example in California they could provide two thirds of electricity use (Kurdgelashvili et al., 2016).

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 also in areas with lower solar insolation *e.g.* in North-Western Europe (Nyholm et al., 2017). Another important factor affecting feasibility is public acceptance, in particular for wind energy and other large-scale renewable facilities, though research indicates that financial participation and serious community engagement can be effective in mitigating resistance (Brunes and Ohlhorst, 2011; Rand and Hoen, 2017).

Studies estimating the use of renewable energy in the future, either at the global or at the national level, are plentiful and considerable debate exists on 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. The estimates depend greatly on the assumptions on costs and technological developments, as well as local geographical circumstances and the extent of storage used (Ghorbani et al., 2017; REN21, 2017). Disruptive innovation, as has been shown with roof-top solar, has led to considerably greater growth than expected and could change the modelling based on traditional assumptions (Green and Newman, 2017b). Several countries have adopted targets of 100% renewable electricity (IEA, 2017c).

4.3.2.2 Electricity storage

The growth in storage for renewables has been around grid flexibility resources that will enable several European places to, in the near future, reach more than half their power from non-hydro renewables (Komarnicki, 2016). Technologies for storage include pumped hydro (presently 150 GW) and grid-connected battery storage which grew between 2015 to 2016 by 50% to 1.7 GW (REN21, 2017). Battery storage has been the main growth feature in energy storage since AR5 (Breyer et al., 2017) due to significant cost reductions as mass production prepares for electric vehicles (EVs) (Dhar et al., 2017; Nykvist and Nilsson, 2015). Although costs and technical maturity look increasingly positive, the feasibility of battery storage is challenged by some concerns over the availability of resources and the environmental impacts of its production (Peters et al., 2017b). The production of lithium, a crustal element, 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 (DMP, 2016). Emerging battery technologies may provide even 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).

Synthetic gas, renewably derived, is increasingly being seen as a feasible storage option for renewables (producing gas for use in industry during times when solar and wind are optimal) though this is mostly still at lab scale (Bruce et al., 2010; Ezeji, 2017; Jiang et al., 2010). The use of EVs as a form of storage has been evaluated very positively (Dhar et al., 2017). Challenges to upscaling technologies like these into grids remain though demonstrations and modelling are now emerging (Dhar et al., 2017; Green and Newman, 2017a); socio-technical are increasingly being surmounted as the fossil fuel regime is destabilising (Geels et al., 2017c).

4.3.2.3 Carbon dioxide capture and storage in the power sector

The IPCC Special Report on CCS (IPCC, 2005) and the AR5 (IPCC, 2014) assign great mitigation potential to CCS in the power sector, in particular in coal-fired power but also in biomass (for a discussion of CCS in non-power industry, see Section 4.3.5; for a discussion of bio-energy with CCS (BECCS), see Section 4.3.8). CO_2 capture in the power sector, and transport and storage of CO_2 in general, however, face numerous barriers that reduce their feasibility, while apart from more cost-effective achievement of shorter- to mid-term emission reduction goals, it does not offer much in terms of co-benefits that might increase feasibility. Since 2017, two CCS projects in the power sector store 2.4 $MtCO_2$ annually, while 30 $MtCO_2$ are stored 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 over the past ten years due to limited learning in commercial settings and increased energy and resources costs (Rubin et al., 2015). Storage capacity estimates vary greatly, but de Coninck and Benson (2014) and Bui et al. () find *high agreement* in the literature that pore space exceeds the CO_2 storage amounts required in below 2°C pathways. On the order of thousands, perhaps ten thousand, $GtCO_2$ could be stored in underground reservoirs although regional availability 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). The social feasibility of CCS is considered low because of public acceptance issues. Though insights on communication of CCS projects to the general public and inhabitants of the area around the CO_2 storage sites (in order to increase public understanding of risks and consequence, and possibly prevent public resistance) have been documented over the years, decision-makers are not consistently implementing the lessons (Ashworth et al., 2015).

CCS in the power sector is hardly being realised at scale, mainly because the incremental costs of capture and the development of transport and storage infrastructures are not sufficiently compensated by market or government incentives (IEA, 2017c). In both full-scale demonstration projects in the power sector that have come online over the past years, part of the capture costs were compensated with revenues from Enhanced Oil Recovery (Global CCS Institute, 2017), a technique that uses CO_2 to mobilise more oil out of depleting oil fields, but that would lead to additional CO_2 emissions, the amount of which depends on the amount of additional oil recovered, and the lifecycle emissions of the oil it replaces (Cooney et al., 2015). In addition, several planned CCS projects in the power sector have been cancelled over the years, mainly because of economic reasons, or have experienced cost overruns (Global CCS Institute, 2017).

4.3.2.4 International transport options

International (or intercontinental) transport has so far been challenging to decarbonise due to the lack of an affordable and simple replacement fuel (Sims et al., 2014a). Aviation emissions could be reduced by between a third and two-thirds by energy efficiency measures (Dahlmann et al., 2016), and on shorter distances be replaced by low-carbon electricity-based high-speed trains (Åkerman, 2011). Some progress has been made on the use of electricity in planes and shipping (Grewe et al., 2017; Jacobson et al., 2017). But for deeper emission reductions and intercontinental travel, most studies indicate that biofuels are the most viable alternative, given their technical characteristics, energy content and affordability (Wise et al., 2017). However, the life-cycle emissions of such bio-based jet fuels and marine fuels can be considerable (Budsberg et al., 2016; Cox et al., 2014), depending on their location (Elshout et al., 2014).

In recent years the potential for synfuels, ethanol, methanol, methane created from renewably derived electricity and CO_2 has developed some momentum though they remain at laboratory scale and need to be demonstrated at a larger scale to contribute to the 1.5ºC agenda (Ezeji, 2017; Fasihi et al., 2017). There has been substantial research into low carbon shipping but the replacement of the world’s 60,000 large vessels is held up by governance barriers (Bows and Smith, 2012; IRENA, 2015; Rehmatulla and Smith, 2015). Removing marine fuels with zero-emission options will also clean up the sulphur and black carbon issues in ports and this can begin by electrifying all large ports (Bouman et al., 2017).

4.3.2.5 Options for adapting electricity systems to 1.5°C

The literature shows *high agreement* that climate change impacts need to be planned for in the design of any kind of infrastructure, especially for the energy sector (Nierop, 2014) and its interdependencies with other sectors that require electricity to function, including water, data, telecommunications, and transport (Fryer, 2017). Amongst the physical impacts that have been observed are 'flooding, silt and salt damage, scour of cabling and foundations, access problems, logistics disruptions, cable heave from uprooted trees, lightning damage, wind damage, higher cooling costs, and stress on components' (Fryer, 2017). The relationship between transmission grid, distribution grid, and microgrids in extreme events has been predominant (Liu et al., 2017) as well as resiliency in transmission and distribution grids are the ones that take longer to be restored after an extreme event (Panteli and Mancarella, 2015).

Recent research has developed new frameworks, models, and assessments that aim to help assess and identify vulnerabilities in energy infrastructure and create more proactive responses (Arab et al., 2015; Bekera and Francis, 2015; Erker et al., 2017; Francis and Bekera, 2014; Fu et al., 2017; Jeong and An, 2016; Knight et al., 2015; Ouyang and Dueñas-Osorio, 2014; Panteli et al., 2016). Independently of the variables and indicators that the different models propose, they emphasise the need for redundancy and the importance of analysing and assessing resiliency. In one case, Liu et al. (2017) introduced four resilience indices measuring impact of extreme events: number of lines on outage, probability of load not being fully supplied, expected demand that cannot be supplied, and difficulty level of grid recovery. The authors demonstrated that controllable and islandable microgrids can increase resiliency and should be an option looked at, especially after extreme weather events (Liu et al., 2017). In the case of minigrids, the case for solar photovoltaic energy has also been made as solar energy doesn't need to wait for the grid infrastructure to be restored and can enhance community resiliency as a back-up option, including through economic and social community resiliency (Qazi and Young Jr., 2014). The three resilience capacities (adaptive capacity, absorptive capacity, and recoverability) have been discussed as part of a resilience analysis framework consisting of system identification, resilience objective setting, vulnerability analysis, and stakeholder engagement (Francis and Bekera, 2014). Another model includes organisational and social resilience together with system restoration models (Ouyang and Dueñas-Osorio, 2014).

For hydroelectric plants, one of the main concerns is the decrease in reservoir reliability (Goytia et al., 2016; Jahandideh-Tehrani et al., 2014; Minville et al., 2009). Hybrid renewably-based power systems with non-hydro capacity, such as with high-penetration wind generation, would provide the required system flexibility (Canales et al., 2015).

Climate change has started to disrupt electricity generation and it is predicted these disruptions will be lengthier and more frequent (Bartos and Chester, 2015; Jahandideh-Tehrani et al., 2014; Kraucunas et al., 2015; van Vliet et al., 2016), if climate change adaptation options are not considered, both to secure vulnerable infrastructure and to ensure the necessary generation capacity (Cortekar and Groth, 2015; Eisenack and Stecker, 2012; Goytia et al., 2016; Minville et al., 2009; Murrant et al., 2015; Panteli and Mancarella, 2015; Schaeffer et al., 2012). Overall, there is *high agreement* that hybrid systems, taking advantage of an array of sources and time of use strategies, will help make electricity generation more robust (Parkinson and Djilali, 2015), given that energy security standards are in place (Almeida Prado et al., 2016).

Water scarcity patterns and electricity disruptions will differ across regions. There is *high agreement* that mitigation and adaptation options for thermal electricity generation and, if that remains based on fossil fuels, CCS, need to consider increasing water shortages. One option that both reduces emissions and lowers water needs is increasing the efficiency of power plants (Eisenack and Stecker, 2012; van Vliet et al., 2016). The technological, economic, social and institutional feasibility of that option is very high, though improving efficiency in fossil-fuelled thermoelectric power plants is 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 (Bartos and Chester, 2015; Bustamante et al., 2016; Chandel et al., 2011; Eisenack and Stecker, 2012; Murrant et al., 2015; van Vliet et al., 2016). There is *high agreement* on the technological, economical, and social feasibility of these new cooling technologies as the lack of proper water cooling technology and guidelines can severely impact the functioning of the power plant as well as safety and security standards. Water shortages are also leading to new technologies that can reduce water consumption, such as for bioenergy (Gerbens-Leenes et al., 2009; Yang et al., 2015).

More options for water management and other combinations of mitigation and adaptation challenges may be developed in the coming years, such as for CCS, bio-energy and nuclear energy, that can help plan for a more synergistic and robust energy sector (Schaeffer et al., 2012). Such options would create a more robust and sustainable energy sector and reduce uncertainty (Parkinson and Djilali, 2015). The integration of possible climate impacts in the planning and development of power projects will enable them to forecast future needs better (Bartos and Chester, 2015).

4.3.2.6 Nuclear energy

Bruckner et al. (2014) have given an extensive treatment of the technical, geophysical, environmental, economic and socio-cultural feasibility of nuclear energy. The degree to which nuclear energy can contribute to limiting temperature rise to 1.5°C is constrained by public concerns in specific countries, which relate to ultimate waste management and potential accidents. The 2011 Fukushima incident seems to have negatively influenced public perception in many places such as South Korea (Roh, 2017) but not China (Yuan et al., 2017). It has resulted in a ban on nuclear energy in countries like Germany, Italy, Sweden, Switzerland, South Korea and Taiwan.

The economic feasibility of nuclear energy has remained high in countries with monopolies or state-owned electricity systems but has decreased in countries that operate in an electricity market environment due to speed and scaling up issues (Schneider et al., 2017). Such market conditions in combination with susceptibility to “negative learning” (Grubler, 2010) as well as safety concerns have led utilities in several developed countries, even without an official ban, to essentially stop considering nuclear energy as an option, while in larger developing countries reactors are still coming online (Schneider et al., 2017). Some authors indicate that safety may be a larger issue in jurisdictions with limited institutional capacity and human capabilities (Budnitz, 2016). Some papers indicate that impacts of a nuclear accident would cross borders, but nuclear safety depends upon the sovereignty of nation-states (Budnitz, 2016; Meserve, 2009), raising the political feasibility question of a world governance of nuclear risks that goes beyond the facilitative role of the International Atomic Energy Agency (Finon, 2013).

4.3.3 Land and ecosystem transitions

This section assesses the feasibility of adaptation and mitigation options related to land-use and ecosystems that could play a role in the transition to a 1.5°C world. Land transitions are grouped around agriculture and food, ecosystems and forests, and coastal systems. At the end of this section, some cross-cutting and synergic issues are also examined.

4.3.3.1 Agriculture and food

In a 1.5°C world, local yields in tropical regions that are major food producing areas of the world (West Africa, South-East Asia, and Central and northern South America) are projected to reduce (Schleussner et al., 2016), while certain high-latitude regions may benefit. This is typically linked to concerns around: food production and quality, conservation agriculture, irrigation, climate services, food wastage, bioenergy, and the use of biotechnologies.

Food production and quality. Increased temperatures, including 1.5°C warming, would affect 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 on nutritional security (DaMatta et al., 2010; De Souza et al., 2015; Högy et al., 2009).

Meta-analyses of effects of droughts and elevated CO_2 and temperature levels conclude that at 2°C local warming, wheat, maize, and rice yield could decrease. This could be reduced if appropriate adaptation measures are taken (Challinor et al., 2014).

Climate resilient development pathways leading to a 1.5°C world need to ensure access to sufficient quality food (see Chapter 5). Three adaptation options can help assist this: conservation agriculture, irrigation efficiency and climate services. For mitigation options, reducing food waste, bio-energy and (bio)technology are assessed below.

Conservation agriculture. Behavioural shifts towards conservation agriculture refer to small changes in agricultural practices such as improving crop varieties, shifting planting times, and irrigation and residue management to increase wheat and maize yields by 7–12% (Challinor et al., 2014). Other analyses show that dietary shift towards low-impact foods, along with increases in agriculture efficiency, offer more environmental benefits than transforming conventional agriculture into organic agriculture or grass-fed beef

(Clark and Tilman, 2017).

A global meta-analysis using 5,463 paired yield observations from 610 studies across 48 crops and 63 countries compared no-till and conventional tillage practices (Pittelkow et al., 2014) and demonstrated that alone, no-till practices reduce yields. However, when combined with residue retention and crop rotation, it significantly increased crop productivity in rain-fed conditions. An expansion of these practices is already happening in Europe (Olesen et al., 2011). In other regions (e.g. Southern Africa and South Asia) (Lobell et al., 2008) this could be less feasible, unless more information about climate changes is available (Schlenker and Roberts, 2009).

Irrigation efficiency. The improvement of irrigation efficiency is critical to meet food security goals, and ensure agriculture viability by minimising the risk of decreasing water security. There is *high agreement* that improvement in irrigation efficiency must be supplemented with ancillary activities, such as shifting agriculture to crops that require less water, and improve soil and moisture conservation (Fader et al., 2016; Hong and Yabe, 2017; Sikka et al., 2017). Cho and McCarl (2017) modelled the influence of climate change in crop shifts in the US and found that most of them will have to be shifted. They assumed that under those conditions, farmers are risk-neutral price takers in cropland allocations. In South Africa, shifts are also expected to occur with climate change, with sugarcane being possibly substituted by other crops (Gbetibouo and Hassan, 2005).

Growing evidence suggests that investing in behavioural shifts towards using irrigation technology such as micro-sprinklers or drip irrigation, is an effective and fast adaptation strategy (Herwehe and Scott, 2017; Sikka et al., 2017; Varela-Ortega et al., 2016). Large dams were found to be less effective (Varela-Ortega et al., 2016) with high financial, ecological, and social costs. There is *high agreement* that improving irrigation efficiency must be supplemented with ancillary activities, such as shifting agriculture to focus on crops that require less water, and improving field soil and moisture conservation (Fader et al., 2016; Hong and Yabe, 2017; Sikka et al., 2017).

Climate services. Improved climate services can play a critical role in aiding adaptation decision making (Lourenço et al., 2015; Singh et al., 2017; Trenberth et al., 2016; Wood et al., 2014). However, 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). Technical, institutional, design-related, financial, and capacity barriers to the application of climate information for better adaptation decision-making remain (Briley et al., 2015; Harjanne, 2017; Jones et al., 2016b; Singh et al., 2017; White et al., 2017). Climate service interventions have met challenges with scaling-up due to low capacity, inadequate institutions, and difficulties in maintaining systems beyond pilot project stage (Gebru et al., 2015; Singh et al., 2016b).

Food wastage. The way food is produced, processed and transported drives greenhouse gas emissions. Around one-third of the food produced in the planet is not consumed (FAO, 2013) and the global volume of food waste is very high. Food wastage is a combination of food loss – decrease in mass and nutritional value of food due to poor infrastructure, logistics, and lack of technologies – and food waste that derives from inappropriate human consumption that lead to food spoil associated with inferior quality or overproduction. Whereas food demand is projected to increase by 60–110% between 2005 and 2050, it is likely that food wastage will lead to increase in emissions estimated to 1.9–2.5 $GtCO_2$-eq yr^{-1}(Hiç et al., 2016). Decreasing food wastage has a high mitigation and adaptation potential and is likely to play an important role in land transitions towards 1.5ºC (Foley et al., 2011). There is *medium agreement* that a combination of individual-institutional behaviour (Refsgaard and Magnussen, 2009; Thornton and Herrero, 2014), and technologies and managing (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.

Bioenergy. There is *high agreement* that sustainable bioenergy potentials in 2050 may be restricted to 100 EJ. Yr^{-1}(Creutzig et al., 2014; Slade et al., 2014). Bioenergy potential typically depends on yield, available land, technology deployment, grazing intensity and diet assumptions (Klein et al., 2014a). Sustainability concerns revolve especially around: competition around land for food production, preservation of ecosystems and biodiversity and potential water and nutrient constraints (Haberl, 2015; Smith et al., 2013; Williamson, 2016). In some regions of the world (e.g. the case of Brazilian ethanol) where the use of bioenergy is mature and industry is well developed, land transitions can potentially be balanced with food production and biodiversity to enable a global impact on CO_2 emissions (Jaiswal et al., 2017) (see Box 4.7 in Section 4.4.4). Although the uncertainty about the effects of bioenergy is high (Robledo-Abad et al., 2017), it has been proposed that large-scale bioenergy production is feasible and aligned with the global SDG agenda (Humpenöder et al., 2017).

(Bio)technologies. New molecular biology tools have been developed that can lead to fast and precise genome modification (De Souza et al., 2016; Scheben et al., 2016) (e.g., CRISPR Cas 9 (Ran et al., 2013; Schaeffer and Nakata, 2015). Such genome editing tools can assist in the adaptation of agriculture to climate change, due to CO_2 elevation, drought and flooding (DaMatta et al., 2010; De Souza et al., 2015, 2016). Developing new plant varieties that can adapt to 1.5°C transition and overshoot could avoid some of the costs of crop shifting (De Souza et al., 2016; Schlenker and Roberts, 2009).

Technological innovation can assist in increased agricultural efficiency (e.g. via precision agriculture), decreased food wastage, and genetics to enable plant transformation and greater adaptation potential, with differential feasibility (Section 4.4.4). Together, they may be able to increase the efficiency of contemporary agriculture to help produce enough food to cope with population increases and help reduce the pressure on natural ecosystems.

4.3.3.2 Ecosystems and forests

Around 45% of the terrestrial carbon and 50% of the net primary production occur in forests. Tropical forests matter for climate dynamics because of their strong evaporative cooling potential (Bonan, 2008). However, the carbon sink of the Amazon appears to be decreasing slowly due to the combined effect of increasing tree mortality and a reduction in net primary productivity. Although some positive conservation action has been taken (Aguiar et al., 2016), Amazonian tropical forests are disappearing due to direct human action, especially deforestation for agricultural land (see Amazon case in Cross-Chapter Box 4.3).

Forest management. The potential for sequestering atmospheric CO_2 in processes that restore degraded land globally has been explored as a transformative climate change intervention. Smith et al. (2007) report that restoring degraded grazing land could reduce atmospheric CO_2 by similar magnitudes as forest and crop interventions. In the tropics, a method for Atlantic forest restoration has been developed (Rodrigues et al., 2009) that can be coupled with bioenergy production (Buckeridge et al., 2012) providing significant synergy.

Innovations in livestock management, the use of fire regimes in savannah and rangeland ecology offer the potential to remove the trade-off between soil carbon restoration and high stocking densities (overgrazing). This can shift the balance of carbon in above-ground biomass, soil carbon and animal protein in support of CO_2 sequestration, reduced atmospheric CH_4 and sustainable development (Archibald and Hempson, 2016; Venter et al., 2017).

Benefits of certification include increased yields, income and capital (Fenger et al., 2017; Jena et al., 2017), but are not uncontested (Blackman and Rivera, 2011; Hidayat et al., 2015; Oya et al., 2017). The interactions between climate change and sustainability certifications are more often assessed (but mostly in passing) regarding bioenergy (Hennenberg et al., 2010; Kraxner et al., 2017; Miyake et al., 2012; Scarlat and Dallemand, 2011; Schlegel and Kaphengst, 2007; Stupak et al., 2011; van Dam et al., 2010) and in discussing the integration of climate change mitigation and adaptation concerns (Harvey et al., 2014; Locatelli et al., 2011). There is *limited evidence* on their potential contribution to achieve ambitious temperature targets.

Wetland management. In wetland ecosystems, temperature rise has direct and irreversible first order impacts on species functioning and distribution, ecosystem equilibrium and services, and second order impacts on local livelihoods (see Chapter 3). There is *high evidence*(Colloff et al., 2016; Finlayson et al., 2017; Wigand et al., 2017) on the adaptation potential of wetland management strategies, including adjustments in infrastructural, behavioural, and institutional practices. In coastal wetlands, strategies range from promoting resistance (e.g. arresting erosion through shoreline stabilisation), enhancing system resilience (e.g. restoring marsh drainage and sediment delivery), to system transformation such as migrating of species upland (Wigand et al., 2017).

Despite international policy initiatives on wetland restoration and management through the Ramsar Convention on Wetlands, there is *medium evidence* (with *high agreement*) that these 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 become increasingly necessary for effective wetland management (Capon et al., 2013; Finlayson et al., 2017).

Indigenous knowledge systems. There is *high agreement* that Indigenous knowledge systems based on inter-generational transmission of knowledge and oral history on human-environmental relationships, personal and community well-being, and spiritual considerations, are critical for adaptation (Ford et al., 2015b; Nakashima et al., 2012). There is *high evidence* that assembling observations of Indigenous communities can provide detailed local descriptions and understanding of environmental change. It can contribute to designing effective strategies to deal with these changes at a local level, with broad consistency in observations made by communities and local instrumental data (Fernández-Llamazares et al., 2017; Mistry and Berardi, 2016; Savo et al., 2016).

Traditional knowledge systems have been documented to underpin the adaptive capacity of Indigenous communities to climate change impacts in many regions, through the diversity and flexibility of Indigenous agro-ecological systems, collective social memory, repository of accumulated experience, and from social networks that are essential for disaster response and recovery (Hiwasaki et al., 2015; Mapfumo et al., 2016; Pearce et al., 2015; Sherman et al., 2016). There is *high evidence* that such knowledge systems are being weakened and threatened by acculturation, rapid environmental changes, colonisation, and social change, increasing vulnerability to climate change (Ford, 2012; McNamara and Prasad, 2014; Nakashima et al., 2012).

Ecosystem restoration. Griscom et al. (2017) examine conservation, restoration and improved land management actions that increase carbon storage and/or avoid GHG emissions across global forests, wetlands, grasslands, and agricultural lands (afforestation and reforestation as a carbon dioxide removal option is assessed in Section 4.3.8, see also the Cross-Chapter Box 3.1).

More than a third of the cost-effective CO_2 mitigation needed through 2030 can be met with these activities. However, cross-biome leakage could considerably reduce this potential (Strassburg et al., 2014) and costs (Dang Phan et al., 2014; Overmars et al., 2014; Rakatama et al., 2017) and co-benefits (Ellison et al., 2017; Jantke et al., 2016; Perugini et al., 2017; Spencer et al., 2017) depending on region and implementation.

One way to realise this potential in the context of tropical forests is known as Reducing Emissions from Deforestation, forest Degradation, and other forest-related activities (REDD+). Its multiple potential co-benefits have made REDD+ important for local communities, biodiversity and sustainable landscapes (Turnhout et al., 2017). There is *low agreement* on whether climate impacts will reverse mitigation benefits of REDD+ (Le Page et al., 2013) or reinforce them through carbon fertilisation (Smith et al., 2014b). In some cases, these co-benefits have been the key to the success of projects, beyond carbon pricing (Ngendakumana et al., 2017; Turnhout et al., 2017). Yet, REDD+ has a relatively high cost and its implementation is slow.

The complexity of institutional and financial frameworks to implement REDD+ is high, and is assessed to remain one of the main factors constraining feasibility. To meet the commitments of the Paris Agreement, the institutional financial architecture of REDD+ will require strengthened coordination, additional funding sources, and access and disbursement points (Well and Carrapatoso, 2016). Emerging regional models offer new perspectives for upscaling, but it remains to be determined which governance regimes need to be fostered for REDD+ to be effective. While there are indications that land tenure (Sunderlin et al., 2014) has a positive impact, a meta-analysis by (Wehkamp et al., 2018) shows that there is *medium evidence* and *low agreement* on which aspects of governance improvements are supportive of forest 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 for Indigenous communities (Brugnach et al., 2017).

4.3.4 Urban and infrastructure transitions

IPCC AR5 identified cities as places from which a large portion of GHGs emanate (Seto et al., 2014). Subsequent literature recognises cities as places in which climate risks such as heat stress, terrestrial and coastal flooding, air pollution and water scarcity coalesce (Dodman et al., 2017a; Revi et al., 2014a; Satterthwaite and Bartlett, 2017) and from which inclusive climate responses can be readily and cost-effectively mobilised (Kennedy et al., 2015; Newman et al., 2017; Revi et al., 2014a; Robert et al., 2014; UN-Habitat, 2017).

The transition to a 1.5°C World may be untenable unless adaptation and mitigation efforts deliberately include cities (Hallegatte et al., 2013; Roberts, 2016; Villarroel Walker et al., 2014), and unless the energy, food, water and materials that are consumed in cities are derived from, and returned to, the natural environment in less damaging ways than has historically been the case (Satterthwaite, 2008; Villarroel Walker et al., 2014).

Thomson and Newman (2016) and Fink (2013), equate the building of cities with a form of climate “geoengineering”. The long-lived urban transport, water and energy systems that will be constructed in the next three decades to support growing urban populations, present an opportunity to support 1.5°C pathways (Cartwright, 2015; Freire et al., 2014; Lwasa, 2017; McPhearson et al., 2016; Roberts, 2016). If they do not, cities will amplify climate risk and haemorrhage economic opportunity (Ahern et al., 2014; Dodman et al., 2017b; McGranahan et al., 2016; Solecki et al., 2013). The rapidly growing cities in developing countries are likely to carry a disproportionate burden of this climate risk (Pelling et al., 2018; Ziervogel et al., 2016).

The urban literature has begun focussing on the 1.5°C threshold, and 113 of the 164 submitted NDC’s feature strong urban references (Calthorpe, 2011; UN-Habitat, 2017). Cities as “multiple, interlocking complex systems” (Cross-chapter Box 5.1 in Chapter 5) are recognised as places that can harness mega-trends for transformative change (OECD, 2016b). The concentration of people, energy, finance and political leadership in urban areas, represents an opportunity to engage the transformative change required in 1.5°C pathways (Revi, 2017; Revi and Rosenzweig, 2013; Wachsmuth et al., 2016a). The capacity for transformative change in cities can be strengthened where social equity and ecological performance are understood to be mutualy enforcing dimensions of urban climate respones (Brown and McGranahan, 2016; Wachsmuth et al., 2016a; Ziervogel et al., 2016) and are associated with sub-national networks for climate action (Cole, 2015b; Jordan et al., 2015).

4.3.4.1 Urban energy systems

Urban economies in all countries tend to be energy intensive due to higher levels of per capita income, mobility and consumption than in rural areas (Broto, 2017; Gota et al., 2017; Kennedy et al., 2015). Cities and towns are also rapidly decoupling economic development from fossils through transitions such as energy efficiency, renewable energy and locally managed smart-grids (Dodman, 2009; Freire et al., 2014; Newman, 2017). Cities have the potential to harness synergies between low carbon electricity supply, electric vehicles and information technology that supports mobility and reduces congestion (Britton, 2017; Floater et al., 2014).

The rapidly expanding cities of Africa and Asia, where energy poverty undermines development and adaptive capacity, have the opportunity to draw on renewable energy technologies and benefit from recent price changes in these technologies (Cartwright, 2015; Lwasa, 2017; Watkins, 2015). This will require strengthened energy governance in these countries (Eberhard et al., 2017). Where renewable energy displaces paraffin, wood fuel or charcoal, it provides the co-benefits of improved indoor air quality, reduced fire-risk and reduced deforestation, all of which can enhance adaptive capacity (Newham and Conradie, 2013; Watkins, 2015; Winkler, 2017).

4.3.4.2 Urban infrastructure, buildings and appliances

In the same way, low-income cities can adopt 'leapfrog' infrastructure, industry and buildings (Newman et al., 2017; Rifkin, 2014; Teferi and Newman, 2017) (Also see case of slum regeneration in Addis Ababa in Cross-Chapter Box 5.1 in Chapter 5).

Improving the embodied energy, thermal performance and direct energy use of buildings can reduce emissions by 1.9GtCO$_2$e per annum (UNEP, 2017b), with an additional reduction of 3.0GtCO$_2$e per annum through energy efficiency in appliances and lighting (UNEP, 2017b). This isimportant to decarbonise urban systems. Adaptation in the urban housing sector is further enabled by designs and spatial planning policies that consider extreme weather conditions and the need to minimise displacement from existing social networks (Mitlin and Satterthwaite, 2013; UN-Habitat, 2011; UNISDR, 2009). Technology, used as part of the Internet of Things, offers opportunities to accelerate energy efficiency in urban buildings and precincts (Hoy, 2016; Moreno-Cruz and Keith, 2013).

4.3.4.3 Urban transport and urban design

Urban form has a marked impact on the demand for energy (Sims et al., 2014b) and a range of other welfare related factors; a meta-analysis of 300 papers reported energy savings of USD 26 per person per year attributable to a 10% increase in urban population density (Ahlfeldt and Pietrostefani, 2017). Significant reductions in car use were associated with the dense urban forms and new mass transit systems in Shanghai and Beijing (Gao et al., 2018b) (also see Box 4.8 in Section 4.4.5). The spatial organisation of urban energy influenced the trajectories of urban development in Hong Kong, Bangladesh and Maputo (Broto, 2017). Compact cities also create the passenger density required to make public transport more financially viable (Ahlfeldt and Pietrostefani , 2017; Rode et al., 2014) and enable combinations of cleaner fuel feed stocks and urban smart-grids, in which vehicles form part of the storage capacity (Oldenbroek et al., 2017). 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 (Lilford et al., 2017; Mitlin and Satterthwaite, 2013) unless new approaches and technologies are harnessed to accelerate rapid in situ slum upgrading (Teferi and Newman, 2017).

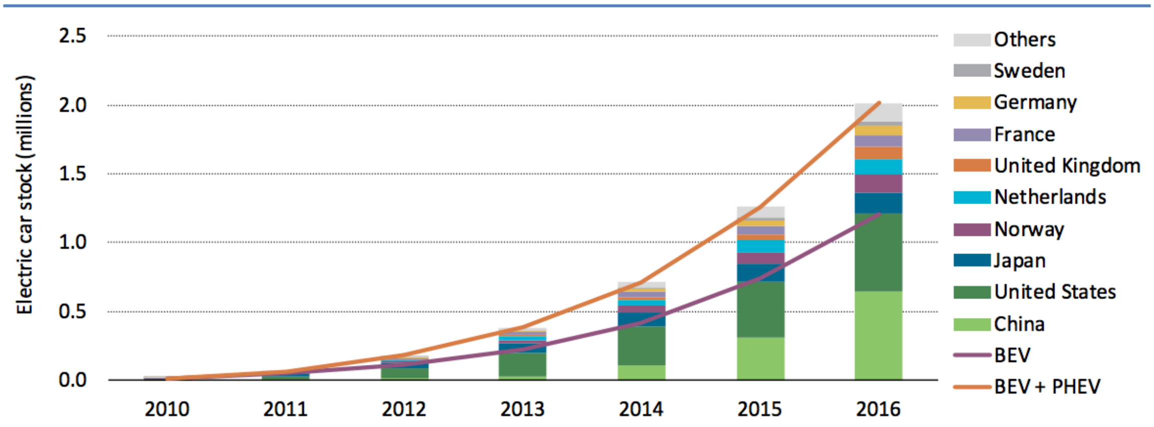
Scenarios consistent with 1.5°C pathways, depend on an almost 50% reduction in final energy use by the transport sector by 2050 (Chapter 2, Figure 2.12). Reducing emissions from transport has lagged the power sector (Creutzig et al., 2015; Sims et al., 2014b) but evidence since AR5 suggests that cities are urbanising and re-urbanising in ways that co-ordinate transport sector adaptation and mitigation (Colenbrander et al., 2017; Gota et al., 2017; Newman et al., 2017; Salvo et al., 2017). The global transport sector could reduce 4.7GtCO2e (4.1–5.3) per annum up to 2030; this is significantly more than is predicted by IAMs (UNEP, 2017b). Such a transition depends on cities that enable modal shifts, avoided journeys, provide incentives for uptake of improved fuel efficiency and changes in urban design that encourage walkable cities, non-motorised transport and shorter commuter distances (IEA, 2016a; Li and Loo, 2017; Mittal et al., 2016; Zhang et al., 2016b). In at least four African cities, 43 Asian cities and 54 Latin American cities, Transit Oriented Development, has emerged as an organising principle for urban growth and spatial planning (BRTData, 2017; Colenbrander et al., 2017; Lwasa, 2017). This trend is important to counter rising demand for private cars in developing country cities (OECD, 2016b).

Cities pursuing complementary sustainable transport, simultaneously 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). 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 of natural resources management in urban development (Lin et al., 2017).

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

4.3.4.4 *Electrification of cities and biofuels*

The electrification of urban systems, including transport, is an important agenda for 1.5°C pathways and has shown significant global progress since AR5 (IEA, 2016a). High growth rates are now appearing in electric vehicles, electric bikes and electric transit (IEA, 2017d). China's 2017 Road Map calls for 20% of new vehicle sales to be electric. India is aiming for exclusively electric vehicles (EVs) by 2032 (NITI Aayog and RMI, 2017). Globally, EV sales were up 42% in 2016 relative to 2015, and in the United States EV sales were up 36% over the same period (Johnson and Walker, 2016). In the city of Shenzen, the 15,000 unit bus fleet is set to be 100% electric by the end of 2017, accounting for a 48% reduction in CO_2 emissions and a 100% reduction in particulate pollution (Castellanos et al., 2017). Figure 4.1 shows evolution of electric car stock globally.



Notes: The electric car stock shown here is primarily estimated on the basis of cumulative sales since 2005. When available, stock numbers from official national statistics have been used, provided good consistency with sales evolutions.

Sources: IEA analysis based on EVI country submissions, complemented by EAFO (2017a), IHS Polk (2016), MarkLines (2017), ACEA (2017a, 2017b) and EEA (2017).

Figure 4.1: Evolution of the global electric car stock. Source: (IEA, 2017d)

Electric railways in and between cities have been expanded (IEA, 2016a; Li and Loo, 2017; Mittal et al., 2016; Zhang et al., 2016b). For oil importing countries, the electrification of transport provides important macro-economic benefits (Chaturvedi and Kim, 2015). In high income cities there is evidence of decoupling 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). There are, however, promising trends emerging from recent urban data (Newman and Kenworthy, 2015) some of which suggest 'peak car' has been reached in Shanghai and Beijing (Gao and Kenworthy, 2017) and beyond (Manville et al., 2017) (also see Box 4.8 in Section 4.4.5).

An estimated 800 cities globally have operational bike-share schemes (Fishman et al., 2015) and China had 250 million e-bikes in 2017 (Newman et al., 2017). Advances in 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 co-ordinated public transport, especially when electrified (Glazebrook and Newman, 2018; Wee, 2015).

Biofuels are a part of the transport sector in some cities and are likely to be an important part of aviation, shipping and freight transport as well as industrial decarbonisation (IEA, 2017g). In Brazil, ethanol constitutes 27% of all gasoline and the IEA forecasts that ethanol and biodiesel will play a role in urban transportation up to 2050 (IEA, 2016a). Lower emissions and reduced urban air pollution are attained by use of ethanol and biodiesel as fuels (Hill et al., 2006; Salvo et al., 2017).

4.3.4.5 Climate resilient land use and urban planning

Land use planning and urban form influence the energy-intensity of cities, risk exposure and adaptive capacity (Araos et al., 2016b; Broto, 2017; Carter et al., 2015; Ewing et al., 2016; Newman et al., 2016). Accordingly, urban planning provides an important climate policy instrument (Francesch-Huidobro et al., 2017b; Parnell, 2015). Reciprocally, the growing number of city climate adaptation plans provide instruments for urban planning (Carter et al., 2015; Dhar and Khirfan, 2017; Siders, 2017; Stults and Woodruff, 2016). Adaptation plans can reduce exposure to flood risk that, under a 1.5°C warming scenario, could double relative to 1976–2005 (Alfieri et al., 2017), fire risk (Chapter 3), sea-level rise (Schleussner et al., 2016) and glacial lake outburst floods (GLOFs) associated with substantial glacial loss (Kraaijenbrink et al., 2017).

All cities will have to consider investment in infrastructure and buildings that can withstand perturbed climates in a 1.5°C world (Chu et al., 2017; Underwood et al., 2017). Where adaptation planning and urban planning both generate a shared sense of risks and promote the type of local participation that enhances adaption capacity, they can be mutually supportive processes (Archer et al., 2014; Kettle et al., 2014; Campos et al., 2016; Siders, 2017). Some studies report limited effectiveness of adaptation planning (Hetz, 2016; Mahlkow and Donner, 2016; Measham et al., 2011; Woodruff and Stults, 2016), especially in developing country cities (Kiunsi, 2013). In some instances adaptation planning further marginalises poor citizens (Archer, 2016; Chu et al., 2017; Shi et al., 2016; Ziervogel et al., 2016, 2017).

Urban planning, 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; Shapiro, 2016; Parnell, 2015; Reckien et al., 2017;Evans et al., 2017). Building codes can enable 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). Building codes requiring the elevation of new buildings and protecting of critical infrastructure through climate adaptive maintenance would for example, provide a cost-effective means of managing flood risk in New York City after recent hurricanes (Aerts et al., 2014; Building Resiliency Task Force, 2013; FEMA, 2014).

Enforcement of building codes and standards is a challenge, particularly in developing countries (Chandel et al., 2016; Hess and Kelman, 2017), with inspection resources often limited and codes poorly tailored to local conditions (Eisenberg, 2016; Mavhura and Collins, 2017; Shapiro, 2016). However, the lack of 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 (Cartwright, 2015; Eberhard et al., 2011, 2016; Watkins, 2015). The Kuyasa Housing Project in Khayelitsha, one of Cape Town’s poorest suburbs, for example, created significant mitigation and adaptation benefits by installing ceilings, solar water heaters and energy efficient lightbulbs in houses independently of the formal housing or electrification programme (Winkler, 2017).

4.3.4.6 Green urban infrastructure

Green infrastructure (including naturally occurring or constructed ecological assets), and urban ecosystem services, provide urban services and link planning, management and governance for adaptation and mitigation at the city-scale (McPhearson et al., 2016; Söderlund and Newman, 2015). Urban green infrastructure can reduce heat island effects and provide flood resilience. Data from 25 urban areas in the USA, Canada and China, showed that investing in ecological infrastructure in cities, and ecological restoration and rehabilitation of rivers, lakes, and woodlands occurring in urban areas, could deliver social, economic and environmental benefits (Elmqvist et al., 2015). Culwick and Bobbins (2016) show this can be highly cost effective, though in the city of Durban similar the cost of ecosystem based adaptation was elevated by the higher prices of urban land (Cartwright et al., 2013).

Integrating and promoting green urban infrastructure (e.g. street trees, parks, green roofs and facades, water features) into city planning can increase urban resilience to climate impacts – see Table 4.3.

Table 4.3: Green urban infrastructure and benefits.

Green infrastructure	**Adaptation benefits**	**Mitigation benefits**	**References**
Urban trees planting, urban parks	Reduced heat island effect, psychological benefits	Less cement, reduced air-conditioning	(Beaudoin and Gosselin, 2016; Demuzere et al., 2014; Green et al., 2016; Lin et al., 2017; Mullaney et al., 2015; Norton et al., 2015; Söderlund and Newman, 2015)
Permeable surfaces	Water recharge	Less cement in city, some bio-sequestration, less water pumping	(Costa et al., 2016; Kaspersen et al., 2015; Lamond et al., 2015; Liu et al., 2014; Mguni et al., 2016; Schubert et al., 2016; Voskamp and Ven, 2015; Xie et al., 2017)
Forest retention, and urban agricultural land	Flood mediation, healthy lifestyles	Air pollution reduction	(Buckeridge, 2015; Culwick and Bobbins, 2016; Elmqvist et al., 2013; Nowak et al., 2006; Panagopoulos et al., 2016; Roland et al.; Stevenson et al., 2016; Tallis et al., 2011)
Wetland restoration, riparian buffer zones	Reduced urban flooding, Low skilled local work, Sense of place	Some bio-sequestration, Less energy spent on water treatment	(Brown and McGranahan, 2016; Camps-Calvet et al., 2015; Cartwright et al., 2013; Collas et al., 2017; Culwick and Bobbins, 2016; Elmqvist et al., 2015; Li et al., 2017; McPhearson et al., 2016; Ziervogel and Joubert, 2014)
Biodiverse urban habitat	Psychological benefits, inner-city recreation	Carbon sequestration	(Beatly, 2011; Brown and McGranahan, 2016; Camps-Calvet et al., 2015; Collas et al., 2017; Elmqvist et al., 2015; Li et al., 2017; McPhearson et al., 2016)

Two forests surrounding the metropolitan area of São Paulo produces an aerial transfer of water that is several times greater than the flow of water across the city in the two main rivers (Buckeridge, 2015). Realising such synergic mitigation and adaptation benefits from urban green infrastructure, sometimes requires a city-region perspective (Wachsmuth et al., 2016a). Where the dependence of urban expansion on ecological systems in and beyond the city is appreciated, the potential for transformative change exists (Söderlund and Newman, 2015; Ziervogel et al., 2016). A locally appropriate combination of green space, ecosystem goods and services and the built environment can increase the set of adaptation options (Puppim de Oliveira et al., 2013).

Milan in Italy, a city with deliberate urban greening policies, created 10,000 ha. 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). This creates the need for monitoring and additional management of urban trees if their contribution to urban ecosystem services and the biodiversity is to be maintained in a 1.5°C world (Buckeridge, 2015; Pretzsch et al., 2017).

4.3.4.7 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 and adaptation, including waste-water recycling and storm water diversion (Poff et al., 2015; Xue et al., 2015). There are, however, governance and finance challenges to balancing sustainable water supply and rising urban demand that can be particularly difficult to address 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, like paved roads, affects the volume and velocity of run-off and flooding during intense rainfall (Kaspersen et al., 2015), but urban design in many cities now seeks to mediate run-off, encourage groundwater recharge and enhance water quality (Costa et al., 2016; Lamond et al., 2015; Liu et al., 2014; Mguni et al., 2016; Schubert et al., 2016; Voskamp and Ven, 2015; 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 and Joubert, 2014) and urban flooding is expected to increase in a 1.5°C World (Alfieri et al., 2017). This risk falls disproportionately on women and poor people in cities (Brown and McGranahan, 2016; Chant et al., 2017; Chu et al., 2016; Dodman et al., 2017a, 2017b; Mitlin, 2005; Ziervogel and Joubert, 2014).

Nexus approaches integrating the management of urban agriculture, forestry, water and energy, provide important adaptation opportunities (see 4.3.3) (Rasul and Sharma, 2016), especially in cities that contain agricultural production areas. Given the many systems that interact in cities, sectoral approaches that do not account for interconnections and interdependencies can increase resource competition (Rasul and Sharma, 2016). The Food-Energy-Water (FEW) nexus is especially important to food, water and energy security (Rasul and Sharma, 2016) that supports sustainable urban livelihoods (Biggs et al., 2015). 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 also support urban flood management (Angotti, 2015; Bell et al., 2015; Biggs et al., 2015; Gwedla and Shackleton, 2015; Lwasa et al., 2015; Sanesi et al., 2017; Yang et al., 2016a). Different nexus approaches have been proposed that can help develop sustainable roadmaps for cities (Chen and Chen, 2016). Despite the multiple reported benefits, there are existing challenges to a cross-disciplinary approach given institutional complexity, political economy, and interdependencies between state and non-state actors (Leck et al., 2015).

4.3.5 Industrial systems

Industry consumes about one third of global energy and contributes, directly and indirectly, about one third of global GHG emissions (IPCC, 2014). If global temperatures are to remain under 1.5°C, industry will need to reach near-zero emissions in 2050 (see Chapter 2). Moreover, the consequences of climate change of 1.5°C or more pose substantial challenges for a diversity of industrial sectors. This section will first briefly discuss the limited literature on adaptation options for industry. Subsequently, new literature since AR5 on the feasibility of categories of mitigation options will be discussed.

Research assessing adaptation actions by industry indicates that only a small fraction of corporations have developed adaptation measures and studies of adaptation in the private sector remain limited (Agrawala et al., 2011; Averchenkova et al., 2016; Bremer and Linnenluecke, 2016; Linnenluecke et al., 2015; Pauw et al., 2016b) and for 1.5ºC largely absent. This knowledge gap is particularly evident for medium-sized enterprises and in low and middle income nations (Surminski, 2013). Part of the reason for this gap may be due to existing mechanisms for addressing risk within industry, with some studies indicating that adaptation takes place in the context of ongoing risk management strategies (e.g. through business continuity management, supply chain resilience or risk management) (Wang et al., 2017a).

Depending on the industrial sector, mitigation consistent with 1.5ºC 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 industry (Lewandowski, 2016; Linder and Williander, 2017), the substitution of materials in high-carbon products with those made up of renewable materials (wood instead of steel or cement in the construction sector, natural textile fibres instead of plastics), and a myriad 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 summarised in Figure

4.2, highlighting the discreteness of choice and path dependency: if an industry goes one way (e.g., keep the existing process), it will be harder to get to one of the options that are associated with changing that process (e.g., electrification) (Bataille et al.).

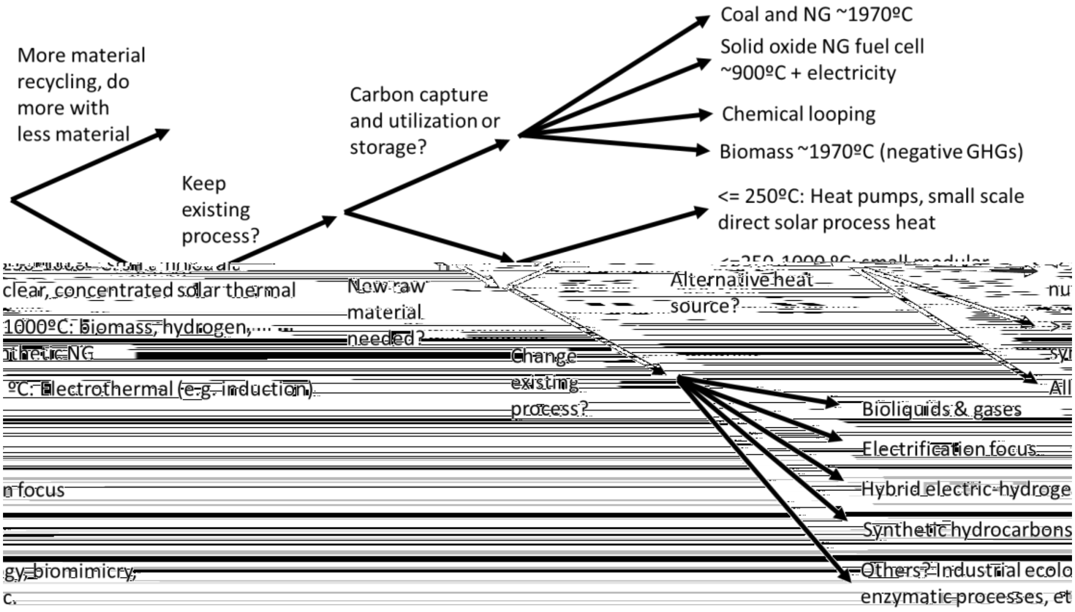


Figure 4.2: Choices of mitigation options and routes in GHG-intensive industry consistent with mitigation to stay below 1.5ºC (Bataille et al.)

Table 4.4 gives an overview of which mitigation options are applicable to which industrial sectors.

Table 4.4: Applicability of different 1.5ºC consistent mitigation options to main industrial sectors, including examples of application (Boulamanti and Moya, 2017; Napp et al., 2014; Wesseling et al., 2017).

	Iron/steel	**Cement**	**Refineries and petrochemicals**	**Chemicals**
Process and energy efficiency	Can make a difference on the order of tens of percents, depending on the plant. Relevant but not enough for 1.5ºC			
Bio-based	Cokes 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		Limited potential	
Electrification & hydrogen	Direct Reduction with hydrogen. Heat generation through electricity	Partial (only electrified heat generation)	Electrified heat and hydrogen generation	
CCS	Possible for process emissions and energy. Reduces emissions substantially but not near-zero		Can be applied on energy emissions and different stacks but not on emissions of products in the use phase (like gasoline)	

4.3.5.1 *Energy efficiency*

Energy efficiency in energy-intensive industry is a necessary but insufficient condition for deep emission reductions (Aden, 2017; Napp et al., 2014). A myriad of options specifically for different industries is available. In general, their feasibility depend 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 techniques, which play a role in all industrial sectors including SMEs and non-energy intensive industry, offer potential for considerable energy efficiency improvements. They include motor systems (electric motors, variable speed drives, pumps, compressors and fans), responsible for about 10% of industrial energy consumption with efficiency potential of around 20–25% (Napp et al., 2014); steam systems, responsible for about 30% of industrial energy consumption and energy saving potentials of about 10% (Hasanbeigi et al., 2014; Napp et al., 2014). Waste heat recovery from industry has substantial potential for energy efficiency and emission reduction (Forman et al., 2016). Low awareness and competition from other investments limit the feasibility of such options (Napp et al., 2014).

4.3.5.2 Bio-based and circularity

Recycling materials and developing a circular economy can be institutionally challenging as it requires advanced capabilities (Henry et al., 2006)but has many 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). .

Bio-based feedstock processes could be partly seen as part of the circular materials economy, but does put pressure on natural resources by increasing land demand, biodiversity impacts (Slade et al., 2014), and, partly as a result, face barriers in public acceptance (Sleenhoff et al., 2015). Because of those barriers, most bioenergy use is found in industry sectors that produce biomass residues on site that are suitable for fuel use (Philibert, 2017). In several sectors, bio-based feedstocks would leave the production process of materials relatively untouched, and a switch would not affect the product quality, making the option more attractive.

4.3.5.3 Electrification and hydrogen

Electrification of manufacturing processes would constitute a greater technological challenge and would mean more disruptive innovation in industry, potentially leading to stranded assets, and reducing the political feasibility and industry support (Åhman et al., 2016). Apart from bio-based options, most of the renewable electricity options need to be further technologically developed as they require a move to electrification in industry, and an ample supply of cost-effective low-emission electricity (Philibert, 2017).

Feasibility of electrification and use of hydrogen is affected by technical development in terms of efficient hydrogen production and electrification of processes, by geophysical factors related to availability of low-emission electricity (MacKay, 2013), and associated public perception, by economic feasibility as costs will have to come down (Philibert, 2017; Wesseling et al., 2017). The high costs of disruptive change to hydrogen- or electricity-based international trade-sensitivity of many 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).

4.3.5.4 CO_2 capture, utilisation and storage in industry

CO_2 capture in industry faces some of the same feasibility challenges as CCS in the power sector (Section 4.3.2, see also that section for a brief discussion of geological storage of CO_2, including its public perception) or from bioenergy sources (Section 4.3.8), but in industry would leave the production process of materials relatively untouched (Åhman et al., 2016). Some CO_2 stacks in industry have a high economic and technical feasibility for CO_2 capture as the CO_2 concentration in the exhaust gases is very high (Metz et al., 2005), but others require strong modifications in the production process, limiting technical and economic feasibility, though costs remain lower than other deep GHG reduction processes (Rubin et al., 2015). The energy use of CO_2 capture through amine solvents (for solvent regeneration) has decreased since 2005 by around 60%, from 5 GJ tCO_2^{-1} to 1.8 GJ tCO_2^{-1}(Idem et al., 2015), increasing both technical and economic potential for this option. Almost all of the current full-scale (>1MtCO_2 yr^{-1}) CCS projects capture CO_2 from industrial sources (Global CCS Institute, 2017). The heterogeneity of industrial production processes might point at the need for specific institutional arrangements for industrial CCS (Mikunda et al., 2014), and may decrease institutional feasibility.

Carbon dioxide utilisation in industry has a limited role to play because of the limited physical potential of re-using CO_2 with currently available technologies (Mac Dowell et al., 2017). The conversion of CO_2 to fuels using renewable energy has a lower technical, economic and environmental feasibility than direct CO_2capture and storage from industry (Abanades et al., 2017).

4.3.6 Overarching adaptation options

This section focuses on assessing overarching adaptation options which cut across systems (a detailed assessment of feasibility is presented in Supplementary Material 4.A and options described in the text below). They are options in the sense that they are specific solutions from which actors can choose and make decisions, in order to reduce climate vulnerability and build resilience. The focus here is on examining their feasibility in the context of four transitions of: energy systems, land and ecosystem, urban and infrastructure systems, and industrial systems. These options can contribute to creating an enabling environment for adaptation (as presented in 4.4)

4.3.6.1 Disaster risk management

Disaster risk management (DRM) is a process for designing, implementing, and evaluating strategies, policies, and measures to improve the understanding of disaster risk, and promote improvement in disaster preparedness, response, and recovery practices (IPCC, 2012). Since SREX and AR5 there is increased demand to integrate DRM and adaptation (Archer, 2016; Haraguchi et al., 2016; Howes et al., 2015; Kelman, 2017; Kelman et al., 2015; Rose, 2016; Serrao-Neumann et al., 2015; van der Keur et al., 2016; Wallace, 2017). This is important in the context of 1.5C warming, which has the potential to increase the magnitude and frequency of disasters (Chapter 3). There is *high agreement* that enabling synergies between DRM and adaptation is critical for reducing vulnerability, with medium evidence on its feasibility.

4.3.6.2 Education and learning

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

4.3.6.3 Financial options

Increasing risks from heatwaves, extreme precipitation, and coastal flooding with 1.5C warming (Chapter 3), have the potential to increase the demand for financial options for adaptation. Insurance can spread risk, provide a buffer against the impact of climate-hazards, support recovery and reduce the financial burden on governments, households, and businesses (Glaas et al., 2017; Jenkins et al., 2017; O’Hare et al., 2016; Patel et al., 2017; Wolfrom and Yokoi-Arai, 2015), with *medium agreement* that insurance can reduce vulnerability and medium evidence on feasibility.

Catastrophe bonds seek to protect those who could suffer devastating financial disruption in the event of a disaster (Linnerooth-Bayer and Hochrainer-Stigler, 2015), and are triggered when a disaster reaches a predetermined threshold during a bond term. The insurance purchaser keeps a portion of the bond value to pay off losses and investors lose some, or all, of their principal invested depending on the event’s severity (Vajjhala and Rhodes, 2015). There is limited evidence on the feasibility of catastrophe bonds for adaptation.

Social protection programmes include cash and in-kind transfers targeted at poor and vulnerable households, with the goal of protecting families from the impact of economic shocks, natural disasters, and other crises (World Bank, 2017). There is *high agreement* that social safety nets build generic adaptive capacity and reduce social vulnerability when combined with a comprehensive climate risk management approach, and medium evidence on feasibility.

4.3.6.4 *Population health and health system adaptation options*

Until mid-century, climate change will primarily exacerbate existing health challenges, with socio-economic factors determining the magnitude and pattern of climate-sensitive health risks (Smith et al., 2014a). Enhancing current health services includes providing access to safe water and improved sanitation, enhancing access to essential services such as vaccination, and developing or strengthening integrated surveillance systems (WHO, 2015), with *high agreement* that when combined with iterative management can facilitate effective adaptation and moderate evidence of feasibility.

4.3.6.5 *Human migration*

Human migration, whether planned, forced or voluntary, is increasingly used to deal with climatic and non-climatic risks. Literature on migration as an adaptation has grown since AR5 with low evidence as to whether migration is adaptive (Bettini and Gioli, 2015; Gemenne and Blocher, 2017) and *low agreement* on its feasibility.

4.3.7 Short lived climate pollutants

The main short lived climate forcer (SLCF) emissions that cause warming are black carbon (BC), methane (CH_4), other precursors of tropospheric ozone (carbon monoxide (CO) and non-methane volatile organic compounds), and some hydrofluorocarbons (HFCs) (Myhre et al., 2013). SLCFs are defined as substances that remain in the atmosphere for a couple of days to roughly a decade, and can be gases as well as aerosols. They also include emissions that lead to cooling, such as sulphur and nitrogen dioxide, organic carbon and ammonia. This section focuses on the primary warming agents black carbon, HFCs and methane, often referred to as short-lived climate pollutants (SLCPs). SLCPs are sometimes co-emitted with CO_2. Tropospheric ozone is not included as it is not directly emitted and therefore cannot be mitigated, but methane is its main precursor. Other precursors include CO (usually co-emitted with BC or CO_2 which are assessed in this chapter) and NMVOCs, which have a relatively small contribution.

The mitigation options for SLCPs are often overlapping with other mitigation options, especially since BC is rarely emitted alone. Hence, typical SLCP mitigation strategies target BC-rich sectors and consider the impacts of all co-emitted SLCPs. Mitigating BC emissions could have significant adaptation and sustainable development co-benefits, especially around human health (Haines et al., 2017). Additional benefits include lower likelihood of non-linear climate changes and feedbacks (Shindell et al., 2017b) and slowing down sea level rise (Hu et al., 2013). Yet, since AR5, new sources, such as shale gas operations and increased meat and dairy consumption have emerged (Shindell et al., 2017a).

Cross-Chapter Box 1.1 provides a discussion of the emission metrics around SLCPs and their long-lived counterparts. Chapter 2 concludes that 1.5°C pathways require stringent reductions in non-CO_2 climate forcers, primarily SLCPs and nitrous oxide, and that non-CO_2 climate forcers reduce carbon budgets by ~1540 $GtCO_2$ per degree of warming attributed to them (see Section 2.2.2.3).

Myhre et al. (2013) concluded that SLCPs have contributions comparable to CO_2 emissions in the short term, and have more tangible co-benefits. Therefore, they provide an opportunity for expeditious emission reduction, whose tangible co-benefits can be realised within a generation or less. Table 4.5 provides an overview of the main SLCPs and their emission sources, with examples of options for emission reductions and associated co-benefits.

Table 4.5: Overview of main characteristics of the most significant SLCPs (core information based on Pierrehumbert (2014) and Schmale et al. (2014); rest of the details as referenced).

SLCP 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. () unless specified otherwise**
Methane (gas)	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 Sections 4.3.2 and 4.3.3.	Reduction of tropospheric ozone (Shindell et al., 2017b) Health benefits of dietary changes Increased crop yields Improved access to drinking water
HFCs (gas)	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-Babiloniab et al., 2017)
Black carbon (solid)	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 4.3.4	Health benefits of better air quality Increased education opportunities Reduced coal consumption for modern brick kilns Reduced deforestation

Mitigating SLCPs leads to a more rapidly cooling climate more quickly, because the warming effect occurs more quickly and more intensely (see Figure 8.32 and 8.33 in Myhre et al. (2013)) and more permanently as compared to scenarios where SLCPs are not reduced. But in scenarios in which CO_2 emissions are not reduced in parallel to SLCPs, rapidly accumulating warming due to CO_2 will overwhelm SLCPs mitigation benefits in a couple of decades (Schmale et al., 2014).

Sources of methane are manifold and include both fugitive and deliberate releases during fossil fuel extraction, transportation and storage, as well as wastewater treatment, rice paddy cultivation, livestock and landfill management (Finn et al., 2015; Schmale et al., 2014). A wide range of options to reduce SLCP emissions were extensively discussed in AR5 (IPCC, 2014).

Reducing black carbon and co-emissions from vehicles has numerous co-benefits, in particular for health, avoiding premature deaths and increasing crop yields (Peng et al., 2016; Scovronick et al., 2015). Interventions to reduce black carbon offer tangible local benefits, increasing the likelihood of local public support (Eliasson, 2014; Venkataraman et al., 2016). Limited interagency co-ordination, poor science-policy interactions (Zusman et al., 2015), weak policy and absence of inspections and enforcement (Kholod and Evans, 2016) are among barriers that reduce the feasibility of options to reduce vehicle-induced black carbon emissions. Switching from biomass cook stoves to cleaner gas stoves (based on liquefied petroleum gas or natural gas (LPG/PNG) or to electric cooking stoves is technically and economically feasible in most areas, but faces barriers in user preferences, costs and the organisation of supply chains (Jeuland et al., 2015). Similar feasibility considerations emerge in switching in lighting from kerosene wick lamps to solar lanterns, from current low efficiency brick kilns and coke ovens to cleaner production technologies; and from field burning of crop residues to agricultural practices using deep-sowing and mulching technologies.

HFC emissions are currently small, but growing rapidly (Myhre et al., 2013). Mitigation options for HFCs are to transition to alternatives with reduced ability to absorb outgoing longwave radiation, ideally combined with improved energy efficiency so as to simultaneously reduce CO_2 and co-emitted air pollutants (e.g. Shah et al., 2015). Technical, social, institutional and environmental feasibility of alternatives is likely to be high, but costs are estimated to be in the same range as other mitigation options; most emission reductions can be done below USD_{2010} 80 $tCO_2\text{-eq}^{-1}$, and the remainder below roughly double that number (Höglund-Isaksson et al., 2017), limiting economic feasibility.

Section 2.3 indicates that most very low-carbon emissions pathways include a transition away from the use of coal and natural gas in the energy sector and oil in transportation (see Section 2.3), leading to a substantial overlap with SLCP mitigation strategies related to methane from the fossil fuel sector and BC from the transportation sector in such scenarios. However, according to Section 2.3, SLCP reductions may be achieved later in such scenarios.

Reductions in SLCPs can provide large benefits towards sustainable development, beneficial for social, institutional and economic feasibility. Benefits 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., 2017a). Institutional feasibility is negatively affected by an information deficit, yet, with the absence of international frameworks for integrating SLCFs into emissions accounting and reporting mechanisms being a significant barrier for policy-making to address SLCF emissions (Venkataraman et al., 2016).

4.3.8 Carbon dioxide removal

4.3.8.1 Bioenergy with Carbon Capture and Storage (BECCS)

BECCS components have been assessed in previous IPCC reports (IPCC, 2005; Minx et al., 2017b; Smith et al., 2014b) and different technologies have been incorporated into Integrated Assessment Models (Clarke et al., 2014). The 1.5°C pathways assessed in Chapter 2 remove 5 $GtCO_2yr^{-1}$ (median) by mid-century and 15 $GtCO_2\,yr^{-1}$ (median) by 2100 through BECCS.[1] BECCS is constrained by the potential of sustainable bioenergy (see Section 4.3.3), and the potential for safe storage of CO_2 (see Section 4.3.2). Most of the literature agrees on a BECCS potential range of 1.5–5.8 $GtCO_2yr^{-1}$ (Figure 4.3). These potentials are not homogenously distributed across regions, and knowledge gaps around distributional impacts and governance mechanisms remain to be addressed (Fuss, 2017).

Assessing the implications of BECCS deployment consistent with the 2°C target, Smith et al. (2016) estimate a land use intensity of 0.3–0.5 ha $tCO_2\text{-eq}^{-1}yr^{-1}$ when forest residues are used as feedstock, of about 0.16 ha $CO_2\text{-eq}^{-1}yr^{-1}$ for agricultural residues, and 0.03–0.1 ha $tCO_2\text{-eq}^{-1}yr^{-1}$ for purpose-grown energy crops. The average amount of BECCS in the considered 2°C pathways requires 25–46% of arable and permanent crop area in 2100, although land area is not necessarily a good indicator for competition with food production or threats to ecosystems, as requiring a large land area for the same potential could indicate that low-productivity degraded or marginal land is used to avoid sustainability conflicts (Schueler et al., 2016)[2]. Global assessments need to be complemented by regional, geographically explicit bottom-up studies of biomass potentials for better insights into the implications of biomass cultivation (*e.g.* de Wit and Faaij, 2010; Ericsson and Nilsson, 2006; Kraxner et al., 2014; Lewandowski et al., 2006; Perlack et al., 2005)

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[1] FOOTNOTE Although emissions are not net negative earlier in the century, removals start in 2030 in some scenarios (Chapter 2).

[2] FOOTNOTE Gibbs and Salmon (2015) report global estimates of total degraded land of 16Gha. Fritz et al. (2011) compare global land cover products finding combined forest and cropland disagreement of 893 Mha. Agreement on the availability of land for land-based CDR is low (see Box 3.11; 4.5.1).

BECCS in a 2°C pathway would produce on average 170 $EJyr^{-1}$ of energy by 2100[3] with a water footprint of 59.5 $km^3GtCO_2^{-1}$ by 2100 or 1.5% of global yearly freshwater withdrawals. Global impacts on nutrients and albedo are more difficult to quantify (Smith et al., 2016).

There is substantial uncertainty about the feasibility of timely upscaling, exacerbated by CCS being largely absent from the Nationally Determined Contributions (Spencer et al., 2015) and CCS deployment lagging behind what roadmaps in line with a 1.5°C or even 2°C limit foresee (IEA, 2016a; Peters et al., 2017b).[4] Economic incentives for ramping up a large CCS or BECCS infrastructure are weak. The 2050 average investment costs for such a BECCS infrastructure for bio-electricity and biofuels are USD138 and USD123 billion yr^{-1}, respectively (Smith et al., 2016). BECCS unit costs vary widely, 50% of the literature agreeing on USD40–100 tCO_2^{-1} (Figure 4.3).

Limited public acceptance is a barrier to BECCS deployment: CCS faces concerns of prolonging the profitability of the fossil fuel industry and of safety and environmental issues, particularly in populated onshore regions (see 4.3.2); bioenergy has come under scrutiny because of concerns relating to competition for resources like land and water. The carbon-neutrality of bioenergy has been challenged[5] because of i.a. indirect land use change (iUC), site-specific barriers, disagreement on Global Warming Potential of biogenic CO_2 emissions, and problems to achieve scale without environmental impacts (e.g. Plevin et al., 2010; Fargione et al., 2008; Searchinger et al., 2009; Havlík et al., 2011; Popp et al., 2014; Harper et al., 2017). Policies accounting for iLUC by formulating sustainability criteria, e.g. the EU Renewable Energy Directive, have been assessed as insufficient (e.g. Frank et al., 2013). Current pathways are believed to have inadequate assumptions on the development of adequate societal support and governance structures (Vaughan and Gough, 2016). There could also be positive side effects of BECCS, e.g. reduced upward pressure on food prices by lowering carbon prices and biomass demand in 2°C scenarios (Muratori et al., 2016) and lower macroeconomic costs in 1.5°C scenarios with accelerated BECCS deployment (Liu et al., 2017).

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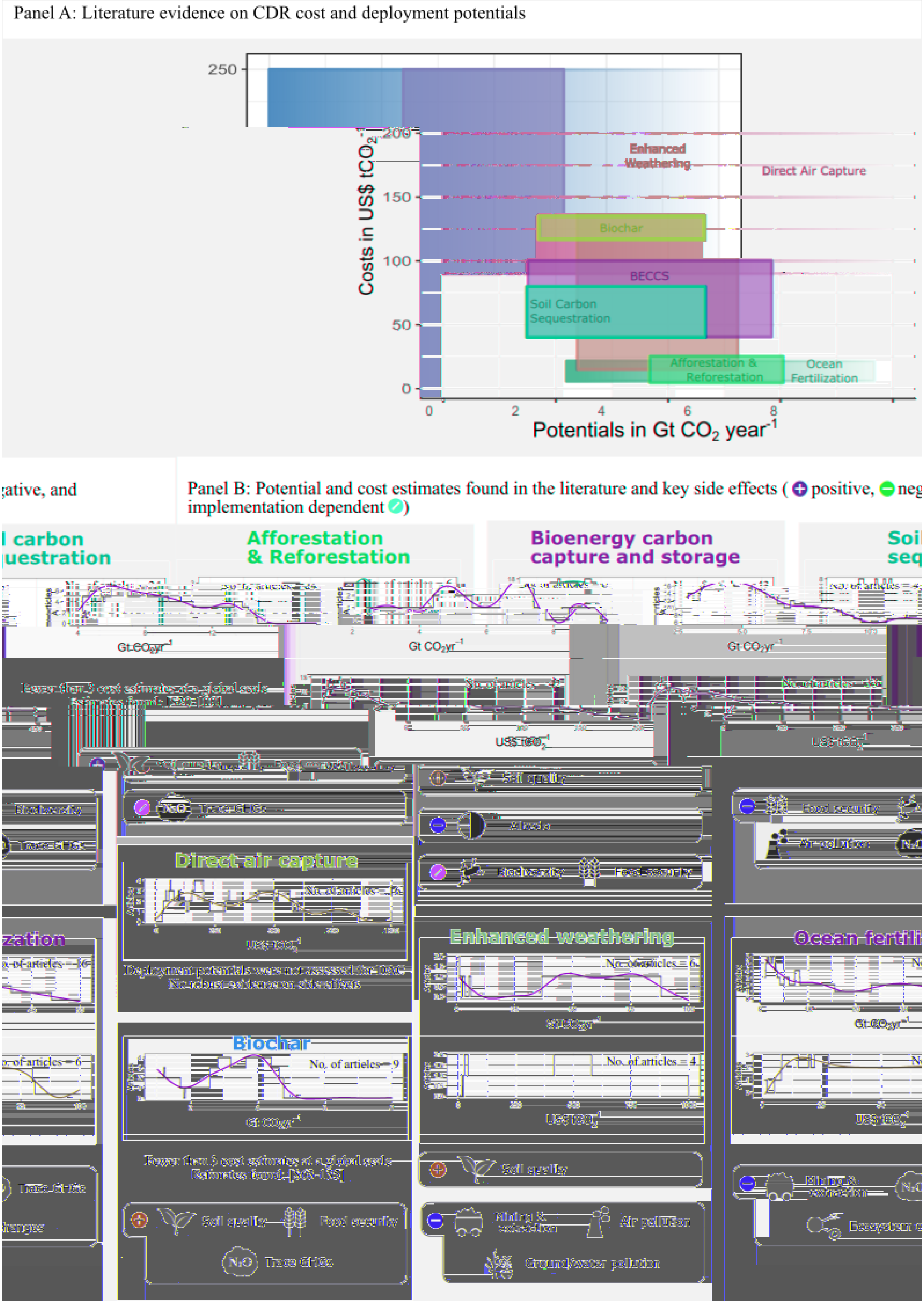
[3] FOOTNOTE Energy footprints can vary widely depending on BECCS supply chain management (Fajardy and Mac Dowell, 2017).

[4] FOOTNOTE Demonstration at scale exists: the Illinois Industrial CCS facilities combined with the Illinois Basin Decatur Project can inject approximately 1,000,000 tCO_2yr^{-1}.

[5] FOOTNOTE Utilization of the captured CO_2 has been suggested to improve the carbon balance of BECCS.



Panel A: Literature evidence on CDR cost and deployment potentials

Panel B: Potential and cost estimates found in the literature and key side effects (⊕ positive, ⊖ neg… implementation dependent ⊘)

Figure 4.3: Evidence on CDR costs, 2050 deployment potentials, and key side effects. Panel A presents the

interquartile range of estimates based on. Ranges are trimmed to show detail; the 75th percentile estimate for Ocean Fertilization is 12.84 $GtCO_2$ yr^{-1}; the 75th percentile cost estimate for Enhanced Weathering is USD320 tCO_2^{-1}. DACCS is only constrained by geological storage capacity. Annual deployments of soil carbon sequestration cannot be sustained as long as other technologies (due to rapid sink saturation). BECCS cost estimates are taken from bioenergy estimates in the literature [EJ yr^{-1}] and converted to $GtCO_2$. Panel B shows the number 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). Technologies with more than 4 studies providing estimates are additionally represented by a generalised additive model.

4.3.8.2 Direct Air Carbon 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 thus offset residual emissions from difficult–to–decarbonise sectors, and 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 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), which appears to be the main challenge (Barkakaty et al., 2017; Sanz-Pérez et al., 2016).

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 $EJyr^{-1}$ by 2100 corresponding to an average 2°C pathway; water requirements are estimated to average 0.8–24.8 km^3 $GtCO_2$-$eq^{-1}yr^{-1}$(Smith et al., 2016 based on Socolow et al., 2011).

However, the literature shows *low agreement* and is fragmented, which challenges assessments (Broehm et al., 2015). This fragmentation is reflected in a large variety of cost estimates, ranging from USD20 to 1,000 tCO_2^{-1}(Goeppert et al., 2012; Sanz-Pérez et al., 2016). The interquartile range (Figure 4.3) is USD40–449 tCO_2^{-1}; there is lower agreement and a smaller evidence base at the lower end of the cost range.

Research and efforts by small-scale commercialisation projects focus on utilisation of captured CO_2 (Wilcox et al., 2017). Other priorities include the incorporation of DACCS into IAM scenarios alongside BECCS (e.g. Chen and Tavoni , 2013; Strefler et al., 2017).

4.3.8.3 Afforestation and reforestation (AR)

Afforestation implies planting trees on land not forested over the last 50 years, while reforestation implies replanting of trees on recently deforested land. Houghton et al. (2015) estimate about 500 Mha could be available (though there is *low agreement*, see e.g. Dinerstein et al. (2015) for the re-establishment of forests on lands previously forested but not currently used productively. This would sequester at least 3.7 $GtCO_2yr^{-1}$ for decades. Smith et al. (2016) find that it is possible to reach the 12 $GtCO_2$ that are on average removed in 2°C pathways by 2100. Unit costs are estimated to be low compared to other CDR options, USD 18–29 tCO_2-eq^{-1}[6]. Yet, realising such large potentials comes at higher land and water footprints than BECCS, although there would be a positive impact on nutrients, and the energy requirement would be negligible (Cross-Chapter Box 3.1).[7]

The most important caveat of the CDR potential of AR arises from the fact that biogenic storage is less permanent, as 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., 2016b) and is subject to

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[6] FOOTNOTE The interquartile range of costs across the literature is US$4.5-25 tCO_2-eq^{-1}, thus encompassing the range by Smith et al. (2016a); the potentials range is 3.7–6 $GtCO_2$ y^{-1} (Box 3.11; Fig. 4.3.6).

[7] FOOTNOTE Griscom et al. (2017) find higher potentials than previous literature with significant co-benefits (see Cross-Chapter Box 3.1), yet their assessment of natural climate solutions are not only CDR and partially overlap with mitigation options of 4.3.3.

disturbances, e.g. to drought, forest fires and pests that can be exacerbated by climate change. This requires careful forest management after afforestation and makes AR less effective as a CDR option over time. Even though there is a lot of practical experience with AR, the pace at which removal will be taking place will be slow, as forests first need to grow to their full potential. Further issues arise from the heterogeneous geographical distribution of AR potentials, where CDR effectiveness of AR is limited by its impact on the albedo in higher latitudes (Bright et al., 2015; Jones et al., 2015), and the lack of forest governance structures and monitoring capacities usually not considered in models (Wang et al., 2016; Wehkamp et al., 2017). Although forest mitigation options appear to be more acceptable than options that involve geological storage, there is only *medium agreement* on the positive impacts of AR on ecosystems and biodiversity, especially if performed through plantations of monocultures (Figure 4.3). Such co-benefits would need to be considered in the design of incentive schemes to support sustainable portfolios of complementary CDR options. Synergies with other policy goals are possible; e.g. land spared by adopting healthier diets in Western Europe could be afforested, increasing the yearly carbon storage potential from 90 to 700 $MtCO_2$ in 2050 (Röös et al. 2017). Such land-sparing strategies could also benefit other land-based CDR options.

4.3.8.4 Soil carbon sequestration and biochar

Biochar is obtained from pyrolysis and can be used as a soil amendment to increase soil carbon stocks, which can also be achieved by changes in land management (soil carbon sequestration, or SCS).The interquartile ranges for 2050 CDR potentials through SCS and biochar are 1.5–4.7 $GtCO_2$ yr^{-1} [8] and 1.7–4.6 $GtCO_2$ yr^{-1}, respectively (Figure 4.3). For biochar, this range is less than previous estimates (e.g. Woolf et al., 2010), which additionally consider the displacement of fossil fuels through biochar. Mitigation cost through SCS are USD40–80 tCO_2^{-1} and USD117–135 tCO_2^{-1} for biochar. Total costs of exploiting the full biochar potential amount to USD 130 billion (Smith, 2016)[9]. For SCS, it is estimated that much of the CDR could be delivered at negative cost (USD –16.9 billion yr^{-1}), and the rest at low (USD9.2 billion yr^{-1}) cost, with overall savings of USD7.7 billion yr^{-1}. This relates to the multiple co-benefits of SCS, e.g. on productivity and resilience of soils (Smith et al., 2014b). Water requirements are close to zero for both options, which is also true for the energy requirement of SCS, while biochar could at full theoretical deployment generate up to 65 EJ yr^{-1} as a side product (Cross-Chapter Box 3.1). Both options affect nutrients and food security favourably, reduce emissions of N_2O and CH_4 (Kammann et al., 2017), and can be applied without changing current land use. However, 40–260 Mha are needed to grow the biomass for biochar for implementation at 2.6 $GtCO_2$-eq yr^{-1}. Large-scale biochar application can darken the surface and reduce albedo, thus partially offsetting the mitigation benefit (Bozzi et al., 2015). Not all land is suitable for SCS and biochar (Caldecott et al., 2015) and biochar is 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). Saturation diminishes its effect, requiring subsequent management.

4.3.8.5 Marine and terrestrial Enhanced Weathering (EW) and ocean alkalinisation

Weathering is the natural process of rock decomposition via chemical and physical processes, controlled by temperature, reactive surface area, interactions with biota and water solution composition – a process aimed to be artificially stimulated by grinding selected rock material and distributing over land (Hartmann and Kempe, 2008; Köhler et al., 2010; Manning and Renforth, 2013; Renforth, 2012; Taylor et al., 2016; ten Berge et al., 2012; Wilson et al., 2009), coasts (Hangx and Spiers, 2009; Montserrat et al., 2017) or open ocean (Hauck et al., 2016; House et al., 2007; Köhler et al., 2013). Ocean alkalinisation adds alkalinity to marine areas to locally increase the CO_2 buffering capacity of the ocean (González and Ilyina, 2016; Renforth and Henderson, 2017).

The potential for terrestrial EW ranges from 0.72 $GtCO_2$ yr^{-1} (Hartmann et al., 2013) to 88.1 $GtCO_2$ yr^{-1}(Taylor et al., 2016); *agreement is low* due to a variety of assumptions and unknown parameter ranges in the

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[8] FOOTNOTE The 4p1000 initiative brings together stakeholders for sequestering 3.5 $GtCO_2yr^{-1}$, which is well within this range.

[9] FOOTNOTE The 2100 average potential to be exploited is estimated as 2.57 $GtCO_2yr^{-1}$ both for SCS and biochar (Smith, 2016).

applied upscaling procedures that need to be verified by field experiments (Fuss et al., 2017).

Evidence and agreement for global cost estimates are low (Figure 4.3) (*low confidence*). Site-specific estimates vary depending on the chosen technology for rock grinding, material transport and rock source (Hartmann et al., 2013; Renforth, 2012), ranging from 15–40 USD tCO_2^{-1} to 3,460 USD tCO_2^{-1}(Köhler et al., 2010; Schuiling and Krijgsman, 2006; Taylor et al., 2016).[10]The evidence base for costs of ocean alkalinization and marine enhanced weathering is even lower. The ocean alkalinisation potential is assessed to be 100 $MtCO_2$ yr^{-1} to 10 $GtCO_2$ yr^{-1} with costs of USD14 - >500 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 can have impacts on health (Schuiling and Krijgsman, 2006; Taylor et al., 2016) depending on implementation. Side effects of marine EW and ocean alkalinisation are high energy demand[11] (Hauck et al. 2016;Köhler et al. 2013) and the potential release of heavy metals like Ni and Cr (Montserrat et al., 2017). Ocean alkalinisation could affect ocean biogeochemical functioning (González and Ilyina, 2016). A further caveat of EW relates to saturation (Cross-Chapter Box 3.1).[12]

Ocean fertilization

Iron or other nutrients can be added to the ocean resulting in algal bloom leading to carbon fixation and subsequent sequestration in sediments. There is low confidence on the amount of carbon that could be removed from circulation on a long-term basis and on the readiness of this technology to contribute to rapid decarbonisation (Williamson et al., 2012). Only small-scale field experiments and theoretical modelling have been conducted to assess this question (e.g. McLaren (2012). The full range of CDR potential is 0.0000152 $GtCO_2$ yr^{-1} (Bakker et al., 2001) for a spatially constraint field experiment to 4.4 $GtCO_2yr^{-1}$(Sarmiento and Orr, 1991) following a modelling approach. The interquartile range of 2050 CDR potentials displayed in Figure 4.3 is 2.2–7.7 $GtCO_2$ yr^{-1}. Various authors point to the low efficiency (Aumont and Bopp, 2006; Zahariev et al., 2008; Zeebe, 2005).

Cost estimates range from USD2 tCO_2^{-1} to 81 (Boyd and Denman, 2008). Fertilisation is expected to impact food webs by stimulating its base organisms (Matear, 2004), and extensive algal blooms may cause anoxia (Matear, 2004; Russell et al., 2012; Sarmiento and Orr, 1991) and deep water oxygen decline (Matear, 2004). Nutrient inputs can shift ecosystem production from an iron-limited system to a P, N-, or Si-limited system depending on the location (Bertram, 2010; Matear, 2004) and non-CO_2 GHGs may increase (Bertram, 2010; Matear, 2004; Sarmiento and Orr, 1991). The greatest theoretical potential for this practice is the Southern Ocean, posing grand challenges for governance, considering that the oceans are a global commons.

The permanence of CO_2 in the ocean is controversial, with estimated residence times of 1,600 years to millennia (Williams and Druffel, 1987; Jones, 2014), on the one hand, and the view that stored carbon would be rapidly released after cessation on the other hand (Aumont and Bopp, 2006; Zeebe, 2005).

4.3.8.6 Other and emerging CDR options

Carbon Capture Utilisation and Storage. In the absence of carbon pricing, regarding the captured CO_2 as a resource is discussed as an entry point for CDR, although not necessarily leading to negative emissions, particularly if the CO_2 is sourced from fossil CCS or if the products do not store the CO_2 for climate-relevant horizons.[13]Von der Assen et al. (2013) show that most Life Cycle Analyses either neglect: (1) that utilised

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[10] FOOTNOTE Operational cost assessment for EW in the UK reports USD70–578 tCO_2^{-1} for mafic rocks and USD24–123 tCO_2^{-1} for ultramafic rocks (Renforth 2012), which could serve for upscaling.

[11] FOOTNOTE See Cross-Chapter Box 3.1 for energy requirements of terrestrial EW, requiring low-emission energy to achieve negative emissions.

[12] FOOTNOTE This analysis relies on the assessment in Fuss et al. (2017), which provides more detail on saturation and permanence.

[13] FOOTNOTE CCU (without storage) is assessed in section 4.3.5.

CO_2 might not actually be carbon-negative; (2) accounting problems with allocating emissions to individual products and (3) CO_2 storage duration. Mac Dowell et al. (2017) compare the scale and rate of CO_2 production to that of utilisation allowing long-term sequestration and assess it to be highly improbable that the chemical conversion of CO_2 will contribute more than 1% to the achieving the Paris goals.

Non-CO_2 GHG Removal (GGR). Methane[14] is a much more potent GHG than CO_2 (Montzka et al., 2011), associated with difficult-to-abate emissions in the food sector, outgassing from lakes, wetlands, and oceans (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 CO_2. There is low confidence that existing technologies for methane removal are economically or energetically suitable for large-scale air capture (Boucher and Folberth, 2010). Co-benefits of methane removal include reduced tropospheric ozone production, decreased stratospheric forcing, energy recycling by exploiting the methane chemical energy, and a further reduction in atmospheric CO_2 (Boucher and Folberth, 2010). Methane removal potentials are limited due to its low atmospheric concentration and its low chemical reactivity at ambient conditions.

Enhancing seagrass meadows ("blue carbon"). While the global CDR potential of blue carbon has not been quantified, individual options have been assessed, finding co-benefits beyond the pure benefit of carbon sequestration (Macreadie et al., 2017). 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 risk of reversal. Seagrass beds will thus likely not contribute significantly to meeting the 1.5°C target.

Uncertainties affecting multiple CDR options. On long time scales, natural sinks could reverse (Jones et al., 2016); more research is needed for robust assessments of the effectiveness of CDR in reverting climate change (Tokarska and Zickfeld, 2015).

4.3.8.7 Overall feasibility assessment of CDR

CDR options are at different stages of technological readiness (McLaren, 2012) and differ with respect to scalability. Nemet et al. (2017) 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. Post-R&D issues will need to be addressed, including incentives for early deployment, niche markets, scale-up, demand, and public acceptance. Further, the CDR potentials that can be realised are constrained by the lack of policy portfolios incentivising large-scale CDR (Peters and Geden, 2017). Near-term opportunities could be supported through modifying existing policy mechanisms (Lomax et al., 2015). More research on policy frameworks and governance for CDR is needed.For Ocean Fertilisation, the governance structure in the form of the London Protocol calls for more research before considering commercial-scale deployment.

Preston (2013) identifies distributive and procedural justice, permissibility, moral hazard, and hubris as ethical aspects that could apply to large-scale CDR deployment. However, the ethics literature on CDR is sparse in contrast to 'radiation modification measures' (RMMs) and future work should reflect on the climate futures produced by recent modelling and implying very different ethical costs/risks and benefits (Minx et al., 2017a). Social impacts of large-scale CDR deployment (Buck, 2016) require policies taking these into account. Burns and Nicholson (2017) propose a human rights-based approach to protect those potentially adversely impacted.

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

4.3.9 Solar radiation management

As in AR5, this report separates Solar Radiation Management (SRM) from Carbon Dioxide Removal (Section 4.3.8). Because of this separation, this report refrains from using the term ‘geoengineering’, which some of the literature uses to cover SRM, CDR, or both. In this report, we classify CDR as mitigation. SRM, from hereon called Radiation Modification Measures (RMMs) (see also Cross-Chapter Box 4.2) is neither adaptation nor mitigation.

Recent papers have asserted that RMMs could reduce some of the global risks of climate change related to temperature rise (Izrael et al., 2014; MacMartin et al., 2014a), but others indicate that the risks of changing precipitation, ozone, cloudiness and implications thereof outdo the benefits (Pitari et al., 2014; Visioni et al., 2017a). No literature supports the complete substitution of mitigation by RMMs, but only as a supplement to deep mitigation, for example in overshoot (“peak-shaving”) scenario (see Cross-Chapter Box 4.2 for details) (MacMartin et al., 2018; Smith and Rasch, 2013). A full discussion of all RMMs currently proposed, and their implications for geophysical quantities and sustainable development, are in Cross-Chapter Box 4.2. This section assesses the feasibility, from an institutional, technical, economic and social-cultural viewpoint, focusing on Stratospheric Aerosol Injection (SAI) unless otherwise indicated, as most available literature is about SAI.

Much of the literature on RMMs appears in the forms of commentaries, policy briefs, viewpoints and opinions, reflecting opinions of researchers (e.g., (Horton et al., 2016; Keith et al., 2017; Parson, 2017). This report is primarily based on original research and such viewpoints are therefore not assessed, also if they appear in scientific journals.

4.3.9.1 Governance and institutional feasibility

RMMs would be intended to result in positive consequences for some, but would have negative consequences for others (Heyen et al., 2015) and would result in an “addiction problem”; once started, it’s hard to stop (Sandler, 2017). There is high evidence for unilateral action potentially becoming a serious RMM governance issue (*e.g.*, (Rabitz, 2016; Weitzman, 2015), but *medium agreement*; others argue that enhanced collaboration might emerge around RMMs (Horton, 2011). An equitable institutional or governance arrangement around RMMs would have to address this, and reflect views of different countries (Heyen et al., 2015; Robock, 2016). The literature mostly suggests that RMMs, like many other climate responses, requires multilateral governance because of the high costs and impact on the global commons, because of the risk of termination, and because of risks that implementation or unilateral action by one country or organisation will produce negative side effects for others, especially in terms of precipitation, extreme events, and photosynthesis (Al-sabah and Brien, 2015; Dilling and Hauser, 2013; Lempert and Prosnitz, 2011; US National Academy of Sciences, 2015). Some have suggested that the governance of research and field experimentation can help clarify the many uncertainties surrounding RMMs (Caldeira and Bala, 2017; Lawrence and Crutzen, 2017; Long and Shepherd, 2014; NRC, 2015).

Several possible institutional arrangements have been considered for RMM governance: under the UNFCCC or the UNCBD (Honegger et al., 2013), under SBSTA (Nicholson), by a single state, or through a consortium of states (Bodansky, 2013; Sandler, 2017). Assessing the feasibility of an international governance framework for RMMs, Lloyd and Oppenheimer (2014) conclude that states will seek to join it because they will want to ensure that others do not act unilaterally, to have a voice in RMM diplomacy and would benefit from collaboration on scientific research.

Nicholson et al. (2017) suggest that, alongside SBSTA, the WMO, UNESCO and UN Environment could play a role in governance of RMMs. For WMO, this is confirmed by (Bodle et al., 2012) as well as Williamson and Bodle (2016). Finally, the UNCBD adopted decisions regarding RMMs (though CBD talks about ‘”geoengineering”’) warning against any actions that could harm biodiversity until an adequate scientific basis justifies such activities. Szerszynski et al. (2013) and Owen (2014) argue that RMM deployment may never be decided by democratic processes.

4.3.9.2 Economic and technical feasibility

The literature on engineering cost of RMMs is limited and none of the papers are based on real-world costing studies. Cost estimates of SAI (not taking into account indirect and social costs, research and development costs and monitoring expenses) are in *high agreement* that costs may be in the range of USD1–10 billion annually for injection of 1–5 Mt of sulphur to achieve cooling of 1–2 W m^{-2}(McClellan et al., 2012; Moriyama et al., 2016; Robock et al., 2009; Ryaboshapko and Revokatova, 2015), suggesting that cost-effectiveness may be high when side-effects are low or neglected (McClellan et al., 2012). The overall economic feasibility of RMMs also depends on any externalities and social costs (Mackerron, 2014; Moreno-Cruz and Keith, 2013), but these are usually not assessed in integrated assessment models because of model limitations (Heutel et al., 2016; Manoussi and Xepapadeas, 2015; Metcalf and Stock, 2015). 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 RMMs (Ricke et al., 2015; Weitzman, 2015).

For SAI, sulphur dioxide (SO_2) is most often suggested as a precursor of sulphate aerosol (*e.g.*,(Crutzen, 2006; Kravitz et al., 2011). There is *highagreement* that aircrafts could inject the millions of tons of SO_2 needed in the lower stratosphere (~20 km or 60 hPa) (Davidson et al., 2012; Irvine et al., 2016; McClellan et al., 2012).

4.3.9.3 Social acceptability and ethics

Key ethical questions discussed in the research literature include those of international responsibilities for implementation, financing, and compensation for negative effects, the procedural justice questions of who is involved in decisions, privatisation and patenting, informed consent by affected publics, intergenerational ethics (because RMMs require sustained action in order to avoid termination hazards), the rights of non-human species, Indigenous peoples and women, and the so-called ‘moral hazard’ that RMMs could reduce mitigation and adaptation efforts (Buck et al., 2014; Burns, 2011; Morrow, 2014; Whyte, 2012; Wong, 2014) (Suarez and van Aalst, 2017). The literature shows *low agreement* on the moral hazard of RMM research and deployment (Linnér and Wibeck, 2015). Sometimes described as ‘mitigation obstruction’, ‘moral hazard’ is used to indicate that RMM research (preceding its implementation) may lead policy-makers to reduce mitigation efforts (Klepper and Rickels, 2014; Lin, 2013; McLaren, 2016; Morrow, 2014). There is empirical evidence on the level of individuals (as opposed to policymakers) that indicates that RMMs might motivate people to reduce their GHG emissions (Merk et al., 2016), though others did not confirm this (Corner and Pidgeon, 2014). A ‘slippery slope’ argument, that RMM research increases the likelihood of deployment, is also made (Quaas et al., 2017).

Lack of transparency, unequal representation and deliberate exclusion are to be expected in decision-making on RMMs, as regional differences in climate outcomes create strategic incentives to form coalitions that are as small as possible, while still powerful enough to deploy RMMs for themselves - excluding non-members that would prevent implementation (Ricke et al., 2013). Whyte (2012) argues that the concerns, sovereignties, and experiences of Indigenous peoples are particularly at risk.

There is some evidence that the public is confused and concerned about RMMs, with those in developing countries unaware of the issue (Carr et al., 2013; Parkhill et al., 2013). There is a limited but emerging literature on public perception of RMMs, showing a lack of knowledge and unstable opinions (Scheer and Renn, 2014). The perception of controllability affects legitimacy and public acceptability of RMM experiments (Bellamy et al., 2017). Merk et al. (2015) and Braun et al. (2017) conclude that, in Germany, laboratory work on RMMs is generally approved of, field research much less so, and immediate deployment is largely rejected. They also find that trust in scientists and firms, the belief that climate change is a serious problem and that “humans should not manipulate nature” affects people’s positions (Merk et al., 2015). Such factors could explain variations in the degree of rejection of RMMs between Canada, China, Germany, Switzerland, the United Kingdom, and the United States (Visschers et al., 2017).

4.4 Implementing far-reaching and rapid change

Transformational change, whether the product of small changes (Sterling et al., 2017; Termeer et al., 2017) or large-scale disruptions (Geels et al., 2017b), is seldom an insular or discrete process. It is influenced by the context in which it takes place. AR5 recognised the "numerous conditions" that influence the efficacy and cost-effectiveness of climate policy and associated instruments, stating that this "enabling environment" is likely to differ across countries (Kolstad et al., 2014).

Section 4.4 describes the governance (Section 4.4.1), institutional capacity (Section 4.4.2), behaviour and lifestyle (Section 4.4.3), technological and innovation (Section 4.4.4), economic and regulatory (Section 4.4.5) and finance (Section 4.4.6) enablers of a 1.5°C world. Pathways to this world require coherence between these domains to support transformational change and to reduce the cost at which change is achieved.

This coherencetypically involves the parameters discussed in Sections 4.4.1 to 4.4.6 spanning local, sub-national, national and transnational scales (Geels et al., 2017b; Revi, 2017), even when this is more difficult (Ziervogel et al., 2016). Decarbonisation of Shenzhen, China, is enabled by China's swing in coal consumption from 3.7% growth in 2013 to 3.7% decline in 2015 (BP Global, 2016; Hsu et al., 2017; Zhang, 2010), and local incentives to manage trade-offs between ecological integrity, urbanisation quality, expanding domestic demand and rural-urban linkages, that are codified in China's New-type Urbanisation Plan (NUP) (Cheshmehzangi, 2016). A significant literature emphasises the "nesting" of institutions across these scales as a prerequisite for aligning incentives and the sharing of risk (Abbott et al., 2012). Others point to the importance of information sharing, trust and reciprocity ahead of narrow alignment (Cole, 2015a; Jordan et al., 2015). Effective governance of common resources, such as the atmosphere, depends on trust; when governing common property resources, requires multi-lateral commitments that are not overly expensive to monitor governments (Cole, 2015a; Ostrom et al., 1994) and can be enhanced by monitoring and reporting mitigation and adaptation progress relative to 1.5°C pathways (Diaz-Rainey et al., 2017; James et al., 2017; Lesnikowski et al., 2016; Magnan and Ribera, 2016; Surminski, 2013).

The limits to our understanding of the climate system and the partial influence on that system of any single country, city or company, implies that enabling environments can be enhanced by inter-disciplinary partnerships (Brondizio et al., 2014; Bulkeley et al., 2013; Tait and Euston-Brown, 2017). Inter-disciplinary knowledge partnerships and science-policy interactions, in particular, can be difficult to establish and sustain, but provide the information, skill, technologies and political support required for the challenging and complex transition to a 1.5°C world (Figueres et al., 2017; Filhoa et al., 2018; Hering et al., 2014; Roberts, 2016; Vogel et al., 2007).

The emergence of polycentric loci of climate action and the transnational and subnational networks that link these efforts (Abbott, 2012), offer the opportunity to experiment and learn from different approaches, thereby accelerating the process led by national governments (Cole, 2015a; Jordan et al., 2015).

Enabling environments are both more durable and more effective when they are inclusive, and take into consideration the tenacity with which people (the poor in particular) protect hard-won livelihoods (Blanchet, 2015; Ziervogel et al., 2016). In this regard, the capacity to engage the growing proportion of people in informal settlements in low-income cities and to manage rural-urban trade-offs, is an important part of an enabling environment for 1.5°C pathways (Freire et al., 2014; Wachsmuth et al., 2016b; Ziervogel et al., 2016), recognising that many people in these cities remain beyond the direct reach of traditional climate policy instruments (Jaglin, 2014). In developing countries, the capacity to transition to a 1.5°C world may depend on addressing the "everyday development failures" that undermine climate responses (Pelling et al. 2017) and embedding climate responses in sustainable development (Hallegatte et al., 2016).

The potential for rapid and widespread climate responses is enhanced by mutually enforcing market instruments, regulations and standards and strategic investment, targeting different barriers to change (Grubb et al., 2014) - a point Campiglio (2016) and Winkler and Dubash (2015) reiterate in the specific contex of carbon pricing.Support for systemic approaches that combine adaptation and mitigation and unlock synergies can accelerate change by respectively mainstreaming and integrating climate policy (Locatelli et al., 2015; Abeygunawardena et al., 2003) reducing cost and securing social and political support (Hallegatte and Mach, 2016).

Public awareness and access to climate information is loosely linked to climate action, but can inform perceptions of climate risk and the capacity to respond (Lee et al., 2015). Where education and climate services inform women, they support an important component of an enabling environment for ambitious climate responses (Azeiteiro et al., 2017; Lutz and Muttarak, 2017; Wamsler, 2017).

Effective enabling environments draw on, rather than resist, global mega-trends such as ICT, financialisation, globalisation and urbanisation, so as to direct changes in behaviour (Araújo, 2014; Geels et al., 2017b). For example, given the scale of the urbanisation trend, it is difficult to imagine how a 1.5°C world will be attained unless the SDG on cities and sustainable urbanisation is attained in developing countries (Revi, 2016), or without major reforms in the global financial system (Pauw, 2017).

Bold political leadership and a clear vision can give direction to innovation and investment in spite of uncertainty (Etzion et al., 2017; Gota et al., 2017). Where leadership enables accountable and targeted government spending and the levying of taxes, it provides investors with clear signals (Geels et al., 2017b; Grubb et al., 2014; Mazzucato and Semieniuk, 2017). Removing perverse subsidies and identifying 'sun-rise' and 'sun-set' sectors and technologies in policy targets (see Section 4.2.2), such as the scheduled phasing out of fossil-fuel powered vehicles in a number of countries and cities, for example, can guide innovation and industrial policy while assisting the smooth reallocation of assets (Battiston et al., 2017; Carter and Jacobs, 2014; Hallegatte et al., 2013).

Leadership that establishes a locally relevant rights framework can enable an environment in which difficult trade-offs between interest groups can be navigated, and perverse outcomes in the context of rapid change avoided (Ziervogel et al., 2017). Such a framework can enable inclusive and more long-lasting sustainability transitions (Swilling and Annecke, 2012).

4.4.1 Enhancing multi-level governance

Addressing climate change and implementing responses for 1.5°C pathways will need to engage with various levels and types of governance to curb emissions and to increase resilience (Betsill and Bulkeley, 2006; Christoforidis et al., 2013; Kern and Alber, 2009; 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 was defined in the broadest sense as the "processes of interaction and decision making among actors involved in a common problem". This definition goes beyond notions of formal government or political authority and integrates other actors, networks, informal institutions, and incentive structures, including communities meeting in a physical arena or online.

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 transformation pathways required to remain below 1.5° C (Munck et al., 2014; Willis, 2017). Individual behaviours are embedded in social institutions, institutional contexts and cultural norms, and are influenced by socio-technical contexts reflecting complex relationship dealing with specific material, political, economic, historic, geographic and cultural factors, competences and associated meanings (Shove, 2010). Governance and cultural transformations are needed to support wide-scale adoption of mitigation and adaptation options. Considerable work remains to align the incentives, aspiration, policies and finance to support the shifts required to remain below 1.5°C (Floater et al., 2014). Institutions and governance structures are strengthened when the principle of the 'commons' are explored as a way of sharing management and responsibilities (Chaffin et al., 2014; Ostrom et al., 1999; Young, 2016). Institutions need to be strengthened to interact amongst themselves, and to share responsibilities for the development and implementation of rules, regulations, and policies (Craig et al., 2017; Ostrom et al., 1999; Wejs et al., 2014), with the goal of ensuring that these embrace poverty alleviation and sustainable development, enabling a 1.5°C world through mitigation and building adaptive capacity (Reckien et al., 2017; Wood et al., 2017).

Multi-level governance in climate change has emerged as a key enabler for systemic transformation and effective governance, combining decisions across levels, as well as a cross-sectors and across various types of institutions at the same level (Romero-Lankao et al., 2018).

Several authors have identified different modes of cross-stakeholder interaction in climate policy. Kern and Alber (2009) recognise different forms of collaboration relevant to successful climate policies beyond the local level. Horizontal collaboration (e.g. transnational city networks sharing best practices) and vertical collaboration within nation-states can play an enabling role with national governments and funding schemes (Ringel, 2017). Vertical and horizontal collaboration require synergistic relationships between stakeholders (Hsu et al., 2017; Ingold and Fischer, 2014). (Ciplet et al., 2015) argue that civil society is likely to be the only reliable motor for driving institutions to change at the pace required. The importance of community participation for mitigation and adaptation is emphasised in diverse scholarship, and in particular the need to take into account equity and gender considerations (see Chapter 5) (Bryan et al., 2017; Graham et al., 2015; Wangui and Smucker, 2017), but also faces 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 policy deadlock (Ford et al., 2016b; Preston et al., 2013, 2015).

Strengthening solutions and policy change requires both a bottom-up approach engaging citizens, businesses, municipalities and local communities and a more traditional top-down approach, enacted by national or supranational governmental institutions (Jordan et al., 2015; Romero-Lankao et al., 2018). A bottom-up approach provides information and a local perspective on what are viable actions and targets, while top/down can respond to short-term political interest linked to electoral cycles (Bataille et al., 2016; Maor et al., 2017). Actions by nation states are discussed in Section 4.4.5 on policy instruments.

4.4.1.2 International governance

Supranational authorities and treaties can help strengthen policy implementation, providing a guide to transition in periods between election cycles to ensure a medium and long-term vision is being considered and followed (Obergassel et al., 2016). International governance is organised via many mechanisms, including international organisations, treaties and conventions (e.g. UNFCCC, Paris Agreement, Montreal Protocol). Other multilateral and bilateral agreements, such as trade blocks, also have a bearing on climate change. Legally binding international agreements will not only ensure implementation, but also ensure that others will act too, enhancing fairness of multilateralism (Winkler and Beaumont, 2010).

International climate governance has some profound differences between mitigation and adaptation governance. Mitigation tends to be global by its nature and it is based on the principle of the climate systems as a global commons (Ostrom et al., 1999). Adaptation has traditionally been viewed as a local process, involving local authorities, communities, and stakeholders (Khan, 2013; Preston et al., 2015), although is now recognised to be a multi-scaled, multi-actor process that transcends international to national to sub-national scales (Mimura et al., 2014; UNEP, 2017a). Many measures are best taken at the national level for reasons of both accountability and effectiveness, with national governments a central pivot for adaptation coordination, planning, determining policy priorities and distributing resources and support. For the majority of low and middle-income nations, international adaptation support is a major source of adaptation financing, and a catalyst for bringing climate change considerations into policy programming. Many of the impacts of climate change are transboundary, so that bilateral and multilateral cooperation are needed on adaptation (Donner et al., 2016; Lesnikowski et al., 2017; Magnan and Ribera, 2016; Nalau et al., 2015; Tilleard and Ford, 2016).

Work on international climate governance has focused on the nature of ‘climate regimes’, coordinating the action of nation-states (Aykut, 2016). Most discussions center on whether this coordination relies upon binding limits allocated by principles of historical responsibility and equity, or on carbon prices, emissions quotas or pledges and review of policies and measures (Grubb, 1990; Newell and Pizer, 2003; Pizer, 2002; Stavins, 1988). Literature about the failure of the system and actors that produced the Kyoto Protocol(KP) gives two important insights from a 1.5°C perspective: the inability to agree on rules to allocate emissions quotas under the UNFCCC principle of Common but Differentiated Responsibility (Gupta, 2014; Méjean et al., 2015; Shukla, 2005; Winkler et al., 2013) and a climate-centric vision of a climate regime (Shukla, 2005; Winkler et al., 2011), separated from development issues which drove identity and resistance among developing nations (Roberts and Parks, 2006). For the former, a burden sharing approach led to an adversarial process among nations to decide who shall be allocated ‘how much’ of the remainder of the emissions budget (Giménez-Gómez et al., 2016; Ohndorf et al., 2015; Roser et al., 2015). Industry group lobbying was fundamental in reducing the capacity of some key major emitting nations to move adequately on the issue of climate change (Dunlap and McCright, 2011; Geels, 2014; Levy and Egan, 2003; Newell and Paterson, 1998) as government-led approaches were derided as cumbersome and ineffective.

The factors that doomed the Kyoto Protocol led to a diametrically opposed approach of no binding commitments in the Copenhagen Accord, the Cancun Agreements, and finally in the Paris Agreement. The transition to 1.5 C requires the elimination of all GHG emissions and thus going beyond the traditional framing of climate as a ‘tragedy of the commons’ to be addressed *via* cost-optimal allocation rules – which have a low probability of enabling a transition to a 1.5°C world (Patt, 2017). The bottom-up approach of the Paris Agreement must be strengthened under conditions that enable effective monitoring and timely reporting on national contributions (including on adaptation), international scrutiny and persistent efforts of civil society to encourage greater and faster action in 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).

The paradigm shift enabled at Cancun by focusing on the objective of ‘equitable access to sustainable development’ (Hourcade et al., 2015) and the use of ‘pledge and review’ now underpins the Paris Agreement. This consolidates the attempts to define a governance approach that relies on National Determined Contributions (NDCs) and on means for a ‘facilitative model’ (Bodansky and Diringer, 2014) to reinforce them. The Paris Agreement enables a more regular, iterative, tightening of NDCs and more flexible, 'experimental' forms of climate governance, which may or may not provide room for higher ambition, and be consistent with the needs of governing for a rapid transition (Clémençon, 2016; Falkner, 2016). Beyond a general consensus on the necessity of Measuring, Reporting and Verification (MRV) mechanisms as a key element of a climate regime, some authors emphasise different governance approaches to implement the Paris Agreement. For example, convergence toward a uniform carbon price and the progressive integration of different regional mechanisms (Bodansky et al., 2014; Metcalf and Weisbach, 2012) under Article 6.3 (ITMOS) and the JCM (Articles 6.4 and 6.7), and speeding up climate action as part of ‘climate regime complex’ (Keohane and Victor, 2011) of loosely interrelated global governance institutions. The CBDR principle can be expanded and revisited under a ‘sharing the pie’ paradigm (Ji and Sha, 2015) as a tool to open a world innovation process towards alternative development pathways.

The Cancun COP16 (2010) represented a pivotal moment in the growing role of adaptation in the Convention, in which it was explicitly stated that adaptation must be addressed with the same priority as mitigation. The Paris Agreement also calls for stronger adaptation commitments from states; is explicit about the multilevel nature of adaptation governance; outlines stronger transparency mechanisms; links adaptation to development and climate justice; and is suggestive of greater inclusiveness of non-state voices and the broader contexts of social change (Fook, 2017; Lesnikowski et al., 2017).

A 1.5°C transition requires further exploration into conditions of trust and reciprocity amongst nation states (Ostrom and Walker, 2005; Schelling, 1991). Seminal suggestions are made, for example to depart from the Nash-based vision of games with actors acting individually in the pursuit of their self-interest to a Berge-based vision of games (Colman et al., 2011; Courtois et al., 2015). Iterated games with the same actors interacting over time show that reciprocity, with occasional forgiveness and initial good faith, can lead to win-win outcomes and to cooperation as a stable strategy (Axelrod, 1984).

Regional cooperation plays an important role in the context of global governance, Literature on climate regimes has only started exploring ways of articulating markets, state and non-state actors like the search of coalitions of transnational actors as a substitute to states (Hermwille et al., 2017; Hovi et al., 2016; Hagen et al., 2017; Bulkeley et al., 2012) or clubs of countries as complement to the UNFCCC (Abbott and Snidal, 2009; Nordhaus, 2015; Biermann, 2010; Zelli, 2011).

4.4.1.3 Community and local governance

Not only do urban centres aggregate the economic demand, capital and information required to affect change, but in many instances cities are able to respond more quickly than national states (Floater et al., 2014). Cities are more willing to address citizens' real concerns such as climate change impacts (Melica et al., 2017). Local governments can play a key role (Romero-Lankao et al., 2018) in influencing mitigation strategies such as those needed to stay below 1.5 C whilst having the ability to cope with impacts of greater warming. It is important to understand how cities, rural and urban municipalities, and communities might intervene to reduce climate impacts (Bulkeley et al., 2011), either by implementing climate objectives defined at higher government levels, or taking initiative autonomously (Aall et al., 2007; Araos et al., 2016b; Heidrich et al., 2016; Reckien et al., 2014). Such efforts might include adopting sustainable energy practices and developing a nexus approach to the governance of the food, water and energy services at the local level. Local governments are a key to coordination and developing effective local responses and more effective policies around energy, vulnerability reduction, and environmental issues (Fudge et al., 2016; Moss et al., 2013). They can enable more participative decision-making (Barrett, 2015; Hesse, 2016). Fudge et al. (2016) note that local authorities are well-positioned to involve the wider community in designing and implementing climate policies, and engaging with the technological aspects of energy generation, for example, by supporting energy communities (Slee, 2015), the delivery of sustainable demand-side energy management strategies, and adaptation development. Work remains in aligning efforts of cities with UNFCCC goals, but the growing networks of mayors and cities sharing experiences on coping with climate change and drawing economic and development benefit from climate change responses represent an important institutional innovation. Non-state actors, including cities, have set up several transnational climate governance initiatives to accelerate the climate response (e.g. Global Island Partnership, Covenant of Mayors, C–40, ICLEI)(Hsu et al., 2017; Kona et al., 2018; Melica et al., 2017; Ringel, 2017) and to exert influence on national governments and the UNFCCC (Bulkeley, 2005).

4.4.1.4 Interactions and processes for multi-level governance

It is unclear how multiple actors with varied motivations and agendas will come together to undertake action towards enabling a 1.5°C transition. There is growing evidence on some aspects of climate governance: a study on 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). (Berrang-Ford et al., 2014)in their assessment of national level adaptation in 117 countries, find good governance to be the one of the strongest predictors of national adaptation policy. (Reckien et al., 2015) in their analysis of climate response by 200 large and medium-sized cities across 11 European countries find that factors such as membership of climate networks, population size, GDP per capita and adaptive capacity act as drivers of mitigation and adaptation plans.

National processes to prepare integrated climate and development plans must be leveraged to meet adaptation and mitigation goals. Adaptation policy has seen growth in some areas (Lesnikowski et al., 2016; Massey et al., 2014), 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 (e.g. National Climate Change Policies, Low Emissions Climate Resilient Development, National Adaptation Programs of Action, National Adaptation Plans).The NDCs have been identified as one such institutional mechanism (Kato and Ellis, 2016; Magnan et al., 2015; Peters et al., 2017b); see also Cross-Chapter Box 4.1 on NDCs.

To overcome barriers to policy implementation, local conflict of interests 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 (e.g. zero emissions by 2050) are more likely to succeed in reducing GHG emissions (Croci et al., 2017; Kona et al., 2018; Rivas et al., 2015). This vision needs to be translated into an action plan, describing the policies and measures needed to achieve the target, the human and financial resources needed, key milestones, and appropriate measurement and verification process (Azevedo and Leal, 2017). Discussing the plan with stakeholders, including citizens, and having them provide input and endorse it, is found to increase the likelihood of success (Rivas et al., 2015; Wamsler, 2017). Effective plans also describe the financial tools for implementation. However, as described byNightingale (2017) and Green (2016), struggles over natural resources and adaptation governance both at the national and community levels need addressing too, ‘in politically unstable contexts, where power and politics shape adaptation outcomes’.

[START BOX 4.1 HERE]

Box 4.1: Multi-level governance in the EU Covenant of Mayors: Example of the Provincia di Foggia

Growing urban populations and the recognition that cities account for a majority portion of GHG emissions, cities have emerged as the locus of institutional and governance climate innovation (Melica et al., 2017), showing significant leadership in driving proactive responses to climate change (Roberts, 2016). Many cities have adopted more ambitious GHG emission reduction targets than countries (Kona et al., 2018). The Covenant of Mayors (CoM) is an initiative in which municipalities voluntarily commit to CO_2 emission reduction. As of September 2016, small municipalities (less than 10 000 inhabitants) covered 66% of the total number of CoM signatories. The involvement of small municipalities has allowed the development and testing of a new multi-level governance model involving Covenant Territorial Coordinators (CTCs), i.e. public authorities such as Provinces and Regions, which commit to providing strategic guidance, financial and technical support to municipalities in their territories willing to deploy climate policies. This supportive trend by CTC is also observed in monitoring the progress of the emission over time. Results from the 315 monitoring inventories submitted shows an already achieved 23% reduction in emissions (compared to an average year 2005) with more than half of the cities under a CTC schema.

The province of Foggia (intermediary government body in southern Italy), acting as a CTC has given support to 36 municipalities (most of them with a population below 10 000 inhabitants) 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 and guided the signatory to identify an appropriate combination of measures to curb GHG emissions, including energy efficiency actions in public buildings, and public lighting. Financial support for the implementation of these actions was found through the European Local Energy Assistance (ELENA) program, a joint initiative of the European Investment Bank and the European Commission. The local Chamber of Commerce had a key role also in the implementation of these projects by the municipalities.

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(Christoforidis et al., 2013; Larsen and Gunnarsson-Östling, 2009; Lee and Painter, 2015; Musall and Kuik, 2011; Pasimeni et al., 2014; Pollak et al., 2011).

Achieving this ambition will take leadership, vision and widespread participation in transformative change (Castán Broto and Bulkeley 2013; Wamsler 2017; Fazey et al., 2017, Romero-Lankao et al., 2018,Rosenzweig et al., 2015). Section 5.6.4 analysis of climate-resilient development pathway case studies (at state and community scales) shows that participation, social learning and iterative decision-making are important governance features of strategies that deliver mitigation, adaptation, and sustainable development in a fair and equitable manner.Further issues are incremental yet significant voluntary changes amplified through community networking, poly-centric partnerships and long-term change to governance systems at multiple levels (Lövbrand et al., 2017; Pichler et al., 2017; Stevenson and Dryzek, 2014; Termeer et al., 2017).

[END BOX 4.1 HERE]

Multilevel governance refers to adaptation activity across administrative levels, consistent with the notion that adapting to climate change involves a range of decisions 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). 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 (Austin et al., 2015). 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 (Adger et al., 2005; Austin et al., 2015).

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 exists (Shi et al., 2016). Multilevel approaches are relevant in low-income countries where limited financial and human resources within local governments often lead to greater dependency on national governments and other (donor) organizations, to strengthen adaptation responses (Adenle et al., 2017a; Donner et al., 2016). A multilevel approach seeks to determine how different levels of government contribute to or obstruct the process of adaptation planning. National governments or international organisations, for example, may motivate urban adaptation externally through broad policy directives or projects by international donors taking place in a city. 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 municipal-level factor driving adaptation policy of early adapters in Quito, Ecuador, and Durban, South Africa (Anguelovski et al., 2014), and for adaptation more generally (Smith et al., 2009).

Box 4.2 exemplifies how multilevel governance has been used for watershed management in different basins.

[START BOX 4.2 HERE]

Box 4.2: Watershed management in a 1.5˚C world

Water management is necessary if the global community is expected to adapt to a 1.5°C scenario. Cohesive planning that includes numerous stakeholders will be required to maximise water utility while also ensuring hydrologic viability.

Response to drought and El Niño Southern Oscillation (ENSO) in Southern Guatemala
Hydro-meteorological events, including the El Niño Southern Oscillation, have impacted Central America (Chang et al., 2015; Maggioni et al., 2016; Steinhoff et al., 2014) and are predicted to increase in frequency in a 1.5°C scenario (Wang et al., 2017b). The 2014–2016 ENSO devastated agriculture in Southern Guatemala, seriously impacting rural communities.

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

Drought management through the Limpopo Watercourse Commission
The Governments sharing the Limpopo river basin and formed the Limpopo Watercourse Commission in 2003 (Mitchell, 2013; Nyagwambo et al., 2008). The Commission has an advisory body comprised of working groups that assess water use and sustainability, decides distribution on national level of water access, and supports disaster and emergency planning. In an analysis of coastal deltas, (Tessler et al., 2015)

find the Limpopo basin highly vulnerable, which is associated with a lack of infrastructure and investment capacity, requiring increased economic development together with plans for vulnerability reduction (Tessler et al., 2015) f and water rights (Swatuk, 2015). The high vulnerability is influenced by gender inequality, limited stakeholder participation and unequal water access management institutions (Mehta et al., 2014). The implementation of IWRM needs to consider pre-existing social, economic, historical, and cultural contexts (Mehta et al., 2014; Merrey, 2009), therefore, the Commission plays an even more important role in improving equity and participation and in providing an adaptable and equitable strategy in 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 15 countries that share the Danube Basin. The International Commission for the Protection of the Danube River (ICPDR), through expert working groups dealing with issues including governance, monitoring and assessment, and flood protection, ensures a strong science-policy link (Schmeier, 2014). The Trans-National Monitoring Network (TNMN) was developed by the ICPDR to do comprehensive monitoring of water quality (Schmeier, 2014). Water quality constitutes the most important challenge and the topic represents almost 50% of ICPDR's scientific publications, which also works on governance, basin planning, monitoring, and IWRM. The ICPDR is one of the best examples of integrated water resource management 'coordinating groundwater, surface water abstractions, flood management, energy production, navigation, and water quality' (Hering et al., 2014).

[END BOX 4.2 HERE]

4.4.2 Enhancing institutional capacities

The implementation of sound responses and strategies for a 1.5°C world will require strengthening governance and scaling up institutional capacities particularly in developing countries (Adenle et al., 2017b; Rosenbloom, 2017). This section examines what is required in terms of changes in institutional capacity to implement actions to make the transition to a 1.5°C world, and adapt to its consequences. This takes into account a plurality of regional and local responses, as institutional capacity is highly context-dependent (Lustick et al., 2011; North, 1990).

Institutions 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 must try to include the growing proportion of the world's population that live in peri-urban and informal settlements and engage informal economic activity (Simone and Pieterse, 2017). This population, amongst the most exposed to perturbed climates in the world (Hallegatte et al., 2017), is also beyond the direct reach of some policy instruments (Jaglin, 2014; Thieme, 2017). Strategies that accommodate the informal rules of the game adopted by these people are more likely to succeed (Kaika, 2017; McGranahan et al., 2016).

The goal for strengthening implementation is to ensure that these rules and regulations embrace equity, equality and poverty alleviation along a low-emission pathway that leads to a 1.5°C world (mitigation) and enables the building of adaptive capacity (adaptation) that together, will enable sustainable development.

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

4.4.2.1 Capacity for policy design and implementation

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

Access to a knowledge base, the availability of resources, political stability, and a regulatory and enforcement framework (*e.g.* institutions to impose sanctions, collect taxes and to verify building codes) are needed at various governance levels to address a wide range of stakeholders, and their concerns. There is a need to support these with different interventions (Pasquini et al., 2015).

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

Additionally, implementing 1.5°C-relevant strategies would require well-functioning legal frameworks to be in place in conjunction with clearly defined mandates, rights and responsibilities to enable the institutional capacity to deliver (Romero-Lankao et al., 2013). As an example, current rates of urbanisation occurring in cities with a lack of institutional capacity for proper 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). In Huambo (Angola), a classified ‘urban’ area extends 20 km west of the city and is predominantly ‘unplanned’ urban settlements (Smith and Jenkins, 2015).

Internationally, the Paris Agreement process has enhanced the capacity of decision-making institutions in many developing countries to support effective implementation. These efforts are particularly reflected in Article 11 of the Paris Agreement on capacity building, as well as Article 15 on compliance (UNFCCC, 2015c).

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Box 4.3: Indigenous knowledge and community adaptation

Indigenous knowledge systems, also referred to as traditional knowledge systems, are a “cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment” (Díaz et al., 2015). 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). A challenge for the research community is to address how to engage indigenous populations and their knowledge systems to improve and support climate science and adaptation.

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 (known as the “ICC,” in Spanish), has resulted in a catalogue of traditional and ancestral knowledge, used to identify indicators for watershed meteorological forecasts (Yax L. and Álvarez, 2016). These indicators are relevant but must also be continually assessed to determine their continued reliability, due to changing climatic and environmental conditions (Alexander et al., 2011; Mistry and Berardi, 2016; Nyong et al., 2007). For more than 10 years, Guatemala has maintained an “Indigenous Table for Climate Change,” which encourages indigenous concerns to be taken into consideration in shaping national policies and, more importantly, that indigenous knowledge contributes to the planning for varying disaster management and adaptation policies.

In Tanzania, increased climate variability of rainfall is a substantial challenge for Indigenous and local communities (Lema and Majule, 2009; for e.g., Mahoo et al., 2015; Sewando et al., 2016). Though seasonal forecasts based on meteorological data are widely disseminated through text message and radio (Mahoo et al., 2013), these forecasts have been met with limited adoption due to perceptions of unreliability and limited relevance of language, timing and scale (Elia et al., 2014; Kadi et al., 2011; Mahoo et al., 2013). The majority of agro-pastoralists use Indigenous knowledge to forecast seasonal rainfall, relying on observations of plant phenology, bird and other animal and insect behaviour, the sun and moon, and the wind (Chang'a et al., 2010; Elia et al., 2014; Shaffer, 2014). Increased variability of climate factors have raised concerns as to whether these indicators are less reliable, as plant and animal populations either decline or adapt to climate variability (Shaffer, 2014). To meet these challenges, initiatives have focused on the co-production of knowledge, through involving local communities in monitoring and discussing the implications of indigenous knowledge and meteorological forecasts (Shaffer, 2014), and creating local forecasts by integrating the two sources of knowledge (Mahoo et al., 2013). The co-production of forecasts has resulted in increased documentation of Indigenous knowledge, increased understanding of relevant climate information amongst stakeholders, and the increased adaptive capacity at the community-level (Mahoo et al., 2013, 2015; Shaffer, 2014).

1.5°C warming poses many challenges to the Pacific Islands, including rising sea levels, hazards from cyclones, and coral bleaching (Chapter 3). The characterisation of the Pacific Islands as highly vulnerable has been criticised however, as undervaluing the cultural resilience of its inhabitants (Nunn et al., 2017). Indigenous communities in the region have a long history of adapting to environmental change. In Fiji and Vanuatu, strategies used by local communities to prepare for cyclones include building reserve emergency supplies, and utilising farming techniques to ensure adequate crop yield to combat potential losses from a cyclone or drought (Granderson, 2017; McNamara and Prasad, 2014; Pearce et al., 2017). Studies have examined the role that social cohesion and kinship exert in a community's responsiveness and preparedness for climate-related hazards in the Pacific Islands; indicators include resource sharing, communal labour, and accessing remittances (Gawith et al., 2016; Granderson, 2017; McMillen et al., 2014; Nakashima et al., 2012). There is a concern that Indigenous knowledge will dissipate, a process driven by westernisation and disruptions in established bioclimatic indicators and traditional planning calendars, increasingly out of sync with the contemporary climate (Granderson, 2017). In some urban settlements, it has been noted that cultural practices (e.g. prioritising the quantity of food over the quality of food and providing for the needs of the community over the nuclear family) can lower food security of households through dispersing limited resources and by encouraging the consumption of cheap but nutrient-poor foods (Mccubbin et al., 2017). Indigenous practices also encounter limitations, particularly in-relating to sea level rise. In Micronesia, Nunn et al.(2017) argue that indigenous stonework structures, which have been used to manage changing sea levels for generations, are unlikely to be adequate for managing future sea level rise.

[END BOX 4.3 HERE]

[START BOX 4.4 HERE]

Box 4.4: Manizales, Colombia: Supportive national government and localised planning and integration as an enabling condition for managing climate and development risks

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

Manizales is exposed to risks caused by rapid development and expansion in a mountainous terrain exposed to seismic activity and periodic wet and dry spells. Local assessments expect climate change to amplify the risk of disasters (Carreño et al., 2017). The city is widely recognised for its longstanding urban environmental policy (Biomanizales) and local environmental action plan (Bioplan), and has been integrating environmental planning in its development agenda for nearly two decades (Hardoy and Velásquez Barrero, 2014; Velásquez Barrero, 1998). 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 reduction, development and climate change (Leck and Roberts, 2015).

Planning in Manizales remains mindful of steep gradients through the 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).

The cities' Mayors emerged as important champions for much of the early integration and innovation efforts. Their role, however, was enabled by Colombia's history of decentralised approach 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).

[END BOX 4.4 HERE]

4.4.2.2 Monitoring, reporting, and review institutions

The availability of independent private and public reporting and statistical institutions is integral to oversight, effective monitoring, reporting and review. One of the central and novel features of the new climate governance architecture emerging from the 2015 Paris Agreement is the transparency framework in Article 13, committing countries to provide regular progress reports on national pledges to address climate change (UNFCCC, 2015c). Many countries will rely on public policies and existing national reporting channels to deliver on their NDCs under the Paris Agreement. Scaling up these efforts 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 GHGs inventories (Ford et al., 2015a; Lesnikowski et al., 2015; Schoenefeld et al., 2016). Consistent with this direction, the Paris Agreement in its Article 14 has invented two mechanisms: progression and the global stock take, to scale up international efforts (UNFCCC, 2015c),although approaches, reporting procedures, reference points, and data sources to assess progress on implementation across and within nations are underdeveloped (Araos et al., 2016a; Ford et al., 2015a; Lesnikowski et al., 2017; Magnan and Ribera, 2016).

4.4.2.3 Financial institutions

IPCC AR5 assessed that to get the world on a 2°C pathway, both the volume and patterns of climate investments need to be transformed. The report argued that annually up to a trillion dollars in additional investment in low-emission energy and energy efficiencymeasures may be required through to 2050 (Blanco et al., 2014). Financing of 1.5°C would present an even greater challenge and would require significant transitions to the type and structure of financial institutions as well as to the method of financing (Ma, 2014). Both public and private financial institutions would be needed to mobilise an appropriate scale of resources for 1.5°C. Yet, in the ordinary course of business, private finance is not expected to be sufficiently forthcoming, for example, given the risks associated with commercialisation and scaling up of renewable technologies to accelerate mitigation (Hartley and Medlock, 2013). Private financial institutions such as carbon markets could face risks of carbon price volatility and supportive political will. In contrast, traditional public financial institutions are limited by both structure and instruments and concessional financing requires taxpayer support for subsidisation. To partially address these challenges, Hoch (2017) suggests the creation of special institutions that underwrite the value of emission reductions using auctioned price floors. Further discussion on finance in Section 4.4.6.

Financial institutions are equally important for adaptation. Linnerooth-Bayer and Hochrainer-Stigler (2015) discuss the benefits of financial instruments in adaptation, including the provision of post-disaster finances for recovery and pre-disaster security necessary for climate adaptation and poverty reduction. These benefits often come at a cost. Pre-disaster financial instruments and options include insurance including index-based weather insurance schemes; catastrophe bonds; and laws to encourage insurance purchasing. At the local level, the development and enhancement of microfinance institutions have been useful to ensure social resilience and smooth transitions in the adaptation to climate change impacts (Hammill et al., 2008).

4.4.2.4 Co-operative institutions and social safety nets

Effective co-operative institutions and social safety nets may help address energy access, adaptation, as well as distributional impacts during the transition to low-GHG emissions societies and enabling sustainable development, but 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 very effective in dealing with climate crises at the local, regional, and national levels (Aldrich et al., 2016).

The shift towards sustainable energy models 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 issue originating from the lack of collective societal ownership of the responsibility for climate risk management. Literature exploring this issue provides numerous explanations, from competing time-horizons due to self-interest of stakeholders to a more 'rational' conception of risk assessment, measured across a risk-tolerance spectrum for the party involved (Moffatt, 2014).

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

4.4.3 Enabling lifestyle andbehavioural change

Humans are at the centre of global climate change: their actions cause anthropogenic climate change, and social change is the key to effectively respond to climate change (Dietz et al., 2013; Hackmann et al., 2014; ISSC and UNESCO, 2013; Vlek and Steg, 2007). Chapter 2 shows that pathways that are consistent with 1.5°C assume substantial changes in behaviour. This section assesses the potential of behaviour change, as the IAMs applied in Chapter 2 have difficulties in assessing this potential comprehensively (Geels et al., 2016a).

Table 4.6 shows mitigation and adaption actions relevant for 1.5ºCpathways. Reductions in population growth can reduce overall carbon demand and mitigate climate change (Bridgeman, 2017), particularly as population growth is associated with affluence and increases in carbon-intensive consumption (Clayton et al., 2017; Rosa and Dietz, 2012). Mitigation actions with a substantial carbon emission reduction potential (see Figure 4.4) that are relatively easy to change would have most climate impact (Dietz et al. 2009).

Table 4.6: Mitigation and adaptation behaviours relevant for 1.5°C(Araos et al., 2016a; Dietz et al., 2009; Jabeen, 2014; Steg, 2016; Stern et al., 2016b; Taylor et al., 2014)

Climate action	Type of action	Examples
Mitigation	Adoption of renewable energy sources	Solar PV Solar water heaters
	Implementing resource efficiency in building	Insulation Low-carbon building materials
	Adoption of low-emission innovations	Electric vehicles Heat pumps
	Adoption of energy efficient appliances	Energy-efficient heating or cooling Energy-efficient appliances

	Energy saving behaviour	Walk or cycle rather than drive short distances Use mass transit rather than fly Lower room temperature Line drying of laundry
	Use low energy products and materials with a low energy content (i.e. requiring little energy to be produced and transported)	Reduce meat and dairy consumption Buy local, seasonal food Reduce use of aluminium products
	Organisational behaviour	Design of low-emission products and procedures Replace business travel by videoconferencing
Adaptation	Growing different crops and raising different animal varieties	Use crops with higher tolerance for higher temperatures or CO_2 elevation
	Flood protective behaviour	Elevating barriers between rooms Building elevated storage spaces Building drainage channels outside the home
	Heat protective behaviour	Staying hydrated Travelling to cool places Installing green roofs
	Drought and lack of freshwater supply	Rationing water Constructing wells or rainwater tanks
Mitigation & adaptation	Citizenship behaviour	Contributing to environmental organisations Petitioning on climate action

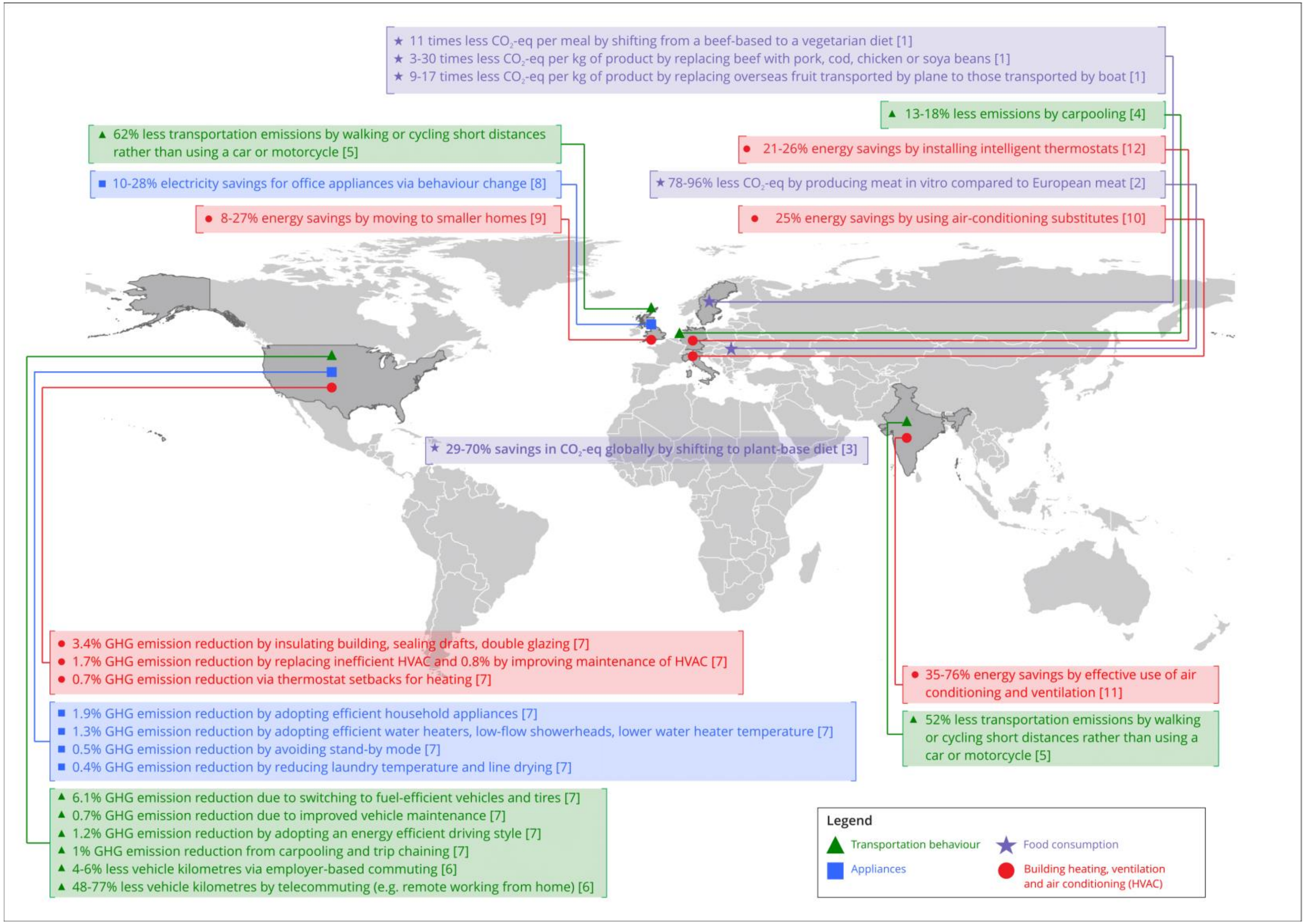

Figure 4.4: Examples of mitigation behaviour and their potential contribution to 1.5°C pathways. Mitigation potential assessments are based on [1] Carlsson-Kanyama and González 2009; [2] Tuomisto and Teixeira de Mattos 2011; [3] Springmann et al. 2016; [4] Nijland and Meerkerk 2017; [5] Woodcock et al. 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.

A wide range of policy approaches and strategies can be employed to encourage and enable climate actions by individuals and organisations. Policy approaches are likely to be more effective when they address key contextual and psycho-social factors influencing climate actions, which differ across contexts and individuals (Steg and Vlek, 2009; Stern, 2011), suggesting that different policy approaches may be needed in 1.5ºCpathways in different context.

GHG emissions are lower when legislators have strong environmental records (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, perceived threat of climate change is higher and personal climate actions are more likely 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 behavioural and lifestyle changes that strengthen implementation of 1.5ºCpathways by assessing psycho-social factors related to climate action, and effects and acceptability of policy approaches targeting climate actions that are consistent with 1.5ºC. Two case studies 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 several types of motivation to engage in behaviour.

Ability to engage in climate action

Individuals are more likely to engage in adaptation (Gebrehiwot and van der Veen, 2015; Koerth et al., 2017)and mitigation behaviour (Pisano and Lubell, 2017) when they feel more capable to do so, so it is important to consider how ability to act on climate change can be enhanced. Ability depends on, among others, income and knowledge. A higher income is related to higher CO_2 emissions; higher income groups can afford more carbon-intensive lifestyles (Dietz et al., 2015; Lamb et al., 2014; 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 (Fleming et al., 2015; Takahashi et al., 2016; Wamsler, 2007). Adaptive capacity further depends on gender roles (Bunce and Ford, 2015; Jabeen, 2014), technical capacities and knowledge (Eakin et al., 2016; Feola et al., 2015; Singh et al., 2016b).

Lack of knowledge on causes and consequences of climate change and ways to reduce GHG emissions is not always accurate (Bord et al., 2000; Tobler et al., 2012; Whitmarsh et al., 2011), 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). They also misperceive climate impacts of energy sources. For example, some people think natural gas is a renewable energy source or think bioenergy is a fossil fuel as it involves burning materials, which can inhibit choices for low GHG emission options (Butler et al., 2013; Devine-Wright, 2003). 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; Hagen et al., 2016; van Kasteren, 2014). How adaptation is framed in the media affects climate change perceptions, establishing some responses as possible and others infeasible (Boykoff et al., 2013; Ford and King, 2015; Moser, 2014).

Knowledge is important, but 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 (Demski et al., 2017; Myers et al., 2012;

Spence et al., 2011); high impact events with low frequency are remembered more than low impact regular events (Meze-Hausken, 2004; Singh et al., 2016b). Personal experience with climate hazards strengthens motivation to protect oneself (Jabeen, 2014) and enhances adaptation actions (Berrang-Ford et al., 2011; Bryan et al., 2009; Demski et al., 2017), although this not always translates into proactive adaptation (Taylor et al., 2014). Collectivelyconstructed notions of risk and expectationsof future climate variability shape risk perception and adaptation behaviour (Singh et al., 2016b). People with particular political views and those who emphasise individual autonomy are likely to 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 such as values, ideology and worldviews than to knowledge (Hornsey et al., 2016). People consider various types of costs and benefits of actions (Gölz and Hahnel, 2016), and focus on consequences that have implications for the values they find most important (Dietz et al., 2013; Hahnel et al., 2015; Steg, 2016). This implies that different individuals consider different consequences when making choices. People who strongly value protecting the environment and other people are more likely to consider climate impact and act on climate change than those who strongly endorse hedonic and egoistic values (Steg, 2016; Taylor et al., 2014). People are more likely 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 (Hornsey et al., 2016; McCright and Dunlap, 2011), 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 (Flynn et al., 2018; Natcher et al., 2007), affecting consideration of future-orientated adaptation and mitigation actions. It is important to consider different values and worldviews when designing climate policy.

People are more likely to act on climate change when individual benefits of actions exceed costs (Kardooni et al., 2016; Steg and Vlek, 2009; 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., 2006a). Yet, transaction costs can inhibit the uptake of mitigation technology (Mundaca, 2007). People prefer decentralised renewable energy systems that guarantee higher independence, autonomy, control and supply security (Ecker, 2017).

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

Next, 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 likely 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).

Also, 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 likely 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 (Arunrat et al., 2017; Chatrchyan et al., 2017; Esham and Garforth, 2013). The more individuals are concerned about climate change and aware of the negative climate impact of their behaviour, the more they think they can help reduce these negative impacts by acting responsively, which will strengthen their moral norms to act accordingly (Chen, 2015; Jakovcevic and Steg, 2013; Steg and de Groot, 2010; Wolske et al., 2017; Woods et al., 2017; Ray et al., 2017). Individuals are less likely to engage in climate actions when they believe others are responsible for climate change (Fielding and Head, 2012). Mitigation actions are more likely when people see themselves as supportive of the environment (i.e. strong environmental self-identity) (Barbarossa et al., 2017; Fielding et al., 2008; Kashima et al., 2014; Van der Werff et al., 2013b); a strong environmental identity strengthens intrinsic motivation to engage in mitigation actions both at home (Van der Werff et al., 2013a) and at work (Ruepert et al., 2016). Environmental self-identity is strengthened when people realise they engaged in mitigation actions, which can in turn promote further mitigation actions (Van der Werff et al., 2014).

Individuals are less likely to engage in adaptation behaviour when they rely on protection measures undertaken by the government (Armah et al., 2015; Burnham and Ma, 2017; Grothmann and Reusswig, 2006; Wamsler and Brink, 2014c) and when they believe ‘God’ will protect them (Dang et al., 2014; Mortreux and Barnett, 2009a). Moreover, individuals with a strong attachment to their community may be unwilling to migrate to protect themselves from climate risks (Adger et al., 2013; Kniveton, 2017).

In sum, multiple motivations may affect climate action that can be addressed by different strategies for behaviour change that will be discussed in Section 4.4.3.2.

Habits and mental shortcuts

Decisions are often not based on weighing costs and benefits, but on habit, both of individuals (Aarts and Dijksterhuis, 2000; Kloeckner et al., 2003) and within organisations (Dooley, 2017) and institutions (Munck et al., 2014). When habits are strong, individuals are less perceptive of information (Aarts et al., 1998; Verplanken et al., 1997), 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, changes in habits are more likely when strategies are employed that create the opportunity for reflection and encourage active decisions (Steg et al., 2017).

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

Besides, biases play a role. A study on farmer adaptation in Mozambique showed that farmers displayed omission biases (unwillingness to take actions with potentially negative consequences to avoid personal responsibility for losses) while policymakers displayed action biases (wanting to demonstrate positive action in spite of 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 (Dinner et al., 2011; Pichert and Katsikopoulos, 2008). 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 are less likely to engage 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 'opt-out' rather than 'opt-in' option (Ebeling and Lotz, 2015; Ölander and Thøgersen, 2014; Pichert and Katsikopoulos, 2008).
It is important to consider habits, biases, and heuristics when developing climate policy, technology, and infrastructure as they can inhibit engagement in climate action even when this would have clear benefits.

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., 2003b; Henstra, 2016; Steg and Vlek, 2009).

In policy and in the media, 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., 2016a; Georgeson et al., 2016).

Current mitigation policies emphasise infrastructural and technology development, regulation, financial incentives and information provision (Mundaca and Markandya, 2016) that can create conditions enabling climate action, but target only some of the many factors influencing climate actions (see Section4.4.5.1). 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 cognitive resources to make informed decisions (Balcombe et al., 2013; Stern, 2011).

Financial incentives or feedback on financial savings can encourage climate action (Bolderdijk et al., 2011; Maki et al., 2016; Santos, 2008) (see Box 4.5), but are not always effective (Delmas et al., 2013), and can be less effective than the social rewards (Handgraaf et al., 2013) or emphasising benefits for people and the environment (Asensio and Delmas, 2015; Bolderdijk et al., 2013b; Schwartz et al., 2015). The latter can happen when financial incentives reduce a focus on environmental concern and crowd out intrinsic motivation to engage in climate action (Agrawal et al., 2015; Evans et al., 2012; Schwartz et al., 2015). Besides, 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 organisation sponsoring incentive programmes (Mundaca, 2007) or when it takes too much effort to receive the incentive (Stern et al., 2016a).

[START BOX 4.5 HERE]

Box 4.5: How pricing policy has reduced car use in Singapore, Stockholm and London

In Singapore, Stockholm and London, car ownership, car use, and GHG emissions have reduced because of pricing and regulatory policies and policies facilitating behaviour change. Notably, support for 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 US$ in 2014 (LTA, 2015). The registration tax incentivises purchases of low-emission vehicles via a feebate system. As a result, per capita transport emissions (approximately 1.25

tonnes CO_2) and car ownership (107 vehicles per 1000 capita; (LTA, 2017) are substantially lower than in cities with comparable income levels. Modal share of public transport was 63% during peak hours in 2013 (LTA, 2013).

The Stockholm congestion charge implemented in 2007 (after a trial in 2006) reduced kilometres driven in the inner city by 16%, and outside the city by 5%; traffic volumes reduced by 20% and remained constant across time despite economic and population growth (Eliasson, 2014). CO_2 emissions from traffic reduced by 2–3% in Stockholm county. Vehicles entering or leaving the city centre were charged during the weekday (except for holidays). Charges varied from 1 and 2€ (maximum 6€ per day), being higher during peak hours; taxis, emergency vehicles and busses were exempted. Before introducing the charge, public transport and parking places near mass transit stations were extended. The aim and effects of the charge were extensively communicated to the public. Acceptability of the congestion charge was initially low, but gained support of about two thirds of the population and all political parties after the scheme was implemented (Eliasson, 2014), which may be related to earmarking the revenues to constructing a motorway tunnel. After the trial, people believed that the charge had more positive effects on environmental, congestion and parking problems while costs increased less than they anticipated beforehand (Schuitema et al., 2010a). The initially hostile media eventually declared the scheme to be a success.

In 2003, a congestion charge was implemented in the Greater London area, with an enforcement and compliance scheme and an information campaign on the functioning of the scheme. Vehicles entering, leaving, driving or parking on a public road in the zone at weekdays at daytime pay a congestion charge of £8 (till 2005 £5), with some exemptions. Revenues have been 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 (Santos, 2008), while CO_2 emission from road traffic reduced by a 20% (Santos, 2008).

[END BOX 4.5 HERE]

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

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 (Abrahamse et al., 2007; Bolderdijk et al., 2013a; Daamen et al., 2001; 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 heat waves (Keim, 2008; Vandentorren et al., 2006). Next, prompts can be effective when they serve as reminders to perform a planned action (Osbaldiston and Schott, 2012a).

Feedback provision is generally effective in promoting mitigation behaviour within households(Abrahamse et al., 2005b; 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 (Darby, 2006; Tiefenbeck et al., 2016), which makes the implications of one's behaviour more salient. Simple information is more effective than detailed and technical data (Ek and Söderholm, 2010; Frederiks et al., 2015; Wilson and Dowlatabadi, 2007). Energy labels (Banerjee and Solomon, 2003; Stadelmann, 2017), visualisation techniques (Pahl et al., 2016), and ambient persuasive technology (Midden and Ham, 2012) can encourage mitigation actions by providing information and feedback in a format that immediately makes sense and hardly requires users' conscious attention.

Social influence approaches that emphasise what other people do or think can encourage climate action (Clayton et al., 2015), particularly when they involve face-to-face interaction (Abrahamse and Steg, 2013). For example, community approaches, where change is initiated from the bottom-up, can promote adaptation (see Box 4.6) and mitigation actions (Abrahamse and Steg 2013;Seyfang and Haxeltine 2012;Middlemiss 2011), especially when community ties are strong (Weenig and Midden, 1991). Furthermore, providing social models of desired actions can encourage mitigation action (Abrahamse and Steg, 2013; Osbaldiston and Schott, 2012a). 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 (Abrahamse and Steg, 2013; Allcott, 2011).

[START BOX 4.6 HERE]

Box 4.6: Bottom-up initiatives: Adaptation responses initiated by individuals and communities

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

In the Philippines, rising sea levels and seismic activity have caused some islands to become inundated 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 highly undesirable because island communities have strong place-based identities (Mortreux and Barnett, 2009b). Instead of migrating, island communities in the Philippines have adapted to flooding by constructing stilted houses and raising floors, furniture, and roads to prevent water damage (Laurice Jamero et al., 2017).

In Fiji, drought and a lack of freshwater are becoming increasingly more prevalent. While some villages have access to boreholes, these are not sufficient to supply the entire village population with freshwater. Villagers are adapting by rationing water, changing their diets, and setting up sharing networks between villages (Pearce et al., 2017). Some villagers also 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 engage in effective actions to adapt to the negative consequences of climate change (Kuruppu and Liverman, 2011).

Adaptation initiatives by individuals may temporarily reduce the impacts of climate change and allow 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 maladaptive behaviour. 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 India, on-farm ponds are promoted as rainwater harvesting structures to adapt to dry spells during the monsoon season. However, individuals have taken to filling these ponds with groundwater, leading to the depletion of water tables and potentially maladaptive outcomes in the long run (Kale, 2015).

Therefore, more long-term and sustainable adaptation initiatives are needed (Pearce et al., 2017). To achieve successful long-term adaptation, integration of individuals' adaptation initiatives with top-down adaptation policy will be critical (Butler et al., 2015b). Failing to do so may lead individual actors to mistrust authority and can discourage them from undertaking adequate adaptive actions (Wamsler and Brink, 2014a).

[END BOX 4.6 HERE]

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

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 then imposed changes that restrict choices (Dietz et al., 2007; Eriksson et al., 2006, 2008; Steg et al., 2006b). Policies punishing maladaptive behaviour can be inappropriate when they reinforce socio-economic inequalities that typically produce the maladaptive behaviour in the first place (Adger et al., 2003a). Change can be initiated by governments at various levels, but also by individuals, communities, profit-making organisations, trade organisations, and other non-governmental actors (Lindenberg and Steg, 2013; Robertson and Barling, 2015; Stern et al., 2016c).

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 more likely when people are more concerned about climate change (Brügger et al., 2015). Consistent actions on climate change are more likely when strategies target general antecedents that affect a wide range of actions, such as values, identities, worldviews, climate change beliefs, awareness of climate impacts of one's actions and feelings of responsibility to act on climate change (Hornsey et al., 2016; Steg, 2016; Van Der Werff and Steg, 2015). 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., 2017a), hold strong pro-environmental values and norms (Thøgersen, J., Ölander, 2003), and when initial actions make them realise they are an environmentally-sensitive person, motivating them to act on climate change in subsequent situations so as to be consistent (Lacasse, 2015, 2016; van der Werff et al., 2014). Yet, some studies suggest that people may feel licensed not to engage in further mitigation actions when they believe they already did their bit (Truelove et al., 2014).

In sum, a wide range of strategies have shown to be effective in enabling and motivating climate action. Generally, strategies are more effective when they address key factors influencing climate action that can differ across individuals, contexts and behaviours, suggesting that the extent to which policy approaches strengthen implementation of 1.5°Cpathways may differ across contexts.

4.4.3.3 Acceptability of policy and system changes

Policy and system changes can meet public opposition. Acceptability will be higher when people expect more positive and less negative effects of policy and system changes (Demski et al., 2015; Drews and Bergh, 2016; Perlaviciute and Steg, 2014), 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 (Eriksson et al., 2008; Steg et al., 2006a). Pricing policy is more acceptable when revenues are earmarked for environmental purposes (Sælen and Kallbekken, 2011; Steg et al., 2006a), or redistributed towards those affected (Schuitema and Steg, 2008). Acceptability can increase when people experience positive effects after a policy has been implemented (Eliasson, 2014; Schuitema et al., 2010a; Weber, 2015); effective policy trials can thus build public support for climate policy.

Climate policy and renewable energy systems are more acceptable when people strongly value other people and the environment, or support egalitarian worldviews, left-wing or green political ideologies (Dietz et al., 2007; Drews and Bergh, 2016; Perlaviciute and Steg, 2014), and less acceptable when people strongly endorse self-enhancement values, or support individualistic and hierarchical worldviews (Drews and Bergh, 2016; Perlaviciute and Steg, 2014). Solar radiation management 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 (Drews and Bergh, 2016; Eriksson et al., 2006; Jakovcevic and Steg, 2013; Kim and Shin, 2017; Steg et al., 2005). 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 (Drews and Bergh, 2016; Schuitema et al., 2011; Sjöberg, 2001), and when fair procedures have been followed, including participation by the public (Bernauer et al., 2016b; Bidwell, 2016; Dietz, 2013) or public society organisations (Bernauer and Gampfer, 2013). Providing benefits to compensate affected communities for losses due to policy or systems changes enhanced public acceptability in some cases (Perlaviciute and Steg, 2014), although people may disagree on what would be a worthwhile compensation (Aitken, 2010; Cass et al., 2010), or feel they are being bribed (Cass et al., 2010; Perlaviciute and Steg, 2014).

Public support is higher when individuals trust responsible parties (Drews and Bergh, 2016; Perlaviciute and Steg, 2014). 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., 2016a). Public opposition may result from a culturally valued landscape being affected by adaptation or mitigation options, such as renewable energy development (Devine-Wright and Howes, 2010; Warren et al., 2005) or coastal protection measures (Kimura, 2016), particularly when people have formed strong emotional bonds with the place (Devine-Wright, 2009, 2013).

Hence, support for climate policy depends on the perceived consequences of policy approaches and how these are distributed; individuals differ in how they evaluate and weigh different costs and benefits.

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

4.4.4 Enabling technological innovation

This section focuses on the role of technological innovation in staying below 1.5ºC warming, and how innovation can contribute to strengthening implementation to move towards or to adapt to 1.5ºC worlds. This builds on information of technological innovation and related policy debates in and after AR5 and the previous sections of Chapter 4.

4.4.4.1 The nature of technological innovations and some recent developments

New technologies emerge, as part of the development of technological systems, that themselves evolve over time, as a large complex system, called a socio-technical system that is integrated with social structures, (Geels and Schot, 2007). This progress is cumulative and accelerating (Arthur, 2009; Kauffman, 2000). To illustrate such a process of co-evolution: the progress of computer simulation enables us to understand material science better, this then contributes to upgrading microscale manufacturing techniques, in turn leading to much faster computing technologies, resulting in better performing PV cells and shale-gas drilling technologies, which in turn impact GHG emissions, in both positive and negative ways.

A variety of technological developments have and will, contribute to climate action or the lack of it. They can do this, as an example in the form of applications such as smart lighting systems, more efficient drilling techniques making fossil fuels cheaper, or precision agriculture. As discussed in Section 4.3.2, costs of PV (IEA, 2017e) and batteries (Nykvist and Nilsson, 2015) have sharply dropped. In addition, costs of fuel cells (Iguma and Kidori, 2015), shale gas and oil (Mills, 2015) have come down, as have those of other technologies that are not usually categorised as "climate technologies" but that will have significant potential impacts on potential rise and reduction of GHG emissions. They include Artificial Intelligence (AI), sensors, internet, memory storage and micro-electro mechanical systems.

4.4.4.2 Technologies as enablers of climate action

Since AR5, literature has emerged as to how much future GHG emission reductions can be enabled by the rapid progress of General Purpose Technologies (GPTs), consisting of Information and Communication Technologies (ICT) including Artificial Intelligence (AI) and Internet-of-Things (IoT), nanotechnologies, biotechnologies, robotics, and so forth (OECD, 2017c; World Economic Forum, 2015).
According to the Global e-Sustainability Initiative, an industry-run organisation, ICT could cut one quarter of global GHG emissions by 2030 (GeSI, 2015). This estimate is based on adding up the contribution of several technologies, such as e-health that replaces traditional face-to-face medical practice with a remote system using ICTs. Similarly, the World Business Council for Sustainable Development (WBCSD) announced that it would aim at cutting agricultural greenhouse gases by at least 30% in 2030 by smart agriculture, also using ICT (WBCSD, 2015).

GHG emission reduction potentials were estimated for passenger car using the combination of two emerging technologies: electric vehicles and car sharing, assuming low-emission electricity (Viegas et al., 2016; OECD/ITF, 2015). An estimate reported an 80% cut of global CO_2 emissions from urban passenger cars by 2050 (Fulton et al., 2017). It is however, possible that GHG emissions may increase due to induced more frequent use of cars, hence an appropriate policy intervention to restrain such rebound effects is necessary (Wadud et al., 2016). While ICT increases electricity consumption, this increase is usually dwarfed by the energy saving by the use of ICT (GeSI, 2015; Koomey et al., 2013).

Mitigation technologies can be strengthened by GPTs and, combined, have a greater potential to reduce GHG emissions. Estimating emission reductions is difficult due to substantial uncertainties, including in projecting future technological performance, costs, penetration rates, and induced human activity. Even if a technology is available, the establishment of business models might not be easy (Linder and Williander, 2017). Studies show a wide range of estimates, ranging from deep emission reductions to possible increases in the emissions due to the rebound effect (Larson and Zhao, 2017). GPT could also enable climate adaptation, in particular through more effective climate disaster risk reduction and improved weather forecasting. Examples are given in Table 4.7.

Table 4.7: Examples of technological innovations in climate action relevant to 1.5°C and General Purpose Technologies (GPT) that would enable them. ICT is information and communication technologies, IoT is Internet of Things, AI is Artificial Intelligence.

Sector	**Examples of mitigation/adaptation technological innovation**	**Enabling GPT**
Buildings	Energy and CO_2 efficiency of logistics, warehouse and shops (GeSI, 2015; IEA, 2017a)	ICT
	Reduction of transport needs because of, for example, remote learning and health services (GeSI, 2015; IEA, 2017a)	ICT
	Smart lighting and air conditioning (IEA, 2016b, 2017a)	IoT
Industry	Energy efficiency and process optimisation	ICT, robots, IoT, nanotechnology
Transport	Electric vehicles (Fulton et al., 2017)	ICT
	Car sharing (Greenblatt and Saxena, 2015)	ICT
	Logistical optimisation, and electrification of trucks by overhead line (IEA, 2017c)	ICT
	Energy saving due to lighter-weight materials and parts in aircraft (Beyer, 2014; Faludi et al., 2015; Verhoef et al., 2018)	Additive manufacturing (3D printing)
Electricity	Solar PV manufacturing	Micro-electro mechanical systems Nanotechnology
	Smart grids and grid flexibility to accommodate intermittent renewables (Heard et al., 2017)	ICT IoT
	Plasma confinement for nuclear fusion (Baltz et al., 2017)	AI
Agriculture	Energy and resource efficiency, including reduction of fertiliser use (reducing N_2O) (Brown et al., 2016; Pierpaoli et al., 2013; Schimmelpfennig and Ebel, 2016)	Biotechnology Bioinformatics
	Methane emission controllers for livestock (Wollenberg et al., 2016)	ICT
Disaster reduction	Weather forecasting and early warning systems, in combination with user knowledge (Hewitt et al., 2012; Lourenço et al., 2015)	ICT, Big Data
	Climate risk reduction (Upadhyay and Bijalwan, 2015)	ICT, Big Data
	Rapid assessment of disaster damage (Kryvasheyeu et al., 2016)	ICT, social media

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 climate technologies in the future will partly depend on progress of GPTs. Governments have established institutions for achieving many social goals including economic growth and addressing climate change (OECD, 2017c).Their activities include investment in basic R&D that can help develop game changing technologies, over time (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 dedicated climate technology policy

Governments aim to achieve many social, economic and environmental goals by promoting a broad range of science and technologies, based on differentiated national priorities. They 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 technology on the demand side (e.g. energy efficiency regulation). They can also help address two kinds of externalities: environmental externalities and proprietary problems (Global Energy Assessment, 2012; IPCC, 2014; 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 the society in general. Some governments have successfully supported innovation policies (Mazzucato, 2013) to address climate change (See Box 4.7 on bioethanol in Brazil).

[START BOX 4.7 HERE]

Box 4.7: Bioethanol in Brazil: Technological innovation driven by co-benefits

The use of sugarcane as a bioenergy source started in Brazil in the 1970s. Government and multinational car factories modified car engines nationwide so vehicles running only on ethanol could be produced. Ethanol production and distribution systems were made more efficient to meet growing demand (de Souza et al., 2014).

After a transition period in which ethanol-only and gasoline-only cars were used, the flex-fuel era started in the 1990s, when all gasoline was blended with 25% ethanol. Brazil became the first country in the world where pure gasoline was no longer available for transportation. Over the next two decades, around 80% of the car fleet in Brazil was converted to use flex-fuel (Goldemberg, 2011).

More than 40 years of innovation led to the deployment of ethanol production, transportation and distribution systems across Brazil and integration of climate-compatible policies, leading to a significant decrease in CO_2 emissions (Macedo et al., 2008). Energy security and agricultural development were the most important motivation, Pollution reduction was also an important co-benefit, leading to a 30% decrease in the emission of ultrafine particles (Salvo et al., 2017).

In 2016, renewables in Brazil accounted for 43% of the energy mix, compared to a global mean of 14% (MME, 2016). Ethanol as a biofuel makes up 40% of all renewables. Hence, Brazil's energy system has become more economically and environmentally sustainable (Buckeridge et al., 2012; Macedo et al., 2008; Smeets et al., 2008).

Despite the intensive use of sugarcane as a bioenergy crop to produce ethanol, it was reported to have limited impact on food production and forests. This due to Brazil's progressive land-use policies and Forest Codes, strict agroecological zoning, and prohibition of bioethanol production in the Amazon. Some adverse effects of bioenergy production were reported, by forest substitution by croplands (Searchinger et al., 2008). More recently, Searchinger and Heimlich (2015) found that bioenergy feedstocks potentially undercut efforts to reduce climate change impact in Brazil.

Modelling exercises have indicated a considerable bioenergy potential in Brazil: Jaiswal et al. (2017) find a potential to reduce up to 6% of the country's net emissions by 2045 without a reduction in forest area or food production. Brazil is currently expanding its land area under bioethanol production, but there is a need to carefully study the potential impacts of bioethanol induced displacement and consequent social movements (McKay et al., 2016).

As a new generation of biofuels is being developed, feasibility and LCA studies need to consider 'all aspects of environmental, economic, and social factors, especially the impacts on biodiversity, water resources, human health and toxicity, and food security' (Rathore et al., 2016). The potential to combine sugarcane bioethanol with CO_2 capture and storage at bio-refineries is a potential cost-effective, short-term technological option for Brazil, and on the longer term, with more innovation, negative emissions could be achieved via large-scale deployment of BECCS (Burns and Nicholson, 2017; Fajardy and Mac Dowell, 2017; Fuss et al., 2014) (see Section 4.3.8).

An open question is whether the Brazilian bioethanol experience and its climate mitigation potential could be extended to other sugarcane growing countries. Attempts made over the last decade to take that experience to Africa were unsuccessful (Afionis et al., 2014; Favretto et al., 2017), and provided lessons for potential future expansion of bioenergy production and use, in land-surplus tropical countries with weaker innovation systems.

[END BOX 4.7 HERE]

Funding for R&D could come from various sources, including the general budget, energy or resource taxation, or emission trading schemes (see Section 4.4.5). Investing in climate-related R&D has as an additional benefit of building capabilities to implement climate mitigation and adaptation technologies (Ockwell et al., 2015). Reframing part of climate policy by technology or industrial policy might contribute to releasing countries from the tragedy of the commons with which emission cut negotiations and carbon pricing are permanently plagued, because countries regard the technologies as their national interests and addressing climate change primarily as in the global interest (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). Yet, the impact of the EU Emission Trading Scheme (EU ETS) on innovation is contested; recent work (based on lower carbon prices) indicates that it is limited (Calel and Dechezleprêtre, 2016) but earlier assessments (Blanco et al., 2014) indicate otherwise.

4.4.4.4 Technology development and transfer in the Paris Agreement

Technology development and transfer were recognised as enablers of both mitigation and adaptation in Article 10 in the Paris Agreement (UNFCCC, 2015c) as well as in Article 4.5 of the original text of the UNFCCC (UNFCCC, 1992). Technology transfer can help adapting technologies to local circumstances, reduce costs, develop indigenous technology, and build capabilities globally (de Coninck and Sagar, 2017; Ockwell et al., 2015)

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

Most technology transfer is driven by human needs and markets, in particular in regions with well-developed institutional and technological capabilities such as developed and emerging nations (Glachant and Dechezleprêtre, 2016). However, the current landscape has gaps, in particular in least-developed countries, where the 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 initiatives may fail to lead to better results; on the other, it is probably more cost-effective to ‘let 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).

For adaptation specifically, Olhoff et al. (2015) argues that networks can build capabilities globally on adaptation technologies (and options and policies). These authors suggest that a balance should be found between technology development and transfer for the short- and medium-term compared to the long term, and that, like mitigation, technology development and transfer around adaptation is crucially dependent on socio-cultural, economic and institutional contexts.

At COP 21, the UNFCCC requested the Subsidiary Body for Scientific and Technological Advice (SBSTA) to initiate the elaboration of the technology framework established under the Paris Agreement (UNFCCC, 2015: Article 10). Among other things, this should facilitate the development and updating of technology needs assessments (TNAs), as well as the enhanced implementation of their results. An enhanced guidance issued by the Technology Executive Committee (TEC) for preparing a technology action plan (TAP) supports the new technology framework as well as Parties’ long-term vision’ on technology development and transfer reflected in the Paris Agreement (TEC, 2016).

4.4.5 Strengthening policy instruments

The immediate policy challenge raised by the transition to a 1.5°C world is to trigger rapid and immediate changes in technical choices, land-use patterns, urbanisation, lifestyles, consumption and behaviour. This will need to overcome potential negative socio-cultural and political responses that could block the transformational process, from the outset.

The search for appropriate policy instruments to do so, revives an old debate in public economics about the relative effectiveness of regulatory measures and 'market-based instruments' delivering a price signal to coordinate individual and collective behaviour. The first approach entails the risk of political arbitrariness and of raising the costs of climate policies. The second can lower these risks but is limited by market and governance failures that are not easy to mitigate against. The effective use and designs of policy mixes apt to balance these risks in the specific conditions of every country is thus a pre-condition of tending towards a 1.5°C world.

4.4.5.1 The nature of the challenge: questions of costs and distributive effects

The transition to a low-emission energy system implies higher energy costs. The corridor of worldwide marginal abatement costs for a 2°C target reported in AR5 was, 35–60 USD tCO_2-eq^{-1}in2020,62–140 USD tCO_2-eq^{-1}in2030 and 140–260 USD tCO_2-eq^{-1}in 2050 (in USD2010). For 1.5°C, figures are not yet available[15].

The unit costs of some low-emission technical options (*e.g.*, solar PV) have dramatically decreased over the past decade (OECD, 2017c). Yet, there are multiple constraints in their leading to system-wide transformation. First, lower costs of some options does not directly result in the proportional decrease of the cost of energy systems, because of the costs of decommissioning and of deploying new infrastructure. Second, a 1.5°C target demands the front-loading of investment. Third, on the demand side, the pace of deployment of negative cost measures and lifestyle changes will be constrained by the inertia of market structures and of cultural habits. Fourth, most economic models assume least-cost planning, no market imperfections, no decision-making uncertainty and compensating transfers for the adverse distributional effects of higher energy prices. All of these assumptions are challenged in policymaking processes.

Learning-by-doing processes and R&D can accelerate the cost-effectiveness of low-emission technologies. However, their deployment can imply higher early-phase costs. The German energy transition resulted in the high consumer prices for electricity in Germany (Kreuz and Müsgens, 2017) and needed strong non-price policy measures to succeed. One risk is that high energy costs can propagate from one sector to amplifying overall production costs. This is important for developing countries that are building their infrastructure that is dependent upon energy intensive products like cement and steel (Crassous et al., 2006; Luderer et al., 2012). Ultimately, during the early stage of a low-carbon transition, both energy prices and the prices of non-energy goods will typically increase, causing lower consumer purchasing power and lower final demand for non-energy goods (see Box 4.8).

[START BOX 4.8 HERE]

Box 4.8: Emerging cities and 'peak car use': Evidence from Shanghai and Beijing

The phenomenon of 'peak car', reductions in per capita car use, provide hope for continuing reductions in greenhouse gas from oil consumption (Goodwin and Van Dender, 2013; Millard-Ball and Schipper, 2011; Newman and Kenworthy, 2011). The phenomenon has been mostly associated with developed cities, though apart from some early signs in Eastern Europe, Latin America and China (Newman and Kenworthy, 2015) there is great need in emerging economies (Gao and Kenworthy, 2017). New research is indicating that peak car is now underway in China (Gao and Gao).

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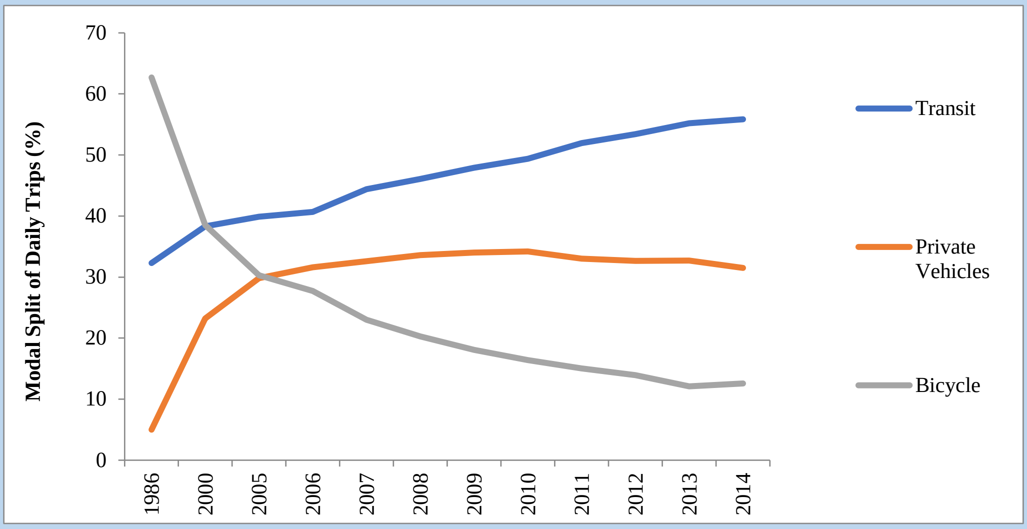
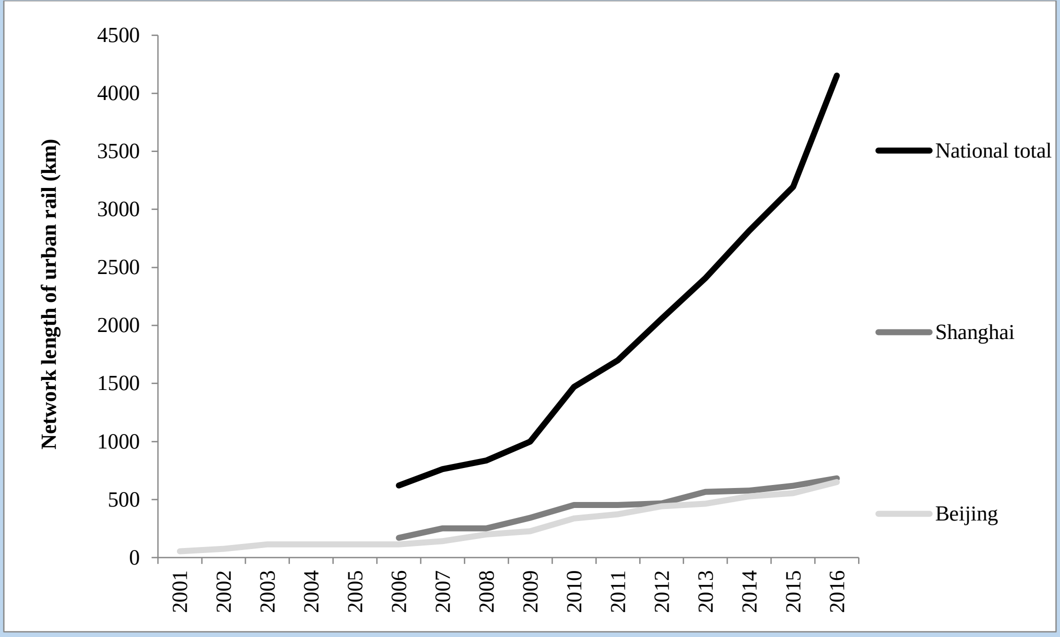
[15] We hope to add these figures based on new Chapter 2 modelling in the Final Draft of the SR1.5.

China's rapid urban motorisation has resulted from strong economic growth, rapid urban development and the prosperity of the Chinese automobile industry (Gao and Kenworthy, 2015). However, recent data (Gao and Gao)suggests that the first signs of a break in the growth of car use is now underway as the growth in mass transit, primarily caused by the expansion of Metro systems, is becoming more significant (see Box 4.8 Figure 1).



Box 4.8, Figure 1: The modal split data in Beijing indicating the peaking in car use as mass transit growth takes over. Source: (BJTRC, 2016).

Similar trends are observable in Shanghai (Gao et al., 2018a). This is explained by understanding how Chinese urban fabrics, featuring traditional dense linear forms and mixed land use, favour such mass transit systems over automobiles(Gao et al., 2018a). However, it does require investment and as shown by Box 4.8 Figure 2 there has been rapid investment in urban Metro systems in recent years. By the end of 2016 there were 133 operational metro lines within 30 cities of mainland China, totalling 4,153 km of operational length (China Association of Metros, 2017).



Box 4.8, Figure 2: Operational length of urban rail transport in Beijing, Shanghai and China by the end of 2016 (km). Source: Compiled from data provided by National Bureau of the People's Republic of China and China Association of Metros (China Association of Metros, 2017; NBSC, 2016).

The dramatic growth of intercity Fast Rail (now by far the largest system in the world) (UIC, 2017) has also been a feature of recent Chinese investment and in the use of electric vehicles (both cars and motor cycles/bikes) with 250 million EV (China Bicycle Association, 2017) and 194 million EV cars in 2017 (EV Volume, 2017). The transition to an all-electric transport system is underway in China, suggesting a model for emerging cities and nations that can enable the 1.5°C limit (Gao and Gao).

[END BOX 4.8 HERE]

In many cases non-market co-benefits of climate policies can act in favour of the poor (Baumgärtner et al., 2017) but high energy costs often have an immediate adverse effect on the distribution of welfare in the absence of accompanying countervailing policies. This negative impact is inversely correlated with the level of income (Fleurbaey and Hammond, 2004; Harberger, 1984) and positively correlated with the share of energy in the households budget, which is high for low- and middle- income households in temperate and cold countries (Barker and Kohler, 1998; Chiroleu-Assouline and Fodha, 2011; Proost and Van Regemorter, 1995; West and Williams, 2004).Geographical conditions matter for heating and mobility needs, and medium-income populations in the suburbs, remote and low-density regions can be as vulnerable as low-income areas in urban areas. Poor households with low levels of energy consumption are also impacted by an overall price increase of non-energy goods caused by the propagation of higher energy cost.

A second matter of concern is the distortion of international competition by the heterogeneity of carbon constraints (Demailly and Quirion, 2008) in highly energy intensive industries. Some of them are not very exposed to international competition because they entail very high transportation costs per value added (Branger et al., 2016; Sartor, 2013) while others could suffer a severe shock to generate 'carbon leakage'; cheaper imports of goods from countries with lower carbon constraints (Branger and Quirion, 2014). This can weaken the surrounding industrial fabric with economy-wide and employment implications.

A third challenge is the depreciation of assets whose value is based on emission-intensive capital stocks which become stranded assets, as they were built under the assumption of low energy prices (Guivarch and Hallegatte, 2011; OECD/IEA/NEA/ITF, 2015; Pfeiffer et al., 2016). This raises challenges of changes in industrial and employment structure, retraining and deployment of workers and the potential instability of financial and social security systems (e.g. based on the asset holding of pension funds). This could impact the valuation of fossil energy resources not yet transformed into economic production of which future revenues may decline precipitously with higher carbon prices (Jakob and Hilaire, 2015; McGlade and Ekins, 2015; Waisman et al., 2013).

4.4.5.2 Mastering the cost-efficiency/equity challenge

Climate and energy policies mobilise dominantly non-price instruments (technical regulations and standards, financial instruments, infrastructure projects, information and training) which generally entail an implicit cost of carbon. Economic literature argues that it would be more efficient to make these costs explicit to secure the overall efficiency of mitigation. After a quarter century of academic debate and experimentation duly reported in IPCC WGIII reports since the SAR, a huge gap persists between aspirational and explicit carbon prices. Today, only 15% of the emissions are covered by carbon pricing schemes, three-quarters of which have prices below USD10 tCO_2^{-1}(World Bank, 2016).

In theory minimising social costs of decarbonisation pathways implies that: (1) the marginal costs of abatement are equated across all sources of emissions; (2) investors make the right choices under perfect foresight and (3) the general equilibrium effects of higher energy prices are managed to minimise their negative impact on activity and income distribution and, if possible, yield welfare gains (see Box 4.9). In a frictionless world with perfect markets, large international compensatory transfers are needed of offset global income inequality, through a unique global carbon price. In their absence, carbon prices must be differentiated by jurisdiction depending on the countries' social welfare function(Chichilnisky and Heal, 2000; Sheeran, 2006). Yet this in turn can distort international competition.

[START BOX 4.9 HERE]

Box 4.9: Climate policy to enhance deep decarbonisation

As policies are context-specific, many case studies have emerged in the social science literature providing a source of empirical evidence of the effectiveness of different policy instruments to deliver on climate, sustainability and economic development goals. Due to the heterogeneity of contexts and approaches, it is usually difficult to systematically assess a large diversity of case studies and distil synthetic lessons that can serve policymakers in optimising their portfolio of policy instruments and ratcheting up on existing policies. The effectiveness of climate policies can often not be assessed, due to a lack of explicit targets and indicators. However two comparative projects – the "Deep Decarbonisation Pathways Project" (DDPP) (Bataille et al., 2016) and the CD-LINKS project (Pahle et al.) have conducted a number of scenarios and national case studies, respectively, the insights of which are synthesised here and complemented with other case studies from the literature.

A common finding of these two projects is that the effectiveness of policy packages depends upon their capacity to align climate and development objectives. For example, the Indian analysis presented in Shukla et al. (2015) shows that domestic sustainable development objectives could impact the design of climate policies by decreasing the cost of ambitious mitigation and dependence on high-risk technologies. Complementary policies are found to systematically improve policy effectiveness through support for infrastructure and capacity building to enable effectiveness of incentive schemes. This is shown in the Canadian case (Bataille et al., 2015) which considers a diversified policy package, with a hybrid and differentiated carbon pricing policy, mandatory carbon intensity regulations in buildings and transport, mandatory control of landfill and industrial methane, and a specific land-use package. This is especially important to accelerate the transition to a 1.5°C world, which can be triggered by such incentives.

Examining four coal dependent country cases (Australia, South Africa, India and China) for the potential of current policies to contribute to a rapid exit from coal, necessary to enable the 1.5°C transition (Spencer, 2018), assesses the lack of complementary policies as a major bottleneck to policy effectiveness. This is necessary to address stakeholders impacted by a coal phase out, for example energy-intensive industry in Australia or resource-poor families and small-scale business in China. Policies not accompanied by the means to mitigate financial risk, were found to be ineffective in triggering targeted investments, across all relevant case studies (Pahle et al.).

Another lesson is that a rise of energy prices has a proportionally greater impact on developing economies, because price-elasticities are higher at lower incomes and because they have a higher ratio of the energy to labour cost, which is the core driver of general equilibrium effects of higher costs of energy (Waisman et al., 2012). This is illustrated by scenarios developed under DDPP for South Africa (Altieri et al., 2016) and Brazil (La Rovere et al., 2017). Both scenarios decrease the ratio of carbon emissions to GDP by 80% between 2010 and 2050. However, this is achieved with lower ranges of absolute carbon prices compared to those reached in other countries. One co-benefit of such low-carbon policies, like the improvement of energy security permitted by the decreased reliance on imported fossil fuels in the Japanese case (Oshiroet al., 2016).

Continuity and robustness of policies were found to critically depend on their flexibility to adjust to new objectives and new situations in a context of uncertainties. This requires attention to a combination of long-lived incentives to form consistent expectations, like a pre-announced escalating carbon price; and adaptive policies which can evolve over time (Mathy et al., 2016). This is the case in Germany, where renewables were first supported as an alternative to nuclear power, but were still supported despite a nuclear phase-out with the new objective of reducing emissions. This is also true in the French case where the low-carbon transition in France envisages a steep rise of building retrofits, but should envisage regular revisions if the impact of this action is limited, and requires future adjustments to the overall strategy.

From a governance perspective, the involvement of different governing bodies with varying objectives was found to systematically lead to efficiency losses. The Swedish and Brazilian experiences examined by

(Silveira and Johnson, 2016) support this finding and illustrate the importance of coordinating policies between local and national levels and across sectors to advance modern bioenergy platforms. Especially interesting for a 1.5°C transition is the robust finding across case studies that ratcheting up of ambition leads to an increase in policy costs, so that cost effectiveness becomes more important (Pahle et al.).

The performance of market mechanisms is another policy concern. In a case study on China's wind power programme, a gradual shift to market mechanisms is considered necessary to sustain the promotion of wind power. Yet, commitment challenges and lack of credibility and transparency of regulation have consistently led to low carbon prices in the case of the EU ETS (Koch et al., 2014; Koch et al., 2016). Hoch (2017)examines the UK's Contracts for Difference Program to support renewable energy and the World Bank's Pilot Auction Facility, which supports methane and N_2O mitigation projects. Auctioned price floors for emission reduction could provide an alternative to existing public climate finance strategies.

Finally, a common lesson identified (Pahle et al.) is that the lack of data on policy performance and observed costs, in almost all case studies, which along with frequent changes of policy that undermine the ability to monitor and evaluate policies. Better ex-ante policy design and ex-post management would greatly help policymakers to monitor performance and steer potential policy reforms. In addition, this would enable more rigorous ex-post analysis effectiveness and impact, which constitutes a knowledge gap in climate policy.

[END BOX 4.9 HERE]

If such impacts, that would undermine support for climate mitigation policy, are to be prevented, negative effects of high energy prices in each country would need to be minimised. An example of a way to do this is by recycling the revenue of explicit carbon pricing, which can offset the propagation effect of high energy costs if the revenues are used under a 'revenue neutrality' condition, to reduce more distortionary taxes (Stiglitz et al., 2017).Explicit carbon pricing offers a tax base that it is difficult to evade, decreasing the gap between the tax burden on the informal sector (Bovenberg, 1999; Goulder, 2013). This could lead to lower labour costs, potentially reducing unemployment, helping to increase real wages, thus counteracting the recessive effect of higher energy prices. The conditions of such a double-dividend of aggregate economic gain along with environmental benefit, is well documented (Combet, 2013; Goulder, 1995, 2013; La Rovere et al., 2017b; Mooij, 2000). This literature is mainly in the context of OECD countries that rely on taxation to fund their social security system. The same principles apply for countries, that are building their social welfare system (for instance China (Li and Wang, 2012)) even though the taxation regime may differ as does the structure of the economy (Lefèvre et al.) and the presence of informal markets.

In all countries, depending on their income distribution and production structure, a balance has to be found between carbon tax revenue use to secure the low-emission transition on the one hand, and the inflationary effect of higher energy prices on the other (Combet et al., 2010). Carbon taxes can offset the adverse redistributive effects of higher energy costs, if their revenues are redistributed through rebates that are divided in such a way that poor households would be better off. Other options include the reduction of value added taxes for basic products or the direct benefit transfers to enable poverty reduction, illustrated by Winkler et al. (2017) for South Africa and Grottera et al. (2016)for Brazil. This positive impact is possible because, even though their carbon fee burden is a relatively smaller share of overall income, higher income people pay more in absolute terms(Arze del Granado et al., 2012). Taxing energy, amounts to taxing revenues and is an implicit tax on sources of income other than wages, like interest and rents.

4.4.5.3 Coordinating long run expectations: a matter of credibility and consistency of incentives

Explicit carbon prices are thus a necessary 'lubricant' to accommodate the general equilibrium effects of higher energy prices. They are also needed to control the rebound effect of emissions due to a higher consumption of energy services enabled by energy efficiency gains, if energy prices do not change (Chitnis and Sorrell, 2015; Fleurbaey and Hammond, 2004; Freire-González, 2017; Greening et al., 2000; Guivarch and Hallegatte, 2011; Sorrell et al., 2009).They will however, not suffice to trigger the low-carbon transition because of an 'implementation gap' which is likely to persist between the 'switching carbon prices' needed to trigger abrupt changes in behaviour and innovation and the carbon prices that are implementable.

The pace of increase of these prices depends on the pace at which they can be embedded in a consistent set of fiscal and social policies. They have to be high enough to outweigh the ‘noise’ from the volatility of oil markets (in the range of USD100 tCO_2^{-1} over the past decade), of other price dynamics (interest rates, currency exchange rates and real estate returns) and of regulatory policies in the energy, transportation and industrial sectors. For example, the dynamics of mobility depends to a large extent upon ‘commuting costs’, the trade-off between housing prices and transportation costs (Lampin et al., 2013)and ‘spatial planning’.

These considerations apply to attempts to secure a minimum carbon price in existing emissions trading systems (Fell et al., 2012; Fuss et al., 2017; Wood and Jotzo, 2011). It also applies to the reduction of fossil fuel subsidies, which are estimated at USD 548 billion in 2012 (OECD, 2012) and USD 650 billion in 2015 (Coady et al., 2017). They represent 25–30% of government revenues in forty mostly developing countries (IEA, 2014). Halting these subsidies is urgent from a 1.5°C perspective, but raises similar issues as carbon pricing with long-term benefits and short-term social costs (Jakob et al., 2015; Zeng and Chen, 2016).

Whensystemicchangesareatplayonmanydimensionsofdevelopment,switchingcarbonpricesare contingentuponotherpolicymeans. Thepricelevels‘depend onthepathandthepathdependsonpoliticaldecisions’(Dréze and Stern, 1990). A transition to a 1.5°C world will therefore require a complex set of price and non-price signals that reinforce each other. For example efficiency standards for housing can increase the efficacy and the acceptability of carbon pricing by overcoming the difficulties posed by high consumer discount rates and price inelasticity (Parry et al., 2014).

Regulatory instruments have been an effective and primary tool of achieving energy efficiency improvements and enhancing renewable energy penetration in OECD countries (e.g., US, Japan, Korea, Australia, the EU) and more recently in other countries (e.g., China) (Brown et al., 2017; Scott et al., 2015). They are also used in many developing countries, to avoid import of products banned in other countries (Knoop and Lechtenböhmer, 2017).

For energy efficiency, these instruments include end-use standards and labelling for equipment like domestic appliances, lighting, electric motors, water heaters and air-conditioners. Often, mandatory efficiency standards are complemented by mandatory efficiency labels to attract consumers’ attention to the most efficient products in the market and to stimulate manufacturers to innovate (Girod et al., 2017) and offer the most efficient products. Experience shows that two policy instruments are effective only if they are regularly reviewed to follow technological developments, such as in the ‘Top Runner’ programme for domestic appliances in Japan.

In a very few countries, regulation and standards have been used in the transport sector, for light and heavy-duty vehicles (only for four countries) by imposing efficiency requirements (e.g. miles/gallon or level of CO_2 emission per km). In the EU (Ajanovic and Haas, 2017) and the US (Sen et al., 2017) regulatory instruments are imposed on manufacturers, which require them to meet an annual CO_2 emission target for the entire fleet they sell. This allows manufacturers to continue selling high-emission vehicles and to compensate this by the introduction of low-emission vehicles with a gradual reduction of fleet emissions over time. This assures more efficient vehicles, but does not limit the driven distance in the absence of carbon tax.

Building codes that prescribe efficiency requirements for new and existing buildings have been adopted at national and local level in many OECD countries (Evans et al., 2017). They are regularly revised to an increased level of efficiency or CO_2 limits per unit floor space. This instrument is relevant for rapidly urbanising countries, to avoid their lock-in to poorly performing buildings that remain in use for the next 50–100 years (Ürge-Vorsatz et al., 2014). In OECD countries where the rate of new building construction is low, their role is rather to incentivise the retrofit of existing buildings. Building codes for both new and existing buildings will ultimatelyconverge for Net Zero Energy Buildings (D′Agostino, 2015). In the context of a 1.5°C (Bertoldi, 2017) underlines that these policy instruments will require public and private co-ordination to achieve consistent integration with the promotion of low-emission transportation modes.

Economic incentives can reinforce the efficacy of all these instruments. Some passes through feed-in tariffs based on the quantity of renewable energy produced or on energy savings (Bertoldi et al., 2013; García-Álvarez et al., 2017; Pablo-Romero et al., 2017; Ritzenhofen and Spinler, 2016) or fee-bates and 'bonus-malus' that foster the penetration of low-emission options (Butler and Neuhoff, 2008). Others include the direct use of market-based instruments (Haoqi et al., 2017). Combinations have been introduced in US and in some EU member states to improve energy efficiency by imposing Energy Savings Obligations or Energy Resources Standards (Haoqi et al., 2017) for energy retailers and to promote renewable energy via Green Certificates or renewable energy portfolio standards (Upton and Snyder, 2017). Thomas et al. (2017) propose to cap utilities' energy sales and other scholars have investigated emission caps at a personal level (Fawcett et al., 2010).

Other instruments (grants, subsidies, loans) foster investment in low-emission technologies. In combination with the critical funding of public research institutes, they are also used to support R&D, where risk and the uncertainty about long-term perspectives reduce the private sector's willingness to invest. Subsidies can take the form of rebates on value-added tax (VAT) or on income tax, of subsidies for investments (e.g. renewable energy or refurbishment of existing buildings) or feed-in tariffs (Mir-Artigues and del Río, 2014). Subsidies may be provided from the public budget or via consumption levies (*e.g.* per kWh) or via the revenues of carbon taxes or a cap-and-trade system. To have a neutral impact on national budgets, the fee-bate instrument, to incentivise low-emission vehicles, products and buildings and penalise high-emissions ones, has been introduced in some countries (*e.g.* for cars) (de Haan et al., 2009).

Information campaigns are a common instrument to foster investment in clean technologies and change end-user behaviour. These campaigns have different forms: from general campaigns (e.g. TV ads) to tailored information provided to specific groups of end-users. Although some authors report large savings obtained by such campaigns, most agree that their effect have a short life and tends to 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). Up to now the vast majority of public-facing campaigns on energy and climate change have been delivered through mass-media channels, and advertising-based approaches (Corner and Randall, 2011; Doyle, 2011). Some studies, building on the experience of HIV/Aids, GM crops or MMR vaccine, suggest better long-term results achieved through interpersonal or community based initiatives (Corner et al., 2016; Mahoney and Thelen, 2010; Peets and Niemeyer, 2004). Fundamentally voluntary actions by non-governmental actors are gaining importance and could make an important contribution to achieving a 1.5°C world. More on strategies to change behaviour for adaptation and mitigation can be found in Section 4.4.3.

Commitments by local authorities and cities are increasingly comment, as demonstrated by the growing Covenant of Mayors, in which many cities have committed to long-term targets of 60% to 80% emissions reductions, some becoming carbon-neutral by 2050 (Kona et al., 2018).
There is thus a diversity of policy packages available to coordinate decarbonisation decisions. The core challenge is how to secure their consistency and their credibility. Literature shows that conflict between poorly articulated policy instruments can undermine their efficiency (Bhattacharya et al., 2017; García-Álvarez et al., 2017; Lecuyer and Quirion, 2013).

The simultaneous launch of multiple policies in many domains is challenging, especially in a regional context where carbon prices are too lowto hedgeagainsttheirarbitrariness. A well-established tradition in public economics is to resort to implicit (notional or 'shadow') prices representing the social values of public goods, to hedge against such a risk. Such notional carbon prices have been adopted in countries like the US, the UK and France, and also in multinational companies, but do not have the volume, price level or degree of systematic application required to accelerate an ambitious decarbonisation programme. Shukla et al. (2017) argue that, to secure the alignment of climate policies with an equitable access to development, these notional prices should (following the Paris Agreement) represent the SocialValueofMitigation Activities(SVMA) including co-benefits in terms of health, security, adaptation and sustainable development. These notional prices could be higher than the explicit carbon prices because they redirect new equipment without an immediate impact on existing capital stocks and vested interests.

A new strand of post–AR5 literature examines a set of policy packages that combine carbon pricing and non-price policies with financial incentives to 'makefinanceflowsconsistentwithapathwaytowardslow greenhousegasemissionsandclimate-resilient development', according to Article 2 in the Paris Agreement.

4.4.6 Enabling climate finance

Finance plays a critical role in governing investment behaviour. There are numerous concerns about the short-term bias of modern financial systems (Black and Fraser, 2002; Bushee, 2001; Miles, 1993) due to the way compensation schemes are designed (Tehranian and Waegelein, 1985), by herd behaviour (Bikhchandani and Sharma, 2000), credit constraints and arbitrage costs (Shleifer and Vishny, 1990) and prevailing patterns of economic globalisation (Krugman, 2009; Rajan, 2016).

This bias lies at the root of the gap between the 'propensity to save' and the 'propensity to invest' that weakens the world economy (Summers, 2016) and leads to chronic under-investment in long-term infrastructure (IMF, 2014) and unrealistic expectations of financial returns in low-carbon and adaptation investments. Emerging literature explores to how to overcome this bias, which operates against climate policies.

4.4.6.1 The quantitative challenge

This assessment of the size of the mitigation and adaptation finance challenge is hampered by the almost complete absence of data in the peer-reviewed literature. We therefore rely on non-peer-reviewed literature in addition to results from IAMs reported in Chapter 2, with accompanying issues of assumptions, comparability of sectoral scope and time periods.[16]

Many assessments have been made of the investment needs to meet a 2°C target. The World Economic Forum (World Economic Forum, 2013) estimates the need for USD 85 trillion in investment in low-emission infrastructure by 2030 to meet a 2°C target. The Global Commission on the Economy and Climate (GCEC, 2014) has a higher estimate, of USD 94 trillion, for the same target and period. Restricting emissions sufficiently to meet a goal of 1.5°C and the SDGs demands an acceleration of action required, and an additional USD 10 trillion per year in the 'two to three years after 2018' (Wolf et al., 2017).

While investment needs in the energy sector show considerable ranges but are fairly well identified, other investments may be underestimated due to data gaps. Examples include other infrastructure (*e.g.*, USD 4.5 trillion to USD 5.4 trillion annually from 2015 to 2030 according to the Cities Climate Finance Leadership Alliance (CCFLA, 2016)) and a multiplier coefficient of 1.2 for upstream investments in the material transformation and manufacturing sectors (Aglietta et al., 2015b).

Despite these uncertainties, an initial assessment shows that the incremental investments for limiting warming to 1.5°C would amount to 1% of global GDP up to 2030 and 4% of total Gross Capital Formation. This increase may be higher in most developing countries (IEA, 2014) that are in a catch-up phase, with heavy dependence on the fast development of energy and energy-intensive sectors, and applies only to mitigation. For adaptation, numbers are even harder to get by, and are more difficult to separate from general social and development investments (Hallegatte et al., 2016).

A critical issue here is whether the low-carbon transition will cause a drain on consumption (Bowen et al., 2017). The response depends on whether shifting savings towards productive adaptation and mitigation investments, instead of real-estate sector and liquid financial products, will reinforce growth trends (King, 2011; Teulings and Baldwin, 2014).

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[16] In the Final Draft of this chapter, the aim is to incorporate a table compiling relevant information in a comparable way.

This is exacerbated by the up-front investment costs being 1.9–3.2-fold the levelised circulated in literature (World Bank, 2016) and the amount of redirected investments being three times higher than incremental investments (Aglietta et al., 2015b). This notion of incremental costs is even less relevant for climate-resilient infrastructure in a 1.5°C world. It is hard to make a distinction between damage due to an incremental climate change and climate vulnerability due to the pre-existing social fragility (Hallegatte et al., 2016). The first priority is then to reduce the funding gap in infrastructure and hence in universal service access (Arezki et al., 2016).

Ultimately the triggering of the transition towards low emissions will depend upon whether reforms of the financial system will succeed in bridging the gap between short-term cash balances and long-term low-emission assets, and on reducing the risk-weighted capital costs of climate-resilient investments.

4.4.6.2 Redirecting savings and de-risking low-emission investment

The financial community's attention to climate change grew after COP 15 in 2009 (ESRB ASC, 2016). The alert by the Governor of the Bank of England about the Tragedy of the Horizons (Carney, 2016) as a threat to the stability of the global financial system is confirmed by the literature (Arezki et al., 2016; Christophers, 2017). It encompasses 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 first will be lower in a 1.5°C world, while the second will be exacerbated.

This diagnosis highlighted the importance of transparency, and climate-relatedriskdisclosureinfinancialportfolios (UNEP, 2015), that is now on the agenda of G20 Green Finance Study Group and of the Financial Stability Board. This may lead 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).

In parallel, an acceleration of the emergence of climate-friendly financial products has taken place since AR5. Estimates of green or climate bonds issuance are about USD 200 billion in 2017 (BNEF, 2017), of which a majority have been designated for renewable energy, energy efficiency and low-emission transport (Lazurko and Venema, 2017), and only 4% for adaptation (OECD, 2017b). These are indications of a changing mind-set amongst financial institutions, but they face an accounting challenge due to the lack of standardisation of green bonds. This trend is too recent to have been analysed by the literature, with the exception of REDD+ for forest protection (Laing et al., 2016). Another debate that is emerging revolves around the matter that relying on climate-related information alone assumes that integrating all climate uncertainties into an ex-ante probability distribution will enable the financial system to allocate capital in an optimal way (Christophers, 2017), although others argue that climate change is a systemic risk (Schoenmaker and Tilburg, 2016) and is unhedgeable by individual strategies (CISL, 2015).
The readiness of financial actors to reduce investments in fossil fuels is another emerging trend (Ayling and Gunningham, 2017; Platinga and Scholtens, 2016). Asset managers may however not resist the attractiveness of carbon-intensive investments in many regions. In addition, decarbonising an investment portfolio is not synonymous with investing in a low-emission development pathway.

Hence, accelerating transformations in the financial sector implies a link between the emergence of climate-friendly financial products and the reduction of the risk-weighted capital costs of low-emission projects, to increase the quantity of bankable projects at a given carbon price. The typical leverage of public funding mechanisms for low-carbon investment is low (2 to 4) compared with the leverage (10–15) in other sectors (Maclean et al., 2008; MDB, 2016; Ward et al., 2009). This weak performance is due to the interplay between the uncertainty of emerging low-carbon technologies in the midst of their learning-by-doing cycle, and of uncertain future revenues due to volatility of fossil fuel prices (Gross et al., 2010; Roques et al., 2008) and regulatory policies, including carbon pricing. This inhibits corporations functioning under a 'shareholder value business regime' (Berle and Means, 1932; Froud et al., 2000; Roe, 2001); cities, local authorities and SMEs with restricted access to capital; and householdswith ahighdiscountrate preference inenergyefficiency.

Recent literature therefore envisages the use of de-risking policy instruments ranging from interest rate subsidies, fee-bates, tax breaks on low-carbon investments, to concessional loans from development banks, and public investment funds. Given the constraints on public budgets, public guarantees to secure high leverage of public financial support, e.g. Green Infrastructure Funds managed by a multilateral development fund (De Gouvello and Zelenko, 2010; Emin et al., 2014; Studart and Gallagher, 2015)[17] are another policy option.

Public guarantees imply a direct burden on public budgets only in case of default of the project. This risk can be mitigated by strong Monitoring Reporting and Verifying systems (MRV) (Bellassen, 2015), subject to the risk of political arbitrariness and lobbying. In the presence of 'carbon pricing gap' the usual response of public economics is to use notional prices. Several papers suggest aligning the financial guarantees per avoided ton of emissions to the agreed Social Values of Mitigation Activity recommended in paragraph 108 of the decision accompanying the Paris Agreement (UNFCCC, 2015b), to ensure the overall economic efficiency of climate policies and internalise the co-benefits of mitigation (Hourcade et al., 2015; La Rovere et al., 2017a; Shukla et al., 2017).

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 financialproductsbackedby a new class of certified assetstoattractsaversinsearchof safeandethical investments(Aglietta et al., 2015b). It could hedge against thefragmentation of climate finance initiatives and trigger higher volumes of low-emission investments at a given level of carbon price (Hirth and Steckel, 2016). This is important for developing and emerging economies, where capital costs are typically higher than in high-income countries.

4.4.6.3 Combining new financial instruments to address the basic needs and adaptation challenges

Adaptation finance differs from mitigation finance in two ways. The first is the notion of incremental needs to enhance climate resilience through the provision of basic infrastructure, that are currently underinvested in (Gurara et al., 2017; IMF, 2014). The second is that the valuation of adaptation needs and costs is complex and contested, with a social value that is difficult to quantify.

Therefore, adaptation investments are typically supported by domestic or overseas development assistance through multilateral development banks (Adenle et al., 2017b; Fankhauser and Schmidt-Traub, 2011; Robinson and Dornan, 2017). Ultimately financing for adaptation currently flows primarily from national and subnational government budgets although there is a slow increase of dedicated NGO and private climate funds (Nakhooda and Watson, 2016).

A significant gap exists between estimates of finance needed for adaptation and committed finance. Based on 2ºC of warming, UNEP (2016) estimated that developing countries may need to be spending between USD 280 to USD 500 billion per year by 2050 on adaptation, with higher costs expected under higher emissions scenarios (see also Climate Analytics, 2015). These figures could be lower in a 1.5°C world. However, they are far higher than the estimated USD 4 to USD 12 billion in public finance per year, retaining a two to four leverage on private finance (Oxfam International, 2015, 2016).

The capacity of nations to implement adaptation projects remains a constraining factor and there is a need for greater policy coordination and focus on systematic transformations(Adenle et al., 2017b; Fankhauser and McDermott, 2014; Lemos et al., 2016; Morita and Matsumoto, 2015; Peake and Ekins, 2017; Sovacool et al., 2015, 2017). Establishing robust mechanisms for tracking, reporting, and verifying adaptation finance are critical to ensuring transparency of financial flows (Donner et al., 2016; Pauw et al., 2016b; Roberts and Weikmans, 2017; Trabacchi and Buchner, 2017). International transfers are thus necessary, but the 18-25% of climate finance flows for adaptation in developing countries (OECD, 2015, 2016a; Shine and Campillo, 2016)remain fragmented, with small proportions flowing through UNFCCC channels (AdaptationWatch, 2015; Roberts and Weikmans, 2017).

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

The question is how to raise more funds (Durand et al., 2016; Roberts et al., 2017). Possibilities include innovative removal of fossil fuel subsidies (Jakob et al., 2016), introduction of carbon taxes (Jakob et al., 2016) or levies on international aviation and maritime transport. However, the critical challenge is less the availability of funds than how to secure the efficient use of funds and the emergence of long-term assets using infrastructure as collateral, which will progressively trigger an evolution correcting the current short-term bias of financial systems require the evolution of financial systems.

4.4.6.4 Public commitments and evolution of climate finance

Most forms of public climate finance guarantees amount to money issuance backed by low-emission projects as collateral. Hence, the link between climate finance and the evolution of the financial and monetary system is important. Amongst suggested mechanisms are the use of IMF's Special Drawing Rights tofundthepaid-incapitaloftheGreenClimateFund(Bredenkamp and Pattillo, 2010) and the creation of carbon remediation assets at a pre-determined face value per tonne (Aglietta et al., 2015a, 2015b). Such an evolution of the financial system might be useful in three ways.

First, to facilitate the access of developing countries to affordable loans via bond markets at lower exchangeraterisk,whichconstitutes a barrier for large long-terminvestments. These loans might be one way of establishing a burden-sharing mechanism between rich and poor countries, that enhances reciprocity and enables them to deploy ambitious NDCs (Edenhofer et al., 2015; Stiglitz et al., 2017).

Second, the emergence of new asset classes may be necessary to redirect financial flows worldwide; compensate for 'stranded' assets caused by divestment in carbon-based activities that back part of the assets of financial and insurance institutions. This new class of assets could facilitate the low-carbon transition for fossil-fuel producers and help them to overcome the 'resources curse' (Ross, 2015; Venables, 2016).

Third, the involvement of non-state public actors like cities and regional public authorities that govern infrastructure investments are critical for the penetration of low-carbon energy systems, shaping urban dynamics (Cartwright, 2015), and fostering changes in agriculture and food systems.

Such an evolution questions the premise that money should remain neutral (Annicchiarico and Di Dio, 2015, 2016; Nikiforos and Zezza, 2017) and implies that Central Banks could act as a facilitator of low-carbon financing instruments, while enabling the stability of the financial system. This may, in time, lead to the use of carbon-based monetary instruments to diversify reserve currencies (Jaeger et al., 2013)and to differentiation of reserve requirements (Rozenberg et al., 2013) in a prospective Climate Friendly Bretton Woods (Sirkis et al., 2015; Stua, 2017).

The unresolved question behind all this is whether investing in low-carbon programmes or adaptation projects would ultimately be cost-saving (The New Climate Economy, 2016) and unlock new economic opportunities (GCEC, 2014), without crowding out private or public investments (Pollitt and Mercure, 2017). They amount to injectingliquidityintothelow-carbontransition via investment in the previously underinvestedinfrastructuresectors. This could haveapotentialrippleeffect,largeenoughtotriggera newgrowthcycle (Stern, 2013, 2015). This could, if managed appropriately, assist in lowering the systemic risk of stranded assets and green financial bubbles (Safarzyńska and van den Bergh, 2017).

Ultimately a transition to a 1.5°C world that is aligned with SDGs implies a move to shift the 'production frontier' of the global economy over both the short- and the long-term. The evolution of the financial system is key for reducing the regional and temporal gap between the 'propensity to save' and the 'propensity to invest', thus mitigating some of the 'fault lines' of the global economy (Rajan, 2010).

4.5 Integration and enabling transformation

4.5.1 Knowledge gaps and key uncertainties

New pathways keeping global warming to 1.5°C by 2100 feature increased scale and a more rapid pace of mitigation. Different methodologies reviewed in Section 4.2 have been developed to put this into historical context and thereby test the realism of the pathways. For a more comprehensive assessment, more knowledge would be needed on historical rates of change in land transitions. While rates of change in energy and land transitions are available, they do not reflect short-term changes and tipping points emerging for some renewable energy options. Current studies on rates of change are focused on generic economic parameters or on technology, but do not take into account realistic behaviour and lifestyle parameters, nor political and institutional (capacity) change.

For impacts and adaptation, large literature gaps remain with respect to the assessment of incremental economic and climate impacts between end-of-century warming levels of 1.5°C and 2°C, especially during mid-century overshoot. There is a lack of knowledge on how much climate damage is reduced globally as a result of being more ambitious and no information on avoided adaptation investments associated with keeping warming to 1.5°C compared to business-as-usual or 2°C. The available evidence outlined in Section 4.2 is mostly on specific regional impacts not allowing for meaningful comparisons or generalisation aiding implementation. Relatively little literature has been published on individual adaptation options since AR5 (see Section 4.3) and neither are there any 1.5°C-specific case studies. The literature on effectiveness of current adaptation is scant and regional information on some options does not exist at all, especially in the case of land use transitions. Even though strong claims are made with respect to synergies and trade-offs, there is little knowledge of co-benefits by region.

Considering the three main systems – energy, land and urban - for which mitigation and adaptation options have been assessed, urban systems feature major gaps in knowledge pertaining to innovation desirable within local governance arrangements that may act as key mediators and drivers for achieving global ambition and local action. An uncovering of the heterogeneous mix of actors, settings, governance arrangements and technologies involved in the governance of urban climate change is needed for this. Considering distributional consequences of climate responses is a key omission in the current literature. The possibility of a new urban science that bridges disciplinary boundaries and practices a mix of approaches to create an evidence base for action should be explored. It is also important to better understand processes and mechanisms linked to co-design and co-production of climate knowledge, particularly at the science-policy interface. Regional and sectoral adaptation cost assessments are missing, particularly in the context of welfare losses of households, across time and space. The political economy of adaptation needs to be better understood, particularly addressing the cost-benefit asymmetry, adaptation performance indicators which could stimulate investment, and distributional aspects of adaptation interventions. For concrete planning, more evidence is needed on hot-spots, for example the growth of peri-urban areas populated by large informal settlements. Major uncertainties emanate from the lack of knowledge on integration of climate adaptation and mitigation, disaster risk reduction, and urban poverty alleviation.

Land-based mitigation will play a major role in 1.5°C stabilisation pathways and more knowledge is needed on how this can be reconciled with land demands for adaptation and development. However, while there is now more literature on the underlying mechanisms, data are often insufficient to draw robust conclusions, with disagreements between the main land use map products being substantial. New efforts using hybrid strategies based on remote sensing, data sharing and crowd-sourcing are emerging to fill this gap. This lack of data counts especially for social and institutional information, which is therefore generally not integrated in large-scale land use modelling. More information on examples of successful policy implementation related to land-based mitigation that have led to co-benefits for adaptation and development is needed.

For the energy system, the special challenges that a 1.5°C target brings with it are: energy demand has very little scope for further growth, while at the same time providing universal access to energy, as many people still suffer from no access or energy poverty. Whilst combinations of new smart technologies and sustainable design are showing how overall reductions in energy demand can be applied to buildings, transport and industrial processes, there is a lack of knowledge about how this can be applied at scale in settlements. Conversely, once implemented, other problems emerge, for example data on power transformation will be harder to obtain as much of the activity will be behind the utility meter. The shift to variable renewables that many countries have implemented are just reaching levels where large scale storage systems or other flexibility options are required to enable resilient grid systems, thus new knowledge on the opportunities and issues associated with scaling up zero carbon grids is needed. Knowledge about how zero carbon electric grids can integrate with the full scale electrification of transport systems is also needed. CCS suffers mostly from uncertainty about the feasibility of timely upscaling, in particular in terms of safely storing the CO_2. One outstanding feature of the 1.5°C scenarios is their increased reliance on negative emissions or removal of CO_2 from the atmosphere. However, the bottom-up analysis of the available options in Section 4.3 indicates that there are still key uncertainties around the individual technologies. In order to obtain more information on realistically available and sustainable potentials, more bottom-up, regional studies are needed. These can then inform the larger models with their insights. Other knowledge gaps pertain to issues of governance and public acceptance, the impacts of large-scale removals on the carbon cycle, the potential to accelerate deployment and upscaling, and means of incentivisation in the absence of carbon pricing. In addition, research into integrated systems of renewable energy and CDR technologies such as the combination of Direct Air Capture with renewable energy generation is needed. Finally, the use of captured CO_2 is not per se generating negative emissions and needs further scrutiny as a mitigation option.

Reducing SLCPs could be one way to reduce the reliance on negative emissions in a 1.5°C pathway, but in the absence of economic incentives, more evidence is needed, particularly from developing countries, to support the argument that targeting SLCP reduction also generates significant co-benefits (e.g., better health outcomes, agricultural productivity improvements). New research that helps articulate how SLCP reduction polices can be aligned with concerns at scale would facilitate such an integration. Frameworks are needed that help integrate SLCPs into emissions accounting and reporting mechanisms at international level and a better understanding of the links between Black Carbon, air pollution, climate change and agricultural productivity must be achieved.

In spite of increasing attention to the different concerns of SRM, knowledge gaps remain not only on the SRM options themselves, but also on ethical issues in general and the governance structure for SRM. In particular, we do not know when, where, and how ‘moral hazard’ might occur and what precautions to take against objectionable mitigation obstruction.

Turning to the implementation of the options to mitigate and adapt, Section 4.4 has generally identified a lack of 1.5°– specific literature, for example on institutions and on lifestyle and behavioural change. Even relying on 2°C–specific literature and extrapolating assuming an increased pace and scale of change, some uncertainties remain: in particular, 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 relation to mitigation and adaptation actions in the 1.5°C context. A paramount challenge is to what extent a representation of (empirically estimated) determinants of mitigation behaviour, including technology choice or adoption, is actually feasible in detailed process-based IAMs, particularly since mitigation behaviour is influenced by a wide range of factors varying across individuals and contexts. These aspects continue to limit our understanding and treatment of behavioural change and the potential effects of related policies in ambitious mitigation pathways. Mitigation behaviour tends to be studied more extensively than adaptation behaviour, except for behaviour in agriculture. The literature appears to be moving towards an understanding that adaptation action has focused too much on assets (e.g. finances for adapting, access to resources and information) as barriers or enablers of adaptation, but tends to underplay the role of cognition (through perceived self-efficacy, risk perception etc.). Most research has been conducted in Western countries (far less in e.g. LMIC and former Soviet bloc countries) and the focus is often on changing individuals - far less on changing organisations and political systems.

With respect to innovation, it is difficult to predict the costs and performance of GHG reduction achievable through innovations ex ante. So far, quantitative estimates of emission cuts at economy or sector scale as a result of the combination of general purpose technologies and mitigation technologies (see Section 4.4.4) have been scarce, particularly in academic literature, except for the transport sector.

There is a lack of monitoring and evaluation (M&E) of adaptation measures, with most studies enumerating the M&E challenges and emphasising the importance of context and social learning. Very few studies evaluate whether an adaptation initiative has been effective or not. One of the challenges of M&E for both mitigation and adaptation is that some communities lack high quality information for models, especially for IWRM.

In spite of the little 1.5°C-specific literature in the area of mitigation, Section 4.4.5 draws important lessons from 2°C-specific literature and taking into account the shorter time window for policies to take effect: some case studies are emerging allowing to study the effectiveness of policies and policy packages for accelerated change and across multiple objectives. Yet, more empirical research is needed to derive robust conclusions on what works and what does not in order to aid decision-makers seeking to ratchet up their national commitments in 2018. Adaptation policy has focused more on engineering and the built environment and institutions, however, 'social' adaptation has been criticised for not addressing climatic risk specifically. So there is a need for adaptation initiatives that address social vulnerability (social protection, cohesion, capacity) while simultaneously considering climatic risk. For climate finance (Section 4.4.6), there is now a better understanding of the flows of finance, but knowledge gaps persist with respect to the vehicles to match this finance to its most effective use in mitigation and adaptation.

Concerning governance, the ability to identify explanatory factors affecting climate policy progress is constrained by a lack of data on adaptation action across nations, regions, and sectors, and frameworks for assessing progress.

An up-scaled and more rapid transition introduces new challenges for efforts to assess the feasibility of projects that would deliver this change. Conventional metrics such as cost-benefit analysis and internal rate of return are prone to quantification bias and limited in the extent to which they capture the relative merits of available options in the context of the 1.5°C target. Equally, however, multi-criteria assessments and expert opinion are subjective and difficult to apply in a consistent manner across all contexts. Additional work is required to develop assessment methodologies prioritising options that will deliver on these challenges in consonance with sustainable development, while simultaneously factoring in the implications of innate uncertainty and the risks of lock-in.

4.5.2 Implementing mitigation

This section synthesises the insights on feasibility of mitigation options from Section 4.3 and the assessment of the enabling conditions in Section 4.4.

4.5.2.1 Feasibility of mitigation options towards 1.5˚C

The feasibility of mitigation options is summarised in Figure 4.5 and in Figure 4.6. An explanation of the approach is given in Box 4.10.

Energy system transitions

The options assessed in energy system transitions are onshore wind, solar PV, electricity storage, nuclear energy, CCS in the power sector, and options to reduce emissions in international transport. Technically and economically they are all classified as "medium" feasibility; they are all on their way to scalability, maturity and cost-effectiveness, but they also all still face challenges, although these vary greatly over jurisdictions. The assessment suggests that all options in the energy systems still need techno-economic support before they can be widely implemented. As for institutional feasibility, the options related to renewable energy and electricity storage look feasible as compared to CCS, international transport and nuclear, all for different reasons. Socio-culturally, nuclear has feasibility barriers and solar PV features more positively. For environmental impacts, only onshore wind has a high feasibility score; all other options entail environmental risks such as toxic waste (solar PV, electricity storage), land use (*e.g.* biofuels for aviation) or risks related to long-term waste or CO_2 storage (nuclear and CCS, respectively). As for geophysical potentials, all options have constraints but none of them are very limited.

Land and ecosystem transitions

Mitigation options related to food production, in particular reducing food waste and efficient food production, have a high feasibility along many of the characteristics. Dietary shifts face more barriers along socio-cultural, institutional (political support) and even technological characteristics. It is clear that bioenergy has feasibility challenges along institutional (how to make sure the biomass is sustainably grown), socio-cultural (social co-benefits and public perception), as well as environmental (biodiversity, water use) characteristics. This challenges the potential use of bioenergy, which is contested (see discussion in Section 4.3.3). Forestry- and ecosystem-related options are generally technically, environmentally and geophysically feasible. The main indicators limiting feasibility are institutional, including institutional capabilities, also for sourcing and certification.

Urban and infrastructure transitions

The feasibility of urban and land planning options for mitigation show high feasibility on all characteristics except institutional. It shows clearly that even one feasibility characteristic can inhibit implementation, as land-use planning and urban planning are not implemented in a 1.5ºC consistent way ubiquitously. In transportation, sharing schemes, and public and non-motorised transport appear highly feasible across many dimensions, and are used in many places, but their greater use is inhibited by institutional and social factors, such as public acceptance and safety. Fuel cell vehicles face greater economic and technological feasibility barriers than electric vehicles, but are more feasible from an environmental and geophysical perspective, mainly because EVs, through batteries, need to use rare resources and have toxic waste challenges. In the buildings sector, efficient appliances are preferred though their maturity and simplicity of use globally, including in least-developed countries, has limitations. Smart grids face lower institutional feasibility due to institutional capacity and transparency (privacy) concerns. Also, the public is not necessarily embracing them and their cost-effectiveness is not evident to the consumer. As for low- or zero-energy buildings: their social-cultural, environmental and geophysical feasibility is high, but investment costs are too high for many consumers, introducing distributional effects, and technologically the option is still under development.

Industrial transitions

In industry, energy efficiency is attractive across the board, but is a necessary but insufficient condition for 1.5ºC pathways. To lower industry emissions to near-zero by 2050, bio-based, electrification, hydrogen or, in some cases, CCS, are needed. CCS in industry is relatively economically feasible compared to more radical options that lead to near-zero emissions, but, like other options, it faces institutional, technological, social and environmental limitations. Renewables-based electricity or hydrogen industries have low economic feasibility but advantages in terms of environmental, geophysical and social feasibility. Like with other bio-based option, a bio-based industry faces constraints in terms of land use and biodiversity impacts.

Carbon dioxide removal

Bioenergy with CCS is an option that is assigned much potential and relevance in the Chapter 2 pathways, but that according to the Section 4.3 feasibility assessment has only medium feasibility, across all feasibility characteristics. This relates to public perception of both CO_2 storage and bioenergy (due to land-use concerns), to environmental limitations, but also to issues with technological maturity and scale, costs and economics, and institutional capacity. Soil carbon sequestration and biochar are considered more feasible but have geophysical limitations. Afforestation and reforestation is assessed similarly to REDD+ in the land and ecosystem section, while enhanced weathering and direct atmospheric CO_2 capture and storage is faced with energy penalties, reducing technological, economic and environmental feasibility.

[START BOX 4.10 HERE]

Box 4.10: How to read the mitigation feasibility assessment figures

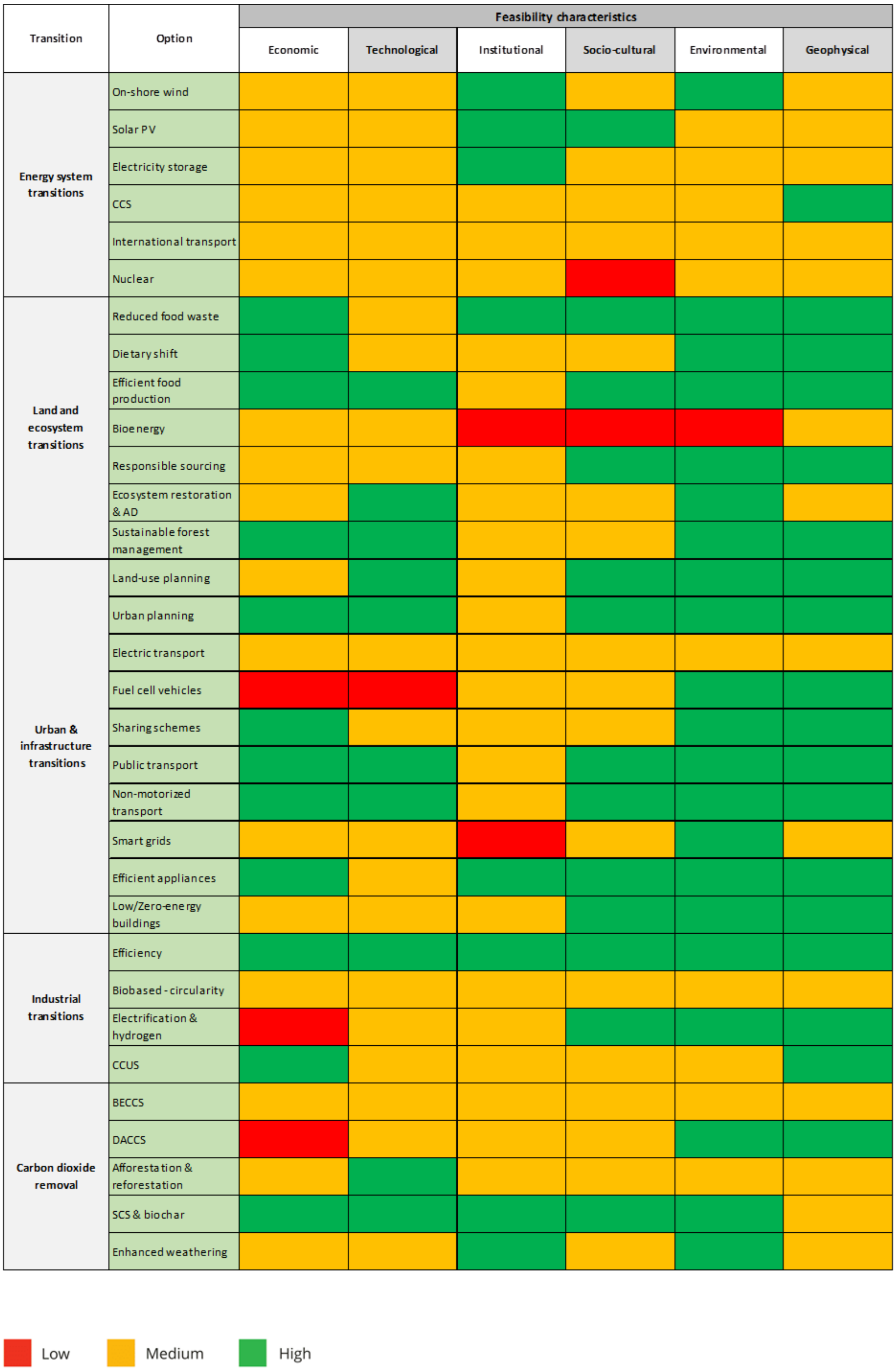
Figure 4.5 summarises a feasibility assessment for mitigation options assessed in Section 4.3 based on the AR5 results (mainly the WGIII Technical Summary), the literature assessment in Section 4.3, and expert judgement. The options are assessed along six feasibility characteristics: economic (Econ), technological (Tech), institutional (Inst), socio-cultural (Soc), environmental (Env) and geophysical (Geo), each based on a set of underlying indicators (see Table 4.2). The underlying indicators are assessed along a 3–point scale of high, medium or low feasibility. The results for each feasibility characteristic are assessed as the mean of combined scores of the indicators, classified into high (2.5 to 3), medium (1.5 to 2.5) and low (below 1.5). In the summarising figure, green indicates high; orange medium and red, low feasibility for the mitigation option along the feasibility characteristic.

The assessment of 28 mitigation options in Figure 4.5 is graphically represented in Figure 4.6 as six–dimensional hexagons, corresponding to the above feasibility characteristics, along a 3–point scale of low, medium and high feasibility. The CDR options and the options for reducing SLCPs are not included in Figure 4.6. For CDR, we refer to Figure 4.3 in Section 4.3.5. For SLCPs, the options to reduce them overlap with other mitigation options, and specific literature on the feasibility of options to reduce SLCPs is sparse, making an assessment difficult.

Figure 4.6 places the mitigation options along two implementation dimensions that are central to strengthening the global mitigation response: speed and scale. A qualitative assessment indicates the degree to which a mitigation option can be implemented speedily in line with what is required to stay below 1.5ºC (see Chapter 2 and Section 4.2.1), and at the large scale and geographical spread, indicating whether an option can be implemented across many geographical areas or can make a difference in a more limited scope.

For readability, each of the systemic transitions presented in this chapter is assessed in a panel in Figure 4.6: energy transitions, land and ecosystem transitions, urban and infrastructure transitions and industrial transitions. The axes speed and scale between the four system transitions are not comparable, meaning that an option placed at high speed in energy systems cannot necessarily be deployed at the same speed as an option that is placed high in land systems.

[END BOX 4.10 HERE]



Transition	Option	Feasibility characteristics					
		Economic	Technological	Institutional	Socio-cultural	Environmental	Geophysical
Energy system transitions	On-shore wind	🟧	🟧	🟩	🟧	🟩	🟧
	Solar PV	🟧	🟧	🟩	🟩	🟧	🟧
	Electricity storage	🟧	🟧	🟩	🟧	🟧	🟧
	CCS	🟧	🟧	🟧	🟧	🟧	🟩
	International transport	🟧	🟧	🟧	🟧	🟧	🟧
	Nuclear	🟧	🟧	🟧	🟥	🟧	🟧
Land and ecosystem transitions	Reduced food waste	🟩	🟧	🟩	🟩	🟩	🟩
	Dietary shift	🟩	🟧	🟧	🟧	🟩	🟩
	Efficient food production	🟩	🟩	🟧	🟩	🟩	🟩
	Bioenergy	🟧	🟧	🟥	🟥	🟥	🟧
	Responsible sourcing	🟧	🟧	🟧	🟩	🟩	🟩
	Ecosystem restoration & AD	🟧	🟩	🟧	🟧	🟩	🟧
	Sustainable forest management	🟩	🟩	🟧	🟧	🟩	🟩
Urban & infrastructure transitions	Land-use planning	🟧	🟩	🟧	🟩	🟩	🟩
	Urban planning	🟩	🟩	🟧	🟩	🟩	🟩
	Electric transport	🟧	🟧	🟧	🟧	🟧	🟧
	Fuel cell vehicles	🟥	🟥	🟧	🟧	🟩	🟩
	Sharing schemes	🟩	🟧	🟧	🟧	🟩	🟩
	Public transport	🟩	🟩	🟧	🟩	🟩	🟩
	Non-motorized transport	🟩	🟩	🟧	🟩	🟩	🟩
	Smart grids	🟧	🟧	🟥	🟧	🟩	🟧
	Efficient appliances	🟩	🟧	🟩	🟩	🟩	🟩
	Low/Zero-energy buildings	🟧	🟧	🟧	🟩	🟩	🟩
Industrial transitions	Efficiency	🟩	🟩	🟩	🟩	🟩	🟩
	Biobased - circularity	🟧	🟧	🟧	🟧	🟧	🟧
	Electrification & hydrogen	🟥	🟧	🟧	🟩	🟩	🟩
	CCUS	🟩	🟧	🟧	🟧	🟧	🟩
Carbon dioxide removal	BECCS	🟧	🟧	🟧	🟧	🟧	🟧
	DACCS	🟥	🟧	🟧	🟧	🟩	🟩
	Afforestation & reforestation	🟧	🟩	🟧	🟧	🟧	🟧
	SCS & biochar	🟩	🟩	🟩	🟩	🟩	🟧
	Enhanced weathering	🟧	🟧	🟩	🟧	🟩	🟧

🟥 Low 🟧 Medium 🟩 High

Figure 4.5: Feasibility assessment of 1.5°C-relevant mitigation options for the six characteristics of feasibility, as high (green), medium (orange) and low (red). For further explanation: see Box 4.10.

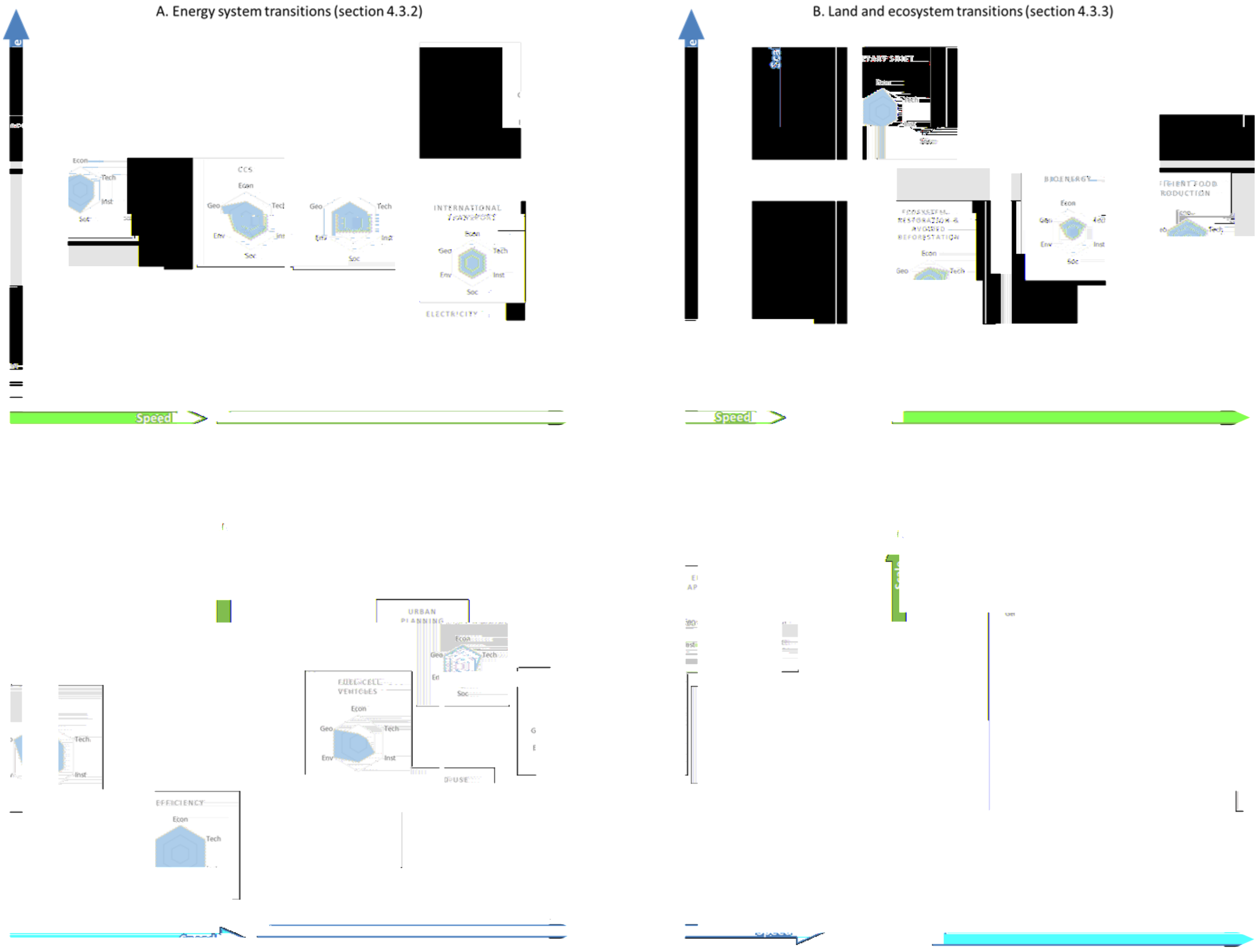


Figure 4.6: Feasibility assessment of 27 mitigation options in four systemic transitions along two implementation dimensions: Speed and scale. Only options in energy transitions (panel A), land and ecosystem transitions (panel B), urban and infrastructure transitions (panel C) and industrial transitions (panel D) are shown. If a mitigation option is placed on the far right on the “speed” axis, its implementation is expected to be able to be sped up quickly to its full mitigation potential, and therefore that enabling conditions can be created and feasibility issues, as discussed in section 4.3 and summarised in this section and in Figure 4.5, can be resolved. If a mitigation option is placed towards the top of the “scale” axis, it can be implemented at on a global scale and is estimated to have a large relative potential to reduce greenhouse gas emissions to 1.5˚C-consistent levels in the decades to come. If it is on the lower end of the scale, its applicability is more geographically constrained or more specific for a single system or sector (e.g., buildings or a specific type of forest). The axes are not the same across the panels (*i.e.*, if an energy systems option is qualified at the speed axes, it does not mean that an urban systems option placed at the same axes location would be classified at the same speed). Note that “speed” and “scale” are also part of the feasibility assessment in the spider diagrams. There may be big differences between speed and scale of implementing options in the Global North and the Global South, for various reasons; this is a best guess at the average. For further explanation about the approach: see Box 4.12 and Table 4.1.

4.5.2.2 Implementation of mitigation options towards 1.5˚C

The feasibility assessment highlights a myriad of characteristics that could form an agenda with items that could be addressed by the areas discussed in Section 4.4: governance, behaviour and lifestyles, innovation, enhancing institutional capacities, policy and finance. For instance, Section 4.4.3 on behaviour offers strategies for addressing public acceptance problems, and how changes can be more effective when communication and the actions relate to people's values.

From Section 4.4, main messages can be constructed: governance will have to be multi-level and engaging different actors, choosing the type of cooperation based on the specific systemic challenge or option at hand. If institutional capacity for financing and governing the various transitions is not urgently built, many countries will lack the ability to change pathways from a high-emission development scenario to a low- or zero-emission scenario. In terms of innovation, governments, both national and multilateral, can contribute to the mitigation-purposed application of general purpose technologies, if this is not managed, some emission reduction will happen autonomously, but not enough for 1.5ºC. International cooperation on technology, including technology transfer where this does not happen autonomously, is needed and can help creating the innovation capabilities in all countries to be able to operate, maintain, adapt and regulate mitigation technologies.

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

Policy instrumentation on the part of governments would benefit from carbon pricing, both for the price and innovation incentive and the revenue that can be used to correct distributional effects or subsidise development of new, more cost-effective or negative-emission technology or infrastructure. However, there is *high confidence* that pricing alone is insufficient, as it is excellent at incentivising incremental change but fails to provide incentives for the system change needed for staying below 1.5ºC. Apart from the incentives to change behaviour and technology, financial systems are an indispensable element of a systemic transition. If the capital markets don't acknowledge climate risk and the risk of transitions, which could be organised by institutions like central banks.

Strengthening implementation revolves around more than addressing feasibility barriers of options. 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, to: "enhance adaptive capacity, strengthen resilience, and reduce vulnerability" (UNFCCC, 2015a). Adaptation implementation is gathering momentum in many regions, guided by national NDC's and NAP's (see Cross-Chapter Box 4.1).

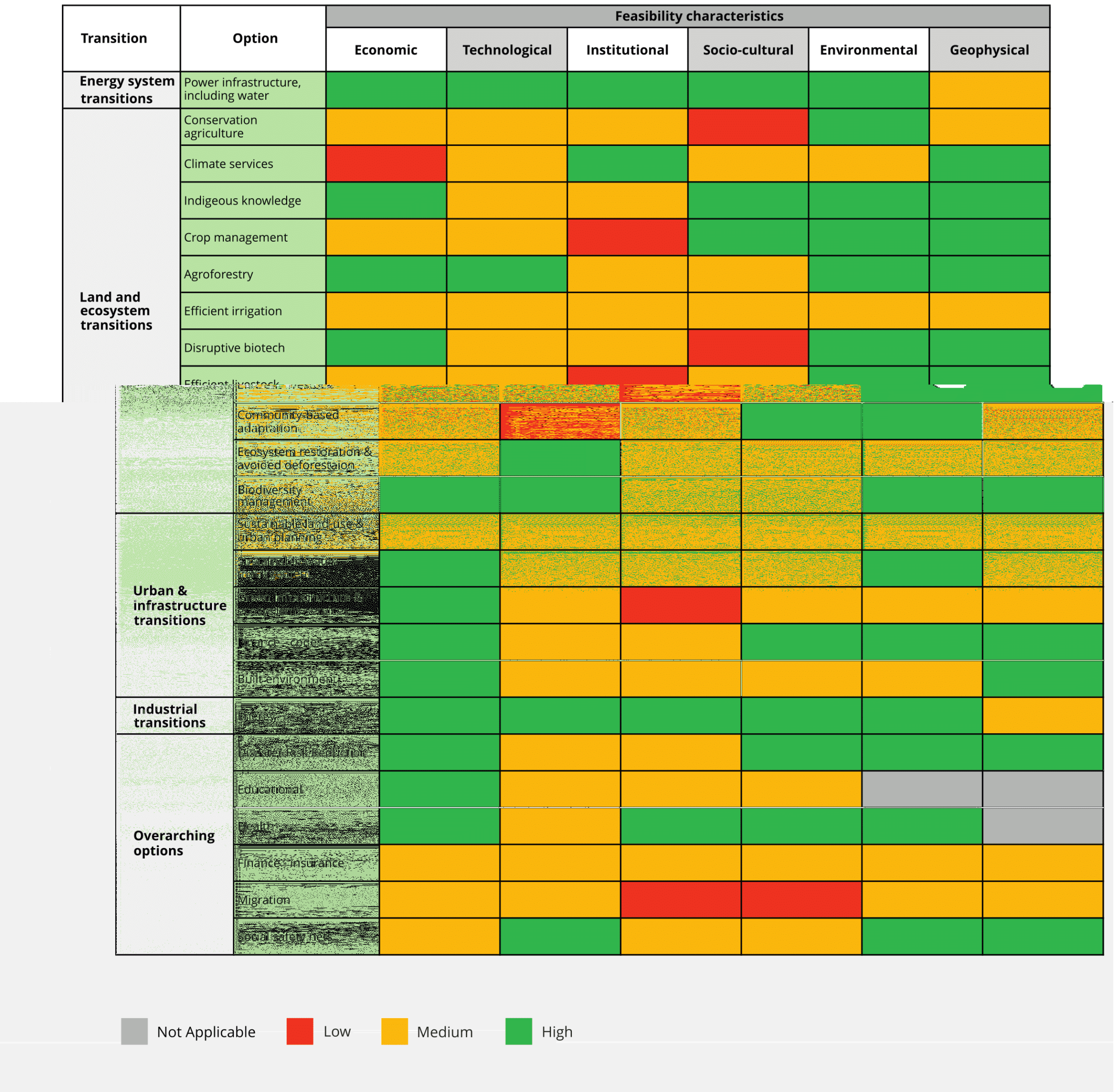
Operationalising adaptation in a set of regional environments on pathways to a 1.5°C world, requires strengthened global and differentiated regional and local capacities. It also needs rapid and decisive adaptation actions to reduce the costs and magnitude of potential climate impacts (Vergara et al.,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

This will need: (1) enabling conditions, especially improved governance, economic measures and financing (Section 4.4); (2) enhanced clarity on adaptation options to help identify strategic priorities, sequencing and timing of implementation (Section 4.3); (3) a robust monitoring and evaluation framework; and (4) political leadership (Lesnikowski et al., 2017; Magnan et al., 2015; Magnan and Ribera, 2016; UNEP, 2017a).

4.5.3.1 Feasible adaptation options

This section summarises the composite feasibility (defined in Cross-Chapter Box 1.2, Table 1 and in Table 4.2) of select adaptation options using evidence presented across this chapter and the expert-judgement of its authors (Figure 4.7). These represent a subset of AR5 adaptation options, selected based on post-AR5 literature availability and 1.5°C-relevance.

There are not only gaps in the literature, around crucial adaptation questions on the transition to a 1.5°C world (see Section 4.5.1), but inadequate literature to undertake a spatially differentiated assessment (as suggested in Cross-Chapter Box 1.2). There are also limited baselines for exposure, vulnerability or risk to help policy and implementation prioritisation. Hence, the compiled results can at best provide a broad framework to inform policymaking. Given the bottom-up nature of most adaptation implementation evidence, care needs to be taken in generalising these findings.



Transition	Option	Feasibility characteristics					
		Economic	Technological	Institutional	Socio-cultural	Environmental	Geophysical
Energy system transitions	Power infrastructure, including water	🟩	🟩	🟩	🟩	🟩	🟧
Land and ecosystem transitions	Conservation agriculture	🟧	🟧	🟧	🟥	🟩	🟧
	Climate services	🟥	🟧	🟩	🟧	🟧	🟩
	Indigeous knowledge	🟩	🟧	🟧	🟩	🟩	🟩
	Crop management	🟧	🟧	🟥	🟩	🟩	🟩
	Agroforestry	🟩	🟩	🟧	🟧	🟩	🟩
	Efficient irrigation	🟧	🟧	🟧	🟧	🟧	🟧
	Disruptive biotech	🟩	🟧	🟧	🟥	🟩	🟩
	Efficient livestock	🟧	🟧	🟥	🟧	🟩	🟩
	Community-based adaptation	🟧	🟥	🟧	🟩	🟩	🟧
	Ecosystem restoration & avoided deforestaion	🟧	🟩	🟧	🟧	🟧	🟧
	Biodiversity management	🟩	🟩	🟧	🟧	🟩	🟩
Urban & infrastructure transitions	Sustainable land use & urban planning	🟧	🟧	🟧	🟧	🟧	🟧
	Sustainable water management	🟩	🟧	🟧	🟧	🟩	🟧
	Green infrastructure & ecosystem services	🟩	🟧	🟥	🟧	🟧	🟧
	Building codes	🟩	🟧	🟧	🟩	🟩	🟩
	Built environment	🟩	🟧	🟧	🟧	🟧	🟩
Industrial transitions	Energy	🟩	🟩	🟩	🟩	🟩	🟧
Overarching options	Disaster Risk Reduction	🟩	🟧	🟧	🟩	🟩	🟩
	Educational	🟩	🟧	🟧	🟧	⬜	⬜
	Health	🟩	🟧	🟩	🟩	🟩	⬜
	Finance, insurance	🟧	🟧	🟧	🟧	🟧	🟧
	Migration	🟧	🟧	🟥	🟥	🟧	🟧
	Social safety nets	🟧	🟩	🟧	🟧	🟩	🟩

⬜ Not Applicable 🟥 Low 🟧 Medium 🟩 High

Figure 4.7: Feasibility assessment of 1.5°C-relevant adaptation options as high (green), medium (orange) and low (red). For further explanation: see Box 4.11.

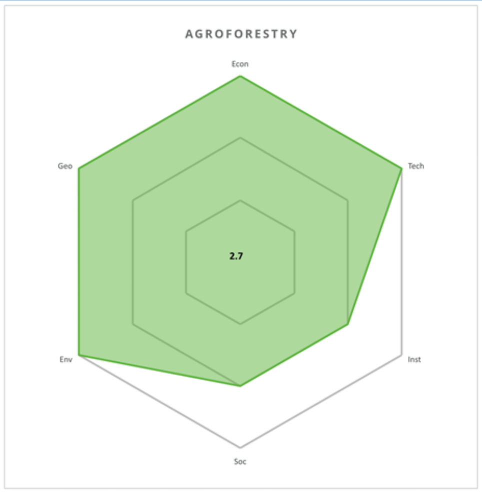
[START BOX 4.11 HERE]

Box 4.11: How to read the adaptation feasibility assessment

Figure 4.7 summarises an expert feasibility assessment for adaptation options assessed in Section 4.3 along six feasibility characteristics: economic (Econ), technological (Tech), institutional (Inst), socio-cultural (Soc), environmental (Env) and geophysical (Geo), each based on a set of underlying indicators. Green indicates high; orange medium and red, low feasibility.Grey denotes that the feasibility dimension is not applicable for a particular option.

The assessment in Figure 4.7 is graphically represented in Figure 4.8 as a six-dimensional hexagon, corresponding to the above feasibility characteristics, along a 3-point scale of low, medium and high feasibility.Composite feasibility (the number in the centre of the hexagon) of the adaptation option is assessed as the mean of combined scores along each feasibility dimension, classified into high (2.5 to 3), medium (1.5 to 2.5) and low (below 1.5). Agreement within the literature assessed is denoted as high (green), medium (yellow), and red (low) colour of the assessment areas. The colour shade denotes depth of evidence wheresolid (high evidence), less dark (medium evidence), and very light (low evidence).

For example, for agroforestry (Box 4.11 Figure 1) technical, ecological and geophysical feasibility are assessed as high while economic, social and institutional feasibility are medium. There is high agreement within the assessed literature on feasibility (green), but only medium evidence (less dark).



Box 4.11, Figure 1: Feasibility assessment of agroforestry as an adaptation option using six feasibility dimensions.

Two key implementation aspects that are central to strengthening the global adaptation response arecost effectiveness and scalability. A qualitative assessment on a three-point scale indicates low, medium and high for cost effectiveness and slow, medium and fast, for scalability.

This is used to create a 3x3 policy matrix for each system transition presented in this chapter: energy and industrial transitions, land and ecosystem transitions, urban and infrastructure transitions and cross-cutting overarching adaptation options.

As a guide to interpretation: the situation of a medium to high composite feasibility option in the upper-right four boxes, with medium to high cost effectiveness and scalability, may deliver the best 1.5°C–relevant implementation outcomes.

The feasibility of 24 adaptation options is assessed in Figure 4.8, within the context four systemic transitions that define potentialpathways to a 1.5°C world.A summary of the findings ispresented below.

[END BOX 4.11 HERE]

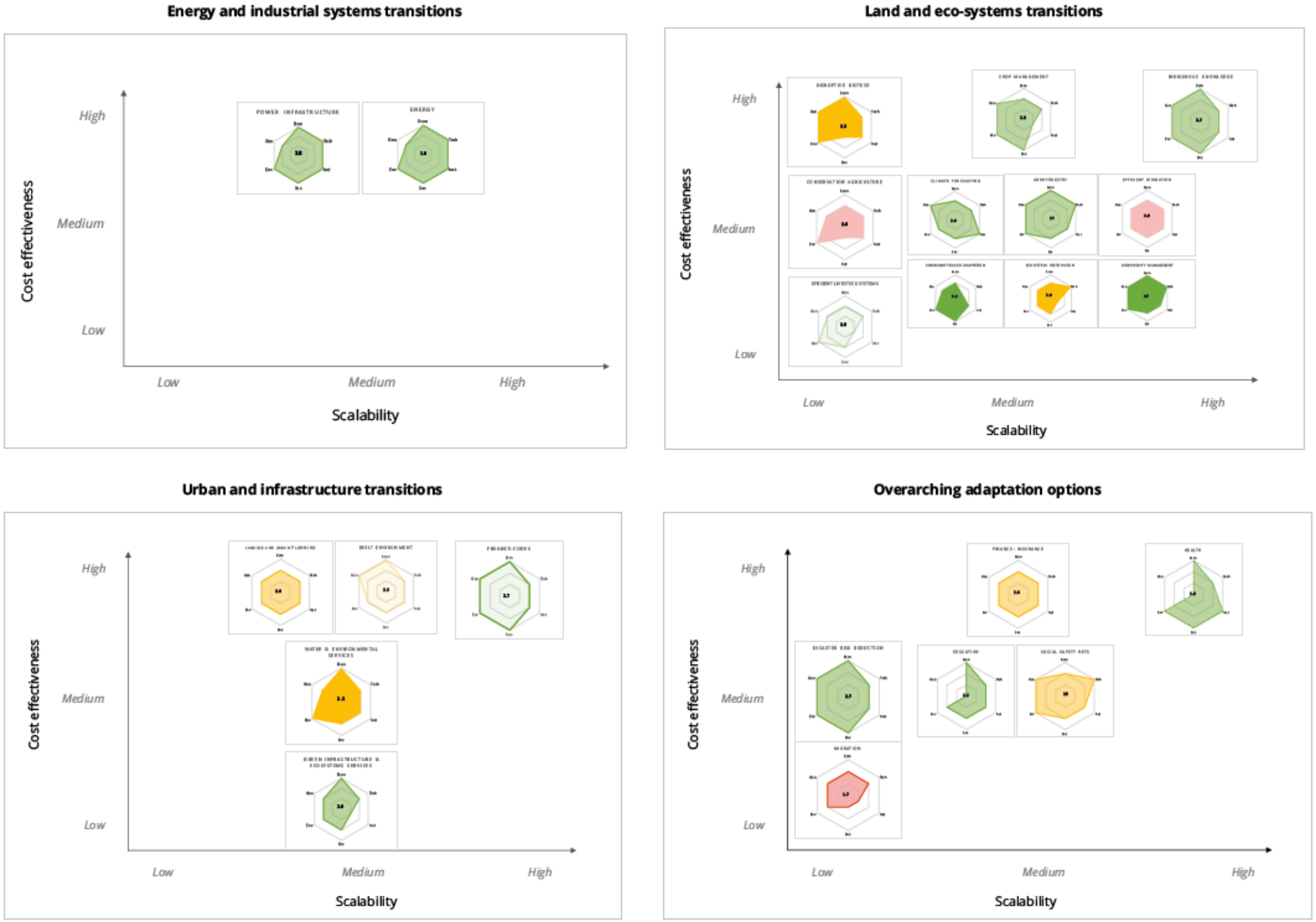


Figure 4.8: Feasibility assessment along a 3-point scale of low, medium and high feasibility of 24 adaptation options. Composite feasibility (number in the centre of the hexagon) is the mean of combined scores along each feasibility characteristic, classified into high (2.5 to 3), medium (1.5 to 2.5) and low (below 1.5). Agreement within the literature assessed is denoted as high (green), medium (yellow), and red (low) colour while colour shade denotes depth of evidence: solid (high evidence), less dark (medium evidence), and very light (low evidence). For explanation about the approach: see Box 4.11.

Energy and industrial transitions

Power infrastructure (assessed in Section 4.3.2) and industrial energy systems (Section 4.3.5) are good candidates for adaptation implementation with high overall feasibility and cost effectiveness, but may not have a significant impact on adaptation potential with the impact on exposure and vulnerability may not be very high (Table 4.8).

Table 4.8: Feasibility of energy and industrial transition adaptation options.

Adaptation option	**Composite feasibility**	**Cost effectiveness**	**Scalability**	***Agreement***	***Evidence***
Power infrastructure	High	High	Medium	*High*	*Medium*
Industrial energy systems	High	High	Medium	*High*	*Medium*

Land and ecosystem transitions

Biodiversity management, agroforestry and leveraging Indigenous knowledge form a high feasibility, high to medium cost effectiveness and highly scalable suite of options (Table 4.9). Efficient irrigation has medium feasibility and medium cost effectiveness. Taken together, they have considerable adaptation potential. Conservation agriculture, efficient livestock management and community-based adaptation are mediumly feasible, but have limited scalability and cost effectiveness. The assessment of these options can be found in Section 4.3.3.

Table 4.9: Feasibility of land and ecosystem transition adaptation options.

Adaptation option	**Composite feasibility**	**Cost effectiveness**	**Scalability**	***Agreement***	***Evidence***
Indigenous knowledge	High	High	High	*High*	*Medium*
Crop management	Medium	High	Medium	*High*	*Medium*
Disruptive biotechnology	Medium	High	Low	*Medium*	*High*
Efficient irrigation	Medium	Medium	Medium	*Low*	*Medium*
Agroforestry	High	Medium	Medium	*High*	*Medium*
Climate forecasting	Medium	Medium	Medium	*High*	*Medium*
Conservation agriculture	Medium	Medium	Low	*Low*	*Medium*
Biodiversity management	High	Medium	High	*High*	*High*
Ecosystem restoration	Medium	Medium	Medium	*Medium*	*High*
Community-based adaptation	Medium	Medium	Medium	*High*	*High*
Efficient livestock systems	Medium	High	Low	*High*	*Low*

Urban and infrastructure transitions

Enabling adaptation in urban systems via regulations and building codes is highly feasible with high cost effectiveness and scalability, but thequality of evidence is not fully established (Table 4.10). Adapting buildings and using land use and planning controls to enable adaptation are less feasible, but have high cost effectiveness and medium scalability, even though the evidence base is lower than desirable. Adaptation of water and environmental services and ecosystem-based adaptation, score medium on overall feasibility with low to medium cost effectiveness. These options are discussed in Section 4.3.4.

Table 4.10: Feasibility of urban and infrastructure transition adaptation options.

Adaptation option	**Composite feasibility**	**Cost effectiveness**	**Scalability**	***Agreement***	***Evidence***
Financing and codes	High	High	High	*High*	*Low*
Adapting buildings and the built environment	Medium	High	Medium	*Medium*	*Low*
Adaptation through land use regulation and planning	Medium	High	Medium	*Medium*	*Medium*

Adaptation of water and environmental services	Medium	Medium	Medium	*Medium*	*High*
Adaptation of green infrastructure and ecosystem services	Medium	Low	Medium	*High*	*Medium*

Overarching adaptation options

Health, social safety nets, and DRM are highly feasible overarching adaptation options, with medium to high cost effectiveness and scalability (Table 4.11). Education and insurance have lower aggregate feasibility, but fall into the same broad suite of policy options, which taken together could enhance adaptation potential. Migration is the least feasible and preferred adaptation option, but the literature is limited on this theme, and may not have enough linkages with livelihood and development opportunities tied to migration. These options are in Section 4.3.6.

Table 4.11: Feasibility of overarching adaptation options

Adaptation option	**Composite feasibility**	**Cost effectiveness**	**Scalability**	***Agreement***	***Evidence***
Health systems	High	High	High	*High*	*Medium*
Insurance	Medium	High	Medium	*Medium*	*Medium*
Social safety nets	High	Medium	Medium	*Medium*	*Medium*
Education	Medium	Medium	Medium	*High*	*Medium*
Disaster risk management	High	Medium	High	*High*	*Medium*
Migration	Low	Low	Medium	*Low*	*Medium*

Many of the assessed adaptation options also have synergies with select mitigation options and processes (assessed in 4.5.2) as well as contextual trade-offs that will need to be carefully considered, while planning climate action. A summary table of synergies and trade-offs for several adaptation options are presented in Supplementary Material 4A.

4.5.3.2 Adaptation governance

Adaptation governance plays an important role in implementation, especially the recognition of non-state and sub-national actors (Chan et al., 2016; Fünfgeld, 2015; Leck and Roberts, 2015; Massey et al., 2014), at the local level (Hjerpe et al., 2015; Nalau et al., 2015; Ruiz-Mallén et al., 2015)..

Case studies have identified bottom-up adaptation actions of governance (Juhola and Westerhoff, 2011). They include local populations and understanding of climate change (Cloutier et al., 2015; Ngaruiya et al., 2015; Ruiz-Mallén et al., 2015). They are based on cultural knowledge and practices (Kuruppu and Willie, 2015), and are supported by knowledge exchange (Leck and Roberts, 2015).

Governments have identified the need for integrated adaptation responses to climate change (Barton et al., 2015) by mainstreaming adaptation and mitigation planning (Aylett, 2015), which is recognised as effective for policy making (Uittenbroek et al., 2013).

Mainstreaming different adaptation options and strategies can help convergence withsustainable development, promote local climate transitions and enable transformative adaptation (Wamsler, 2015), but these processes need to be monitored carefully, to enable feedback and learning.

4.5.3.3 Adaptation finance

The World Bank estimates the adaptation cost envelope from USD 70 to more than USD 100 billion annually through to 2050 (Bank, 2010). UNEP's Adaptation Gap report (2016) estimates the costs of adaptation to be two-to-three times higher than current global estimates by 2030, and potentially four-to-five times higher by 2050, which could range between USD 140–300 billion by 2030, and between USD 280–500 billion by 2050 (UNEP, 2016b).

Four broad issues need attention around climate adaptation financing (Hallegatte and Corfee-Morlot, 2011; Hallegatte and Rozenberg, 2017): (1) confronting the political economy of adaptation, particularly addressing the cost-benefit asymmetry; (2) lack of a set of adaptation performance indicators to stimulate investment; (3) involvement of multiple interest groups in adaptation, requires a mechanism to compensate 'losers'; (4) distributional impacts, rather than only aggregate losses need to be addressed.

Addressing the convergence across adaptation, development and infrastructure finance to be able to re-direct capital flows to address deeply embedded vulnerabilities and create a platform that allows for generating the right kind of market signals, continues to be a challenge.

4.5.4 Convergence with sustainable development

This chapter discussed the opportunities and challenges associated with strengthening and implementing the global response to 1.5°C warming. It also explored the necessary systemic transitions, feasibility of adaptation and mitigation options and enabling conditions to redirect the world and regional economies, socio-ecological and socio-technical systems, towards a more sustainable and equitable 1.5°C world, over the 21st century.

A sustainable and equitable 1.5°C world would be organised around the goals of sustainable development: the end of extreme poverty and hunger; decent jobs and infrastructure; universal access to clean and renewable energy and other basic services; sustainable cities and regions, with safe and affordable housing and sustainable mobility; universal access to healthcare and education; gender equality and reduced inequality; reduced risk and climate resilience; and living within planetary boundaries, including appropriate climate action (Mach et al., 2017; United Nations, 2015) (See Chapter 5 for more details).

The reality is more complex and regionally differentiated. The global human population is expected to grow from the current 7.5 billion to over 9 billion by mid-century (United Nations, 2017). This is an increasingly interconnected world, facing an interlocked set of environmental crises, rising resource consumption, inequality, exclusion and social stratification, and many regions locked into poverty (Deaton, 2013; Piketty, 2014; Steffen et al., 2015). The 2008 global financial crisis, and the subsequent 'great recession', exposed multiple 'fault lines' in the global economy and polity (Rajan, 2010) that are yet to be fully addressed.

Nevertheless, over the last few decades there has been a consistent growth of global economic output, urbanisation, wealth and trade, with a significant reduction in extreme poverty and development outcomes, driven by differential progress in some regions. There has also been a growth of technological, social and institutional innovation and the expansion in the use of disruptive information, energy, and bio-technologies. These trends are expected to continue and deepen over the next few decades (Burt et al., 2014). There has also been an unprecedented wave of international solidarity and partnership, reflected in the commitment to the SDGs and 'leaving no one and no place behind' (Revi, 2017; United Nations, 2015) and the Paris Agreement (UNFCCC, 2015c).

Numerous examples are presented in the chapter show that 1.5°C-compatible, inclusive, prosperous and healthy societies are possible, and that numerous actors are formulating strategies consistent with 1.5°C. Box 4.12 gives another example. At the same time, very few cities, regions, countries, businesses or communities are truly in line with 1.5°C. It is in this context that the strengthening of the global response to the transition to a 1.5°C world is situated. The broad frame to enable this was laid out in AR5, and outlined a range of mitigation and adaptation measures and enabling conditions to stay below a 2°C target. Many of these hold for the 1.5°C transition, except that the global mitigation response to stay below 1.5°C will have to be more rapid, systemic and far-reaching.

This would need to simultaneously trigger the decarbonisation and transformation of energy and industrial systems, land and ecosystems, and urban and infrastructural systems, across all regions. Necessary enabling conditions, identified by this chapter include: (1) rapid deployment low-emission technologies, as well as social and technical innovations, to enable a global and sustainable energy, land, urban, infrastructure and industry transition; (2) enabling the acceleration of adaptation of key systems at risk, before both hard and soft limits are crossed; (3) creating the conditions for widespread governance, institutional, financial and behavioural change; (4) enabling the synergy between development, mitigation and adaptation actions and alleviating the impact of trade-offs between them; (5) ensuring the mobilisation of adequate financial resources to front-load these actions and manage the economic impact and potential resistance to the transition out of fossil fuels; (6) addressing intra- and inter-generational and regional equity concerns; and (7) filling gaps in knowledge to facilitate the transition to a 1.5°C world. If these processes are to be realised, they would need to be in strong alignment with the principles of sustainable development and, until 2030, with the SDGs. This will be further elaborated in Chapter 5.

[START BOX 4.12 HERE]

Box 4.12: Bhutan: Integrating economic growth, carbon neutrality and happiness.

Bhutan has three national goals: its famous Gross National Happiness index (GNH), economic growth (GDP) and carbon neutrality. These goals clearly interact and raise questions about whether they can all be maintained into the future. Interventions in the enabling environment are required to comply with all three roles. This case study gives a short discussion of how Bhutan integrates its three goals.

Bhutan is well known for its GNH, which contains 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). In many ways the GNH is an expression of the SDGs (Allison, 2012; Brooks, 2013) and reflects enabling environments as discussed in this section. The GNH has been measured twice, 2010 and 2015, and this showed an increase of 1.8% (Ura et al., 2015). In addition, like most emerging countries, Bhutan wants to increase its wealth and become a middle-income country by 2020 (RGoB, 2013, 2016), and it aims to remain carbon-neutral which has been in place since COP19 (2011) and was reiterated in its INDC (NEC, 2015). Bhutan achieves its current carbon-neutral status through hydropower and forest cover (Yangka and Diesendorf, 2016).

However, Bhutan faces rising GHG emissions. Transport and industry are the largest growth areas (NEC, 2011). Modelling by Yangka() has shown that the carbon-neutral status would be broken by 2037 or 2044 depending on rates of economic growth, if business-as-usual approaches continue. Increases in hydropower are being planned based on climate change scenarios that suggest sufficient water supply will be available (NEC, 2011). The biggest issue is to electrify the transport system and plans are being developed to electrify both freight and passenger transport (ADB, 2013). Bhutan wants to be a model for achieving economic growth consistent with limiting climate change to 1.5˚C and improving its Gross National Happiness.

[END BOX 4.12 HERE]

Deep structural changes from the local to the global level in governance, financing and innovation systems will be necessary to accelerate actions for the transition to a 1.5°C world. These include: (i) accelerating the short-term co-benefits of joined up mitigation, adaptation and development action; (ii) mobilising broad based political and public support by aligning climate policy with other public policies, enabling greater access to basic needs and services, also known as the goals of sustainable development; (iii) establishing appropriate enabling national and international environments that address institutional, financial, regulatory, pricing and behavioural barriers to implementation; (iv) supporting innovation processes, changes in lifestyles and spatial dynamics that will allow for deeper reductions in GHG emissions, together with long-term development benefits; (v) establishing appropriate monitoring and tracking mechanisms to accelerate local to global implementation; (vi) changes in the international governance and financial architecture to enable unhindered access to finance and technology, and address climate-related trade barriers.

Even this suite of policy and implementation measures may be inadequate to prevent an overshoot and move to a zero-emission regime early enough in the century to avoid serious impacts on natural and human systems. This may imply, the rapid and large-scale deployment of a range of CDR options, many of which have limited feasibility and are currently in their early stage of development. The chapter also explores the serious challenges, concerns and uncertainty around the potential deployment of 'peak-shaving' measures like RMMs that have been mentioned to address limited overshoot over 1.5 or 2°C. Such RMMs appear to be in conflict with many potential sustainable development measures. Considerable governance, institutional and technical innovation may be necessary to enable this, as elaborated in the chapter, and social resilience would have to guide this to make mitigation, adaptation and, if considered, RMMs feasible.

The positive outcome of transitioning to a 1.5°C world without a significant period of overshoot is that expected climate impacts will be lower than otherwise. They are nevertheless significant (see Chapter 3), and will need to be addressed by a mix of transformative adaptation actions, linked sustainable development interventions, and convergent disaster risk reduction measures.

Considering all this would benefit from a deeper and more nuanced exploration of the relationship of 1.5°C transitions, that also touches on key questions of equity, justice and ethics. This is the topic of Chapter 5.

[START CROSS-CHAPTER BOX 4.1 HERE]

Cross-Chapter Box 4.1: Consistency between nationally determined contributions and 1.5°C scenarios

Authors: Paolo Bertoldi, Michel den Elzen, James Ford, Richard Klein, Debora Ley, Timmons Roberts, Joeri Rogelj

This box provides an assessment of the literature on nationally determined contributions (NDCs) for emission reductions in 2030 in relation to 1.5°C compatible pathways. This Box also assesses the adaptation plans in the NDCs.

Mitigation

1. Introduction

The Paris Agreement seeks to strengthen the global response to the threat of climate change, limiting the increase of global average temperature to 'well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels', with the 'aim to reach global peaking of greenhouse gas emissions as soon as possible' and 'achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century' (UNFCCC, 2015a).

The Paris Agreement departs from the top-down approach of the Kyoto Protocol, which assigns mandatory reduction limits to Annex B countries, and it adopts a bottom-up approach in which each country determines its contribution to reach the common target. These national targets, plans and measures are called 'nationally determined contributions' (NDCs). NDCs shall be revised and increased every five years through a 'global stocktake' mechanism established by the UNFCCC, supported by a facilitative dialogue in 2018, and a first formal review in 2023. According to Article 4.2 of the Paris Agreement, each party is obliged to 'prepare, communicate and maintain successive NDCs' as well as to pursue domestic mitigation measures to achieve the NDC's objective' (van Asselt and Kulovesi, 2017). Subsequent NDCs must increase in ambition and be based on the principles of 'highest possible ambition' as well as 'common but differentiated responsibilities and respective capabilities, in the light of different national circumstances'. According to the UNFCCC by the end of April 2016, a total number of 189 Parties, or 96% of all Parties to the UNFCCC, have submitted 161 INDCs (UNFCCC, 2016), For the 170 countries that have ratified the Paris Agreement (28 November 2017), the INDCs turned into NDCs.

There is *high agreement* in the literature that NDCs provide an important part of the global response to climate change and represent an innovative bottom-up instrument in climate change governance (see Section 4.4.1), which has all signatory countries committed to contributing to global emissions reductions(den Elzen et al., 2016; Fawcett et al., 2015; Luderer et al.; Rogelj et al., 2016; UNEP, 2017b; Vandyck et al., 2016; Vrontisi et al.). The global emission projection resulting from full implementation of the NDCs represent in any case an improvement compared to the business as usual (Rogelj et al., 2016) and current policies scenarios to 2030 (den Elzen et al., 2016; Roelfsema et al.). UNEP (2017a) assessed the emissions associated with the NDCs and current policies of the G20 economies (*e.g.*, Vandyck et al. 2016; den Elzen et al. 2016; Kuramochi et al., 2017), and conclude that most economies require new policies and actions to achieve their NDC targets.

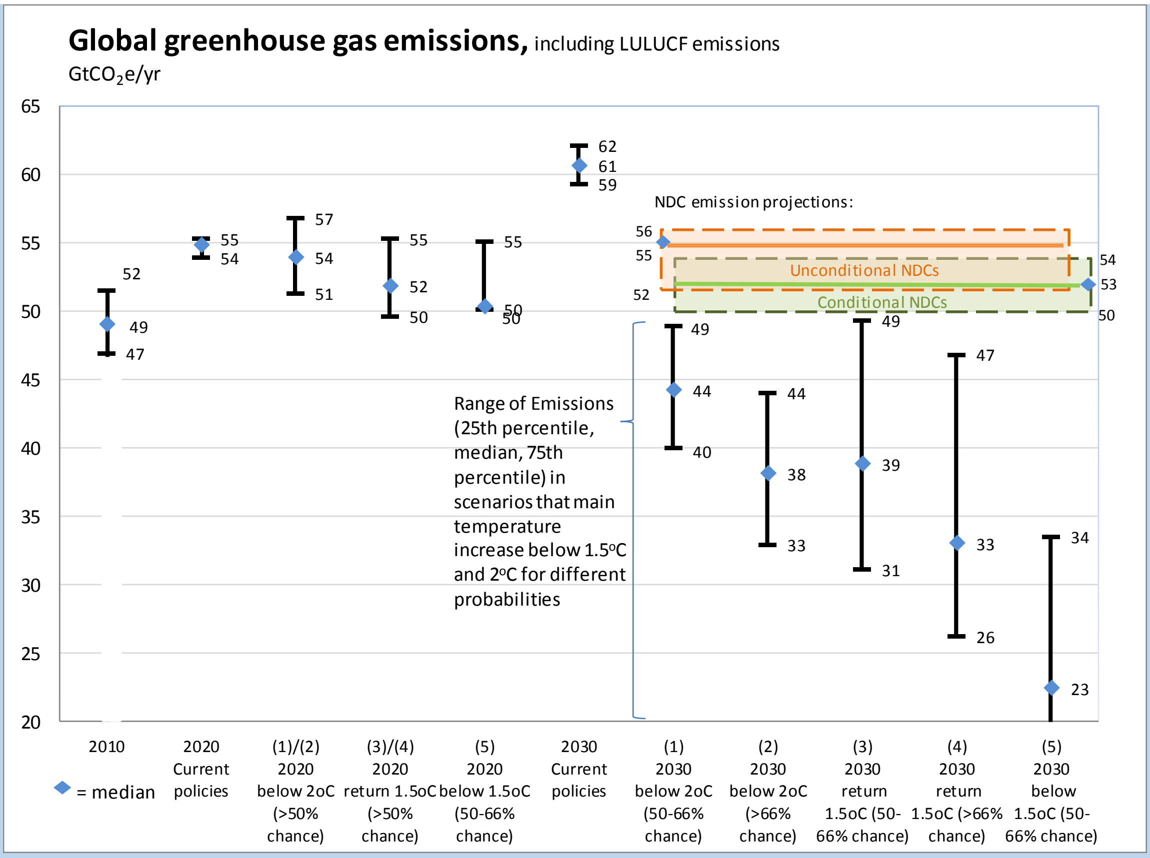
The NDCs are also recognised by some authors as increasing the transparency and credibility of the process (Nemet et al., 2017), even if the format is left very open and, as a result, different types of targets are pledged (Rodríguez and Pena-Boquete, 2017).

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

Estimates of the global average temperature increase would reach 2.9–3.4°C above preindustrial levels with a greater than 66% probability by 2100 (Rogelj et al., 2016; UNEP, 2017b), under a full implementation of unconditional NDCs and comparable action afterwards. Full implementation of the conditional NDCs would lower the estimates by about 0.2°C by 2100. This range has been broadly confirmed by earlier peer-reviewed literature (Fawcett et al., 2015). To give an indication of the carbon budget implications of NDC scenarios, Rogelj et al. (2016) estimated cumulative emissions in the range of 750 to 800 $GtCO_2$ for the period 2011–2030 if the NDCs are successfully implemented. The carbon budget for post-2010 emissions compatible with limiting global temperature increase to below 1.5°C with a 50–66% probability was earlier estimated at about 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. This estimate has been updated in this report (Section 2.2 and Section 2.3.1). The budget for limiting global temperature increase to 1.5°C with at least 66% probability is lower (Clarke et al., 2014).

3. The effect of NDCs on global GHG emissions

Several studies estimate global emission levels that would be achieved under the NDCs (e.g., (den Elzen et al., 2016; Fawcett et al., 2015; Luderer et al., 2016; Rogelj et al., 2016, 2017a; Rose et al., 2017; Vandyck et al., 2016). Rogelj et al. (2016)and (UNEP, 2017b) have assessed this literature and present the global emission projections resulting from full implementation of the NDCs, as analysed in about ten studies, and concluded that the full implementation of the unconditional and conditional INDCs are expected to result in global GHG emissions of about 55 (52–56) and 53 (49–54) $GtCO_2$-eq yr^{-1}, respectively (Cross-Chapter Box 4.1 Figure 1).



Cross-Chapter Box 4.1, Figure 1: Global greenhouse gas emissions as implied by NDCs compared to current-policy scenario and five scenarios that keep temperature increase below 1.5°C and 2°C for different probabilities. The 25th–75th-percentile ranges are shown for the five 1.5°C and 2°C scenarios (for details, see Table 2.7). For current-policies and NDC scenarios, the 10th–90th-percentile range across all assessed studies are given (for the list of studies, see (Rogelj et al., 2016; UNEP, 2017b). Source: based on Rogelj et al. (2016) and UNEP (2017a).

4. The 2030 emissions gap with 1.5°C and urgency of action

The key question related to current NDCs and 1.5°C pathways is whether the implied emissions reductions are in line with 1.5°C pathways. As the 1.5°C pathways require deep decarbonisation over multiple decades to reach carbon neutrality by around mid-century, the NDCs by themselves cannot be sufficient, as they only have a timehorizon until 2030. Several authors (Fujimori et al., 2016; Hof et al., 2017; Rogelj et al., 2016; Vandyck et al., 2016) have run, used results or compared NDCs pathways with emissions pathways produced by integrated assessment models to assess the contribution of NDCs to achieve the 1.5°C targets in the Paris agreement. There is strong agreement coming from multiple assessments that current NDC emission levels are not in line with pathways that limit warming to 1.5°C by the end of the century (Fawcett et al., 2015; Hof et al., 2017; Luderer et al., 2016; Robiou du Pont et al., 2016; Rogelj et al., 2016, 2017a; UNEP, 2017b; Vandyck et al., 2016). This is confirmed in Cross-Chapter Box 4.1 Figure 1 showing that estimates of 2030 emissions levels in line with the current NDCs fall outside the range of 2030 emissions found in 1.5°C pathways, but also the 2°C pathways (see Section 2.3.3 and Table 2.7 in this report, Figure 2.10 and Cross-Chapter Box 4.1 Figure 1). A large gap exists between 2030 emission levels resulting from the NDCs and those consistent with least-cost pathways to the 2°C and 1.5°C goals respectively. The median 2°C emissions gap (>66% chance) for the full implementation of both the conditional and unconditional NDCs for 2030 is 15 to 17 GtCO$_2$-eq. The gap in the case of the 1.5°C target (>66% chance) is about 5 GtCO$_2$-eq greater.

The analysis of NDC-specific measures and targets (*e.g.,* for renewable energy) can provide insights into whether a move towards the required transition for a 1.5°C pathway is already envisaged. Earlier studies indicated important trade-offs of delaying global emissions reductions in the context of trying to limit global mean temperature increase to 1.5°C (Sections 2.3.5 and Section 2.5.1). AR5 identified some flexibility in 2030 emission levels when pursuing a 2°C objective (Clarke et al., 2014) indicating that the 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 have showed that full implementation of the NDCs by 2030 (but nothing more) would imply much deeperand faster emission reductions beyond 2030 in order to meet 2ºC, and also higher costs and a higher effort of negative emissions (Fujimori et al., 2016; Luderer et al.; Rose et al., 2017; Sanderson et al., 2016; van Soest et al., 2017). However, no such flexibility has been found for 1.5°C pathways (Luderer et al., 2016; Rogelj et al., 2017a) indicating that the post–2030 emissions reductions required to still remain within a 1.5°C compatible carbon budget during the 21st century (Section 2.2) are not within the feasible operating space of state-of-the-art process-based global integrated assessment models of the energy-economy-land system. This indicates that the risks of failure to reach a 1.5°C pathway are significantly increased (Riahi et al., 2015).

Accelerated and stronger short-term action and enhanced longer-term national ambition that go beyond the NDCs are needed if the 1.5°C limit is to remain within reach. Implementing more ambitious emissions reduction than current NDCs implies 2030 action towards the levels identified in Section 2.3.3, either as part of NDCs or by over-delivering on NDCs, would significantly reduce the risk of failure to stay below 1.5ºC. The mechanisms for stock-taking and ratcheting-up of the targets can help reinforcing the national pledges (Wakiyama and Kuramochi, 2017).

5. *The impact of uncertainties on NDC emission levels*

Some studies assume full successful implementation of all of the NDCs' proposed measures, sometimes with variations to account for some of the NDC features which are subject to conditions related to finance and technology transfer. As the measures proposed in NDCs are not legally binding under the Paris Agreement, there is no strong guarantee that they will be implemented or that they will achieve the proposed national 2030 targets (Nemet et al., 2017). There are also indications that some countries might over-deliver on their pledged emissions reductions. This would further impact estimates of anticipated 2030 emission levels.

The aggregation of targets results in high uncertainty (Rogelj et al., 2017a). This uncertainty could be reduced with more focused energy accounting and clearer guidelines for compiling the future NDCs (Rogelj et al., 2017a). Furthermore, the usefulness of conditional NDCs as a potential mechanism to facilitate international mitigation cooperation and thus enable greater global ambition has also been highlighted in the literature (Holz et al., 2017).

There are many factors that influence the global aggregated effects of NDCs. There is limited literature on the impact of uncertainties on the NDC projections with some exception (Rogelj et al., 2017a). The UNEP Gap Report (UNEP, 2017b) contains a box on uncertainties and NDCs. The mains factors, including socio-economic factors are: (1) variations in overall socioeconomic conditions, such as Gross Domestic Product and population growth, (2) uncertainties in historical emission inventories, (3) the conditionality of certain NDCs, (4) the 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, as renewable energy or otherwise. In addition, there are land-use mitigation uncertainties, with some literature (Forsell et al., 2016; Grassi et al., 2017), and also the literature on the impact of GWPs (UNFCCC, 2016).

As an example, the Paris Agreement does not indicate which metrics and time horizon should be used in the calculations of CO$_2$-equivalent emissions (Allen et al., 2016). In addition, some developing countries have reduction targets based on a percentage of business-as-usual emission projections, which adds additional uncertainty on the level of emissions in 2030 (Puig et al., 2017).

6. The impact of sub-national and non-state actions, and other factors (like Kigali etc.)

Additional emissions reduction to those reported in NDCs may be generated by international cooperative initiatives by non-state actors, however problems in double-counting and the absence of a transparent reporting framework have been highlighted in literature (Bakhtiari, 2017). The assessment byUNEP (2017a) suggests that the aggregated additional impact of the various non-state initiatives is of the order of a few GtCO$_2$-eq in 2030, over and above current NDCs.

7. Comparing countries' NDC ambition (equity, cost optimal allocation and other indicators)

Various assessment frameworks have been proposed to analyse, benchmark and compare NDCs at national, regions or at global level, and to indicate possible strengthening, based equity principles and other indicators (Aldy et al., 2016; den Elzen et al., 2016; Fridahl and Johansson, 2017; Höhne et al., 2017; Jiang et al., 2017; Wakiyama and Kuramochi, 2017). The variation in conformity/fulfilment with particular equity principles across NDCs and countries is large. Many authors use multi-criteria assessment frameworks based entirely or partly on the six effort sharing categories in the Table 6.5 of Chapter 6 of the WGIII contribution to AR5 (Clarke et al., 2014; Höhne et al., 2014; Kartha et al.; Stanton et al., 2009), with the underlying principles of 'responsibility,' 'capability,' and 'equity', and/or combined with other criteria such as 'equal marginal abatement costs' (Höhne et al., 2017; Pan et al., 2017; Robiou du Pont et al., 2016). It should be noted that there is an important methodological gap in relation to the assessment of the NDCs fairness and equity implications, partly due to lack of information on countries' own assessment (Winkler et al., 2017). The equity principle in embedded in the Paris Agreement in Article 2 on CBDRs , however possible different interpretations of equity principles lead to different assessment frameworks (Lahn, 2017; Lahn and Sundqvist, 2017), and the AR5 categories are complemented by other credible equity framework (Kartha et al.). Some authors propose a different assessment framework, for example where countries with similar GDP level have the same benchmark (Herrala and Goel, 2016).

Adaptation

The Paris Agreement brings greater recognition to adaptation by establishing a global goal for adaptation (Kato and Ellis, 2016; Kinley, 2017; Lesnikowski et al., 2017; Rajamani, 2016; UNEP, 2017a). This global goal is currently qualitative as the success to achieve a temperature goal will determine adaptation needs and the necessary levels of ambition for adaptation goals (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 key challenge for understanding whether progress is being made on the global goal for adaptation is making sense of so many national adaptation goals and the diversity of approaches that countries take to achieve them. 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 anNDC, a National Adaptation Plan, or a National Communication. Of the 197 Parties, 140 NDCs have an adaptation component, almost exclusively from developing countries. NDC adaptation components can be an opportunity for enhancing adaptation planning and implementation by highlighting priorities and goals (Kato and Ellis, 2016). At an international level, they signal political will for enhancing action on adaptation and support adaptation efforts under the UNFCCC. At the national level they provide momentum for the development of NAPs and raise the profile of adaptation (Pauw et al., 2016a, 2017).Likewise, the transparency framework includes adaptation, through which 'adaptation communication' and accelerated adaptation actions are submitted and reviewed every 5 years (Hermwille, 2016; Kato and Ellis, 2016). The Paris Agreement created a robust 'transparency framework for action and support' in which each Party must submit information on mitigation, adaptation, and finance. This framework, unlike others used in the past, is applicable to all countries taking into account differing capacities amongst Parties (Rajamani, 2016).

Adaptation goals in NDCs have been presented quantitatively and qualitatively. Countries have used the NDCs to communicate their adaptation goals in quantitative terms with NDC adaptation cost estimates aggregated to the global level are at USD653.2 billion (reporting from 35% of NDCs with adaptation component) (Smithers et al., 2017). Estimated costs for already planned activities are USD146.2 billion (reporting from 21% of NDCs with adaptation component). Quantified requested support for general adaptation implementation amounts to more than USD38 billion (reporting from 4% of NDCs with adaptation component). Quantified committed support for specific adaptation measures and/or sectors is USD19 billion (only 5% of NDCs with adaptation component).

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 water sector (71% of NDCs with adaptation component), agriculture (63%), and health (54%), and biodiversity/ecosystems (50%) (Pauw et al., 2016a, 2017).

To strengthen the NDCs framework to deliver on adaptation goals it is essential to improve the structure, content and planning processes. Smithers et al. (2017) suggest that linking the NDCs with the NAPs can bring multiple benefits including a greater emphasis on countries' transparency frameworks regarding adaptation policy and greater support for adaptation/mitigation co-benefits and synergies as the NAP process can inform development of the NDCs’ adaptation goals and how these goals are implemented. Like NDCs, NAPs are country-owned and country-driven. NAPs seek to enhance coherence between adaptation and development planning, and are designed so countries can monitor and review them on regular bases.

[END CROSS-CHAPTER BOX 4.1 HERE]

[START CROSS-CHAPTER BOX 4.2 HERE]

Cross-Chapter Box 4.2: Solar radiation management

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'Solar radiation management' (SRM) refers to a range of non-greenhouse gas related radiation modification measures including modifications of the solar incoming shortwave radiation as well as modification of the outgoing longwave radiation budget in order to limit global warming. Hereafter, for clarity, we use the term 'radiation modification measures' (RMMs) to refer to all modifications of the Earth's radiative budget that do not intend to change atmospheric greenhouse gas concentrations.

RMMs are discussed as potential measures if mitigation efforts do not keep global mean temperature below 1.5°C or to reduce the climate impacts of a temporary temperature overshoot while also implementing mitigation and adaptation options (Chen and Xin, 2017; Irvine et al., 2016; MacMartin et al., 2014b). This moderate and time-bound "peak-shaving" implementation of RMMs has been proposed to reduce some of the risks associated with elevated temperatures (Keith and Irvine, 2016), although it would introduce new risks and challenges (Pitari et al., 2014; Visioni et al., 2017a), which make RMMs a highly debated topic.

This Cross-Chapter Box discusses sustainable development in Section A, introduces different categories of RMMs in the context of peak-shaving in Section B, discusses general RMM impacts in Section C, discusses implications for carbon budgets in Section D, and concludes with an overall assessment of feasibility, also based on Section 4.3.9, in Section E. Governance, public perception and ethics are discussed in Section 4.3.9.

A. Sustainable development and RMM

RMMs can interact with sustainable development and the Sustainable Development Goals (SDGs) through impacts that reduce, increase or redistribute impacts of climate change on development priorities to reduce poverty, hunger, and inequality, and protect health, water and ecosystems. In terms of sustainable development, some see RMMs as a relatively lower cost and lower impact way to bring down global temperatures compared to the costs of mitigation or damages, or to respond to humanitarian emergencies caused by climate change, with resulting benefits for SD and equity from reduced climate impacts in terms of food, water, health and ecosystems (Al-sabah and Brien, 2015; Anshelm and Hansson, 2014; Buck, 2012; Harding and Moreno-Cruz, 2016; Heutel et al., 2016; Morrow, 2014; Nicholson, 2013).

But because RMMs have uncertain regionally-specific climate effects including on precipitation (see Sections C and D) and do not solve problems of ocean acidification and associated impacts on fisheries, RMMs entail risks to SD (Heyen et al., 2015; Irvine et al., 2017; Nicholson, 2013; Robock, 2012). For example, some models and analogues with historic volcanic eruptions produce results that reduce temperatures but include a weakening of circulation, stronger drought in the Sahel, and a weaker monsoon with droughts in Asia (Ferraro et al., 2014; Irvine et al., 2017). A small number of studies examine ecosystem, hydrological, and agricultural effects, are inconclusive and emphasise regional uncertainties (Irvine et al., 2017; Ito, 2017; Parkes et al., 2015; Russell et al., 2012; Xia et al., 2014).

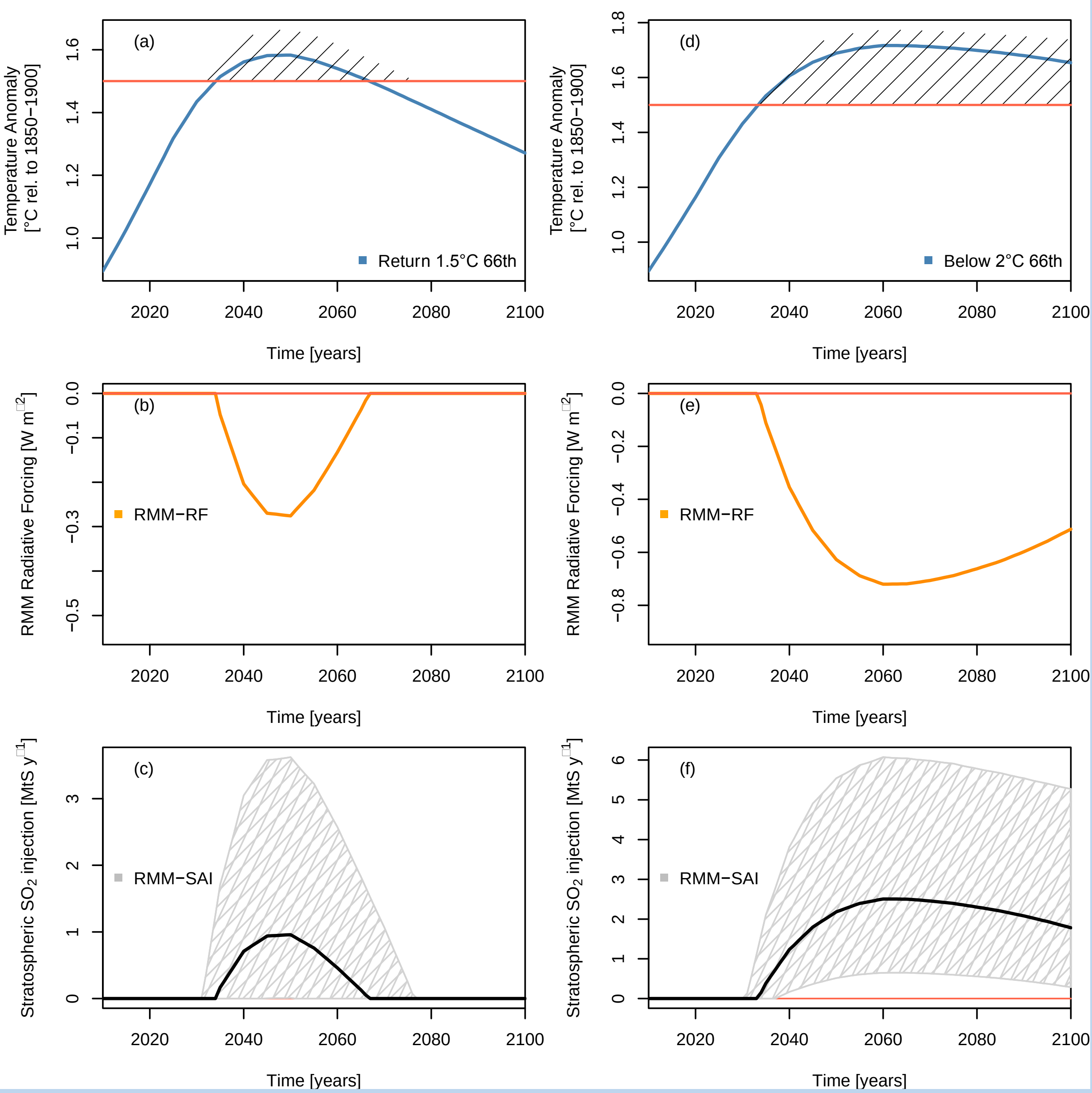
B. Introduction to radiation modification measures in the context of peak-shaving

This section discusses the four most discussed RMMs: Stratospheric aerosol injection (SAI), marine cloud brightening (MCB), cirrus cloud thinning and ground-based albedo modifications (GABM). The main characteristics are summarised in Cross-Chapter Box 4.2 Table 1.

The most often simulated RMM approach is SAI, which aims at mimicking climate effect of volcanic eruption by injecting sulphate aerosol precursors into low stratosphere leading to a negative radiative forcing (Crutzen, 2006; Visioni et al., 2017a). Globally averaged, a radiative forcing from sulphate aerosols between 0.4 and 0.8 Wm^{-2} would be needed to counter 1°C of warming (Crook et al., 2016; Plazzotta et al.). The radiative forcing efficiency of sulphate aerosol injection is not linearly correlated with the amount of sulphur injected and decreases with increasing injection rates (Niemeier and Timmreck, 2015), leading to large uncertainties in the required SO_2 injection. For peak-shaving 1.5°C levels, the injection amount would have to increase annually, while the fixed annual amount of injection could approximately compensate the global temperature overshoot for a few decades until reaching steady state (Kashimura et al., 2017).

The response of global temperature to sulphur injection is uncertain and varies depending of the model parametrisation and emission scenarios from about 2 to 8 TgS yr^{-1} for a decrease in global mean temperature of 1°C (Crook et al., 2015; Izrael et al., 2014; Jones et al., 2011; Kashimura et al., 2017; Kravitz et al., 2011; Niemeier and Timmreck, 2015; Tilmes et al., 2016). Uncertainty also arises on the nature and the optical properties of injected aerosols. We estimate the maximal range to be 1–4 TgS $W^{-1}\,m^{2}\,yr^{-1}$ based on Heckendorn et al. (2009), Robock et al. (2008), Tilmes et al. (2016) and Crook et al. (2015).

The timing and magnitude of potential RMM deployment for peak-shaving would depend on the temperature overshoot associated with mitigation pathways. Cross-Chapter Box 4.2 Figure 1 shows potential RMM radiative forcing and SAI deployment two such situations: 1) “adaptive RMM” (Kravitz et al., 2011; Tilmes et al., 2016), where global mean temperature exceeds 1.5°C by mid-century and returns below before 2100 with a 66% likelihood (indicated as “Return 1.5°C 66%” mitigation pathways in Chapter 2). In this case, the duration of RMM could span from 13 to 67 years with the earliest possible threshold exceedance in 2031; and 2) RMM compensating for an overshoot pathway that stays below 2°C but not 1.5°C by 2100 with 66% likelihood (indicated as “Below 2°C 66%” mitigation pathways in Chapter 2).



Cross-Chapter Box 4.2, Figure 1: Evolution of RMM (based on SAI) in the context of two classes of mitigation pathways. Temperature outcomes as simulated by MAGICC (see in Section 2.2), RMM radiative forcing and stratospheric SO_2 injection are shown for mitigation pathways exceeding 1.5°C at mid-century and returning below by 2100 with a 66% likelihood (panels a, b and c, respectively) and exceeding 1.5°C over the 21st century with a 66% likelihood and returning below 2°C but not 1.5°C (panels d, e and f, respectively). RMM surface radiative forcing has been diagnosed using a mean cooling efficiency of 0.301°C $(W\ m^{-2})^{-1}$ of (Plazzotta et al.). Magnitude and timing of SO_2 injection have been derived from published estimates of Heckendorn et al. (2009) and Robock et al. (2008)

While the radiative forcing from stratospheric aerosols is potentially relatively uniform in space and time, marine cloud brightening (MCB) would create spatially heterogeneous forcing and potentially more spatially heterogeneous climate effects (Latham et al., 2012, 2014; Wang et al., 2011). The injection is usually simulated in a constant rate in the marine boundary layer between 30 N and 30 S, as this is the area where the largest radiative effects have been predicted from sea salt seeding (Alterskjær et al., 2012, 2013; Jones and Haywood, 2012; Kravitz et al., 2013). The ability of MCB to bring global temperature back down towards to 1.5ºC has not been studied. The sea salt injection rates needs to generate a global-mean Earth radiative forcing of -2.0 W m^{-2} at the TOA vary between different models simulation from 200 to 590 Tg yr^{-1} dry sea-salt aerosol (Ahlm et al., 2017; Kravitz et al., 2013). The global temperature sensitivity for net radiative forcing reduction due to MCB varies from 0.2 to 0.5˚C (W m^{-2})$^{-1}$(Ahlm et al., 2017; Crook et al., 2015; Kravitz et al., 2013).

Cirrus cloud thinning (CCT) is not well studied. Generally the effects of cirrus cloud thinning depend on the degree of cloud optical depth modification the location and purity of the ice clouds and the time of day or year (Jackson and Webster, 2016; Muri et al., 2014). The best guesses of maximum global cooling effect vary from 1°C (Crook et al., 2015; Jackson et al., 2016; Muri et al., 2014) to 2˚C (Storelvmo et al., 2014). There is *low confidence* in the effectiveness of this method and the underlying physical process.

Ground-based albedo modifications (GBAM) is unlikely to impact substantially global temperature (Irvine et al., 2011; Seneviratne et al.) and are therefore evaluated in terms of regional impacts. The overall effects from land albedo modifications would be bounded to about 0.1 at most over a fraction of the land area (Crook et al., 2015; Davin et al., 2014; Irvine et al., 2011; Seidel et al., 2014; Seneviratne et al.). The increase in albedo by selecting different crops and grasses (biogeoengineering) could potentially contribute to a decrease of net radiative forcing and reduce global mean temperature by 0.2˚C if crop albedo is increased by 0.08 over the territory of about 6% of the global land (Crook et al., 2015). Other modifications could include albedo increases from no-till farming, use of greenhouses, and increased reflectivity in cities. Regionally, cooling effects of up to 1–3°C may be achieved(Seneviratne et al.).. The use of massive solar farms with high albedo using reflective fill-in material has been investigated for the desert regions of Australia, and simulations show regional temperature reductions of up to 10ºC over the solar farm area, and reductions in rainfall of up to 30–70% depending on array size, location and albedo of the fill-in material (Nguyen et al., 2017).

Cross-Chapter Box 4.2, Table 1: The other possible method of surface albedo modification is increase of ocean albedo by generating microbubbles and brightening the ocean surface. A uniform increase in ocean albedo by 0.03 could decrease net radiative forcing by 2 W m^{-2} and reduce global mean atmospheric temperature by 1.6ºC (Crook et al., 2016). Overview of the main characteristics of the most studied RMMs in the context of peak shaving 1.5°C pathways.

Radiative Modification Measure	**Radiative forcing efficiencies**	**Amount needed for 1°C overshoot**	**Maturity of science**	**RMM specific impacts**	**Key references**
SAI	1-4TgS W–1 m2 yr–1	2–8 TgS yr^{-1}	Robust volcanic analogues. Agreement amongst simulations	Changes in precipitation patterns and circulation regime; Disruption to stratospheric chemistry (for instance leads to NOx depletion and change methane lifetime); ozone loss; significant increase of surface UV; increase in stratospheric water vapour and tropospheric-stratospheric ice formation affecting cloud microphysics; adverse effects for solar power	(Robock et al., 2008) (Heckendorn et al., 2009)(Pitari et al., 2014; Tilmes et al., 2012)(Crook et al., 2015; Tilmes et al., 2016)(Visioni et al., 2017a) (Smith et al., 2017) (Visioni et al., 2017b)
MCB	100 to 295 Tg dry sea salt yr^{-1} per W m^{-2}	70 Tg dry sea salt yr^{-1}	Observed ships tracks but maybe regionally limited	Regional rainfall responses; reduction in hurricane intensity;increases in coral bleaching conditions; reduction in the number mild crop failures	(Alterskjær et al., 2012; Jones and Haywood, 2012; Kravitz et al., 2013)

					(Latham et al., 2013)(Parkes et al., 2015) (Ahlm et al., 2017; Kravitz et al., 2013) (Crook et al., 2015)
CCT	Not known	Not known	No clear physical mechanism	Changes in precipitation patterns and circulation regime; Disruption to stratospheric chemistry (for instance leads to NOx depletion and change methane lifetime); ozone loss; significant increase of surface UV; increase in stratospheric water vapour and tropospheric-stratospheric ice formation affecting cloud microphysics; adverse effects for solar power	(Jackson et al., 2016) Kärcher (2017) (Kristjánsson et al., 2015) (Lohmann and Gasparini, 2017). (Storelvmo et al., 2014)
GBAM	Small on global scale, up to 1–3°C on regional scale	0.04–0.1 albedo change in agricultural and urban areas	Several simulations confirm mechanism	Mostly cooling over region of albedo; some possible impacts on precipitation in monsoon areas; could target hot extremes	(Irvine et al., 2011) (Crook et al., 2015) (Seneviratne et al.) (Crook et al., 2016) (Davin et al., 2014) (Akbari et al., 2012; Jacobson and Ten Hoeve, 2012)

C. General impacts of radiation modification measures

An overarching implication associated with RMM is continued ocean acidification. Regionally, in particular in the North Atlantic, RMMs may worsen ocean acidification, for example in the case of global-scale SAI implementation (Tjiputra et al., 2016).

Deploying RMMs in a peak-shaving scenario could potentially reduce global temperature-related extremes such as rainfall intensity increases, and lessen the resulting impacts, such as further loss of coral from increasing sea-surface temperatures (Keith and Irvine, 2016). Global RMMs, such as SAI, would not allow for regionally optimising the resulting radiative forcing, but regional RMMs, for instance related to changes in land albedo may be able to directly reduce impacts in most-affected areas (Seneviratne et al.)Regional physical climate impacts induced by global RMMs, such as changes in rainfall patterns or occurrence of extreme weather, could have global impacts due to complex global supply chains, and thus affect food prices, commodity prices, trade flows and political stability (Sillmann et al., 2015).

Even when RMMs are not used as a mitigation substitute, a ‘termination shock’ or ‘termination effect’ of suddenly stopping RMMs might cause rapid temperature rise and associated impacts (Izrael et al., 2014; Jones et al., 2013a; McCusker et al., 2014; Robock, 2016).

The large uncertainties in identifying the physical impacts of RMM deployment in model simulations or field experiments, and socio-economic dynamics add to the risks of deployment. The inherent variability of the climate system makes it difficult to detect benefit or harm and attribute it to RMM intervention (Jackson et al., 2015). Given the level of uncertainty in the various underlying processes, and the lack of comprehensive assessments in the literature, there is *low confidence* in any assessment of the effects of RMMs on food production and ecosystem health.

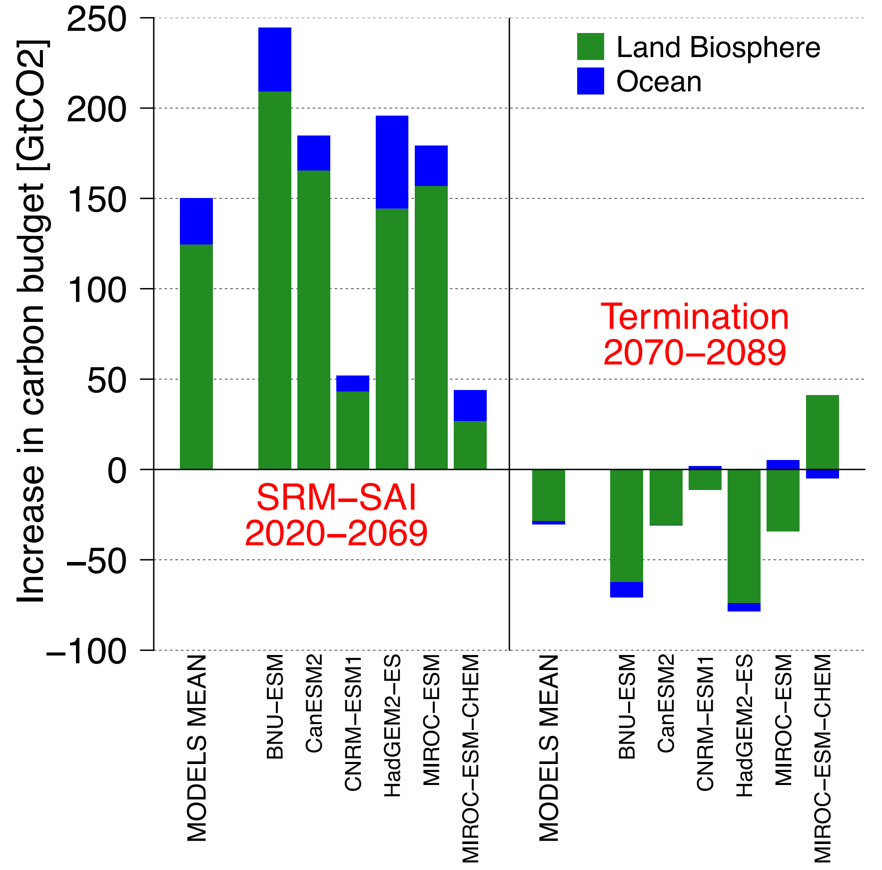
Other risks of relying on RMMs include: (1) the lack of testing of the proposed deployment schemes, in particular for SAI (*e.g.*(Schäfer et al., 2013); (2) possible tropospheric impacts of SAI (incl. chemistry, circulation and meteorology) (Irvine et al., 2016); (3) effects on vegetation and crop production (for which risk is less certain, see hereafter); and (4) the “moral hazard” that discussion, research or planning for RMMs may weaken mitigation (see Section 4.3.9).

D. Impacts of RMMs on the carbon budget

The deployment of RMMs can impact the 1.5°C or 2°C carbon budget because of its effects on ecosystems and take up of carbon (Eliseev, 2012; Keith et al., 2017; Keller et al., 2014; Lauvset et al., 2017). Robust conclusions cannot be drawn in absence of a dedicated set of peak-shaving simulations. However, the impacts of abrupt SO_2 injection as studied in several idealised simulations (Irvine et al., 2016; Kravitz et al., 2011) can be assessed.

Simulations suggest *high agreement* that RMMs lead to increased carbon budgets compatible with 1.5°C or 2°C because all models simulate an increase of natural carbon uptake by land biosphere and the ocean (see 0). This results in an increase of the RCP4.5 carbon budget of 146 GtC after 50 years of SO_2 injection with a rate of 4 $Tg(SO_2)\ yr^{-1}$. However, compared to the amount of CDR that is deployed to limit warming to 1.5°C or 2°C by 2100 (see Section 2.3), the impacts of SAI are weak.

Differences between modelled RMM experiments, modelling set-up and emissions pathways, a lack of understanding of the radiative processes driving the global carbon cycle response to RMMs (Eliseev, 2012; Mercado et al., 2009; Ramachandran et al., 2000; Xia et al., 2016), uncertainties about how the carbon cycle will respond to termination effects of RMMs (see also Cross-Chapter Box 4.2, Figure 2), and uncertainties in climate-carbon cycle feedbacks (Friedlingstein et al., 2014) lead to *low confidence* in any quantitative determination of the amount of carbon which could be released to the atmosphere by the start or termination of RMMs.



Cross-Chapter Box 4.2, Figure 2: Changes in carbon budget (in $GtCO_2$) due to the use of RMM by stratospheric aerosol injection (RMM–SAI) as simulated in the experiment G4 of GeoMIP for each of six Earth system models and the models mean. Changes in carbon budget are estimated from cumulated carbon fluxes over the RMM period (2020–2069, left) using the approach of Jones et al. (2013b). Changes in carbon budget over the twenty years after the cessation of RMM (2070–2089, right) are computed using the same approach but with respect to the 2020–2069 carbon budget. Land biosphere and ocean carbon uptake are represented respectively in green and blue.

E. Overall feasibility of RMMs

RMMs, if effectively and responsibly deployed in a peak-shaving scenario, could lessen temperature-related impacts of temperatures overshooting 1.5°C. Yet, even in the uncertain case that some of the most harmful side effects of RMMs can be avoided, governance issues, ethical implications, public resistance and impacts on sustainable development could render RMMs economically, socially and institutionally infeasible. The uncertainties are not as large for SAI compared to other mechanisms as there is a stronger body of research to draw on, but research also emphasises its continued unpredictability and risks. Overall, the combined uncertainties surrounding the various RM approaches, including technological maturity, physical understanding, efficiency to limit global warming, and ability to scale, govern and legitimise, constrain our ability to responsibly implement RMMs.

[END CROSS-CHAPTER BOX 4.2 HERE]

[START CROSS-CHAPTER BOX 4.3 HERE]

Cross-Chapter Box 4.3: Risks, adaptation interventions, and implications for sustainable development and equity across five systems: Arctic, Caribbean, Mekong Delta, Amazon, and cities

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This box presents five case studies from different climate regions to provide examples of the risks of 1.5C warming and higher (Chapter 3); challenges to adaptation, development and implementation (Chapter 4); and poverty, livelihoods and sustainability consequences of adaptation actions (Chapter 5).

[A map that locates these case locations will be included in the Final Draft]

Adaptation in the Arctic

The Arctic is the region undergoing the most rapid climate change globally (Larsen et al., 2014). A circumpolar warming trend of 1.9ºC has been documented over the last 30 years, with some regions warming well beyond this (Forino et al., 2017; Walsh, 2014), with the biggest impact on sea ice conditions (Galley et al., 2016; Johnson and Eicken, 2016). Changes in extreme events and wildlife species have also been detected, along with enhanced rates of permafrost thaw (Larsen et al., 2014). An ice free Arctic Ocean in late summer is very unlikely, however, if warming is limited to 1.5ºC (Screen and Williamson, 2017), although permafrost melt, increased instances of storm surge, and extreme weather events are anticipated along with later ice freeze up, earlier break up, and a longer ice free open water season (Bring et al., 2016; Chadburn et al., 2017; DeBeer et al., 2016; Ford et al., 2016a; Jiang et al., 2016; Melvin et al., 2017; Screen and Williamson, 2017; Yang et al., 2016b). Negative impacts on health, housing availability, infrastructure, and economic sectors (AMAP, 2017) are projected, although the extension of the summer ocean shipping seasons will bring associated economic opportunities (Dawson et al., 2016; Ford et al., 2015b; Pizzolato et al., 2014).

Human systems are recognised for their resilience, Indigenous and local knowledge systems, diversified livelihoods, and governance systems that include institutions for collective action (AMAP, 2017; Arctic Council, 2013; Ford et al., 2015b; Pearce et al., 2015). 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; Ford et al., 2015a; Pearce et al., 2015; Wenzel, 2009). Besides climate change (Keskitalo et al., 2011; Loring et al., 2016), economic and social conditions can constrain the capacity to undertake the necessary adaptations unless resources and cooperation are available from public and private sector actors (AMAP, 2017; Clark, 2016; Ford et al., 2014b, 2015b). In Alaska for instance, the economic impacts of climate change on public infrastructure are significant, estimated at USD5.5billion to USD4.2billion from 2015 to 2099, with adaptation efforts halving these costs estimates (Melvin et al., 2017).

Adaptation initiatives and actions have been increasingly observed (AMAP, 2017; Ford et al., 2014a; Labbé et al., 2017). Most documented initiatives occur at local levels in response to both observed and projected environmental changes as well as social and economic stresses (Ford et al., 2015b). In a recent study of Nunavut, Canada, most adaptations were found to be in the planning stages, largely driven by a select few institutions and individuals, and constrained by financial and institutional challenges (Labbe et al., 2016). Studies have suggested that a number of the adaptation actions are not sustainable, lack evaluation frameworks, and hold potential for maladaptation (Ford et al., 2015b; Larsson et al., 2016; Loboda, 2014). Incorporating Indigenous knowledge and stakeholder views is important to the development of adaptation policies and initiatives (AMAP, 2017), and more proactive and regionally coherent adaptation plans and actions have been identified (AMAP, 2017; Larsson et al., 2016; Melvin et al., 2017).

Adaptation in the Mekong food-basket region

The Mekong Basin is a climate change hotspot (de Sherbinin, 2014; Lebel et al., 2014)and plays a critical role in regional economy and food security (Smajgl et al., 2015). Projections point to an increase in annual average temperature and precipitation (Zhang et al., 2016a). The persistent rise of summer temperature might accelerate melting of glaciers, impacting local freshwater availability. Summer precipitation will almost certainly increase, increasing flood-related disaster risk (Ling et al., 2015; Smith et al., 2013; Zhang et al., 2016a). Sea level rise and saline intrusion are ongoing risks agricultural systems are facing and adapting to (Renaud et al., 2015). The main climate impacts will be on ecosystem health through salinity intrusion, biomass reduction and biodiversity losses (Le Dang et al., 2014; Smajgl et al., 2015); agricultural productivity and food security (Smajgl et al., 2015); livelihoods such as fishing, farming (Wu et al., 2013); and disaster risk (Hoang et al., 2016; Wu et al., 2013) with implications for human mortality, and economic and infrastructure losses.

Agricultural adaptation strategies include improving water use technology (*e.g.* pond capacity improvement, rainwater harvesting), soil management, crop diversification, and strengthening allied sectors such as livestock rearing and aquaculture (ICEM, 2013). Several ecosystem-based approaches have been implemented, such as integrated water resources management, demonstrating successes in mainstreaming adaptation into existing strategies (Sebesvari et al., 2017). Coastal adaptation strategies include dike construction and mangrove restoration (Smith et al., 2013) and ecological engineering such as densification of coastal vegetation (Renaud et al., 2015). However, some of these adaptive strategies have had negative impacts: dike construction and resultant sedimentation have sharpened the divide between land-rich and land-poor farmers and reshaped the socioeconomic system (Chapman et al., 2016). The entry of high dikes ushered triple-cropping which benefits land-wealthy farmers but forces debt on poorer farmers (Chapman and Darby, 2016).

Institutional innovation has happened through the establishment of the Mekong River Commission (MRC) in 1995, an intergovernmental body between Cambodia, Lao PDR, Thailand and Viet Nam. The MRC has facilitated impact assessment studies, regional capacity building, and local project implementation (Schipper et al., 2010), although the region has been critiqued for inadequate mainstreaming of adaptation into development policies, explained by significant capacity barriers and other national priorities (Gass et al., 2011).

Adaptation needs include more investment in developing crop diversification and integrated agriculture-aquaculture practices (Renaud et al., 2015). Putting in place more flexible institutions dealing with land use planning and agricultural production, improved monitoring of saline intrusion, setting up early warning systems that can be accessed by the local authority or farmers are also recommended (Renaud et al., 2015). It is critical to identify and invest in synergistic strategies from an ensemble of infrastructural options (building dikes) and soft adaptation measures (land-use change) (Smajgl et al., 2015), to combinations of top-down government-led strategies, such as relocation, and bottom-up household strategies such as increasing house height (Ling et al., 2015) and CBA initiatives that merge scientific knowledge with local solutions (Gustafson et al., 2017). Critical attention needs to be given to strengthening social safety nets and livelihood assets whilst ensuring that adaptation plans are mainstreamed into broader development goals (Kim et al., 2017; Sok and Yu, 2015).

Adaptation in the Caribbean

Hurricanes represent one of the largest risks facing Caribbean island nations as illustrated by the devastation left in the wake of the active hurricane season of 2017. Damage is manifested through a range of socioeconomic and ecological impacts including loss of life and GDP (Pielke et al., 2003), negative impact on agricultural products and crops (Beckford and Rhiney, 2016; Lashley and Warner, 2015; Mohan, 2017), and loss of biodiversity (Laloë et al., 2016)(See Cross-Chapter Box 4.3 Table 1). Non-economic damages include detrimental health impacts, forced displacement and destruction of cultural heritages. Projections of increased frequency of more intense storms at 1.5ºC (Box 3.1) are a significant cause for concern, making adaptation a matter of survival (Mycoo, 2017).

Notwithstanding a shared vulnerability arising from commonalities in location, circumstance and size (Bishop and Payne, 2012; Nurse et al., 2014), adaptation approaches, including disaster risk management actions, are nuanced by differences in governance structure and style (López-Marrero and Wisner, 2012). While sovereign states, *e.g.* Jamaica, can directly access climate funds and international support, dependent territories, *e.g.* the UK Outer Territories (UKOT), are largely reliant on their controlling states (Bishop and Payne, 2012). Styles of governance affect vulnerability and adaptive capacity with Cuba's approach identified as one of the reasons for its lower vulnerability to extreme events as compared to other nations in the region (Aguirre, 2005; Pichler and Striessnig, 2013). Table 2 shows this comparison.

(Pittman et al., 2015) suggest that achieving effective climate governance should incorporate holistic and integrated management systems, improving flexibility in existing collaborative decision-making processes, utilising adequate social-environmental monitoring programs and increasing the capacity of local authorities with support from government and private-social partnerships. Social work programs promoting human and community well-being have also been proposed (Aldy, 2017). Robust institutions utilising suitable technology will also help in the use of early warning systems and in emergency situations (Eakin et al., 2015; Ley, 2017). The implementation of the 2030 Sustainable Development Agenda and the Sustainable Development Goals (SDG) 1–17 and the 2030 Agenda will likely contribute to addressing the risks related with extreme events (Box 5.1).

Cross-Chapter Box 4.3, Table 1: Hurricane damages since 2014.

Year	Hurricane		Cuba	Carribean UKOTs	Jamaica
2017	Irma, Maria	Financial Cost (true USD)	None	Initial estimate: USD2,010 million	
		Deaths	10	13	0
		People impacted	5.7 million (1.8 million persons sheltered, 0.16 million homes affected)	In BVI, 20% of population temporarily displaced.	--
		Damages	Substantial damage to buildings, widespread flooding.	Widespread power outages, four health centres closed in Anguilla, 80–90% of homes damaged in South Caicos.	--
2016	Matthew, Nicole	Financial Cost (true USD)	USD 2,430.8 million	USD15 million (Bermuda).	--
		Deaths	0	0	0
		People impacted	0.19 million people impacted	Unknown.	--
		Damages	Communication tower, bridge collapsed, 46,706 houses affected and 8,312 houses completely destroyed	27,431 customers without power, agriculture crop strongly impacted.	Minor damage.
2014	Fay, Gonzalo	Financial Cost (true USD)	--	USD200-400 million (Bermuda)	--
		Deaths	0	--	0
		People impacted	--	Unknown.	--
		Damages	--	31,000 customers lose power in Bermuda,	--

				widespread tree and utility pole loss	
2012	Sandy	Financial Cost (true USD)	69,669 million USD	--	USD107.1 million
		Deaths	11	--	1
		People impacted	0.16 million	--	0.22 million
		Damages	0.36 million homes	--	0.46 million people faced power interruptions, 0.25 million people had disrupted water supply. Substantial damage to agriculture, especially banana crops.
2010	Nicole, Earl	Financial Cost (true USD)		USD15,300,000 in Anguilla, BVI and Montserrat.	USD150 million
		Deaths	--		15
		People impacted	300		0.5 million
		Damages	Minor flooding, 5,000 pounds of lost crops and livestock	Power and water supply lost to BVI and Anguilla, moderate damage to homes in Montserrat	
2008	Fay, Gustav, Ike, Paloma and Hannah	Financial Cost (true USD)	USD9.4 billion is another estimate	USD654,400,000 (Cayman Islands, Turks and Caicos)	USD210 million
		Deaths	7	4	15
		People impacted	0.49 million	Unknown.	4,000
		Damages	0.65 million homes	900 homes damaged in Cayman Islands, 80-95% of homes destroyed in Grand Turk and South Caicos.	Collapse of two bridges
2007	Noel, Dean	Financial Cost (true USD)	11,554 million USD losses	--	USD300 million
		Deaths	1	0	4
		People impacted	0.19 million	2000 people seek temporary shelter in Cayman Islands.	33,188
		Damages	59,826 homes	Minimal damage.	Mudslides, 3127 damaged homes, severe agricultural damage
2006	Ernesto, Florence	Financial Cost (true USD)	951 million losses	USD2 million (Bermuda)	--
		Deaths	0	0	0

		People impacted	0.6 million	Unknown.	--
		Damages	1,819 homes	Power lines down, relatively minor damages	--
2005	Dennis, Rita, Wilma, Emily	Financial Cost (true USD)	3036 million USD losses	--	USD3.45 million
		Deaths	20	0	6
		People impacted	2.6 million	--	10,396
		Damages	0.18 million homes	--	

Cross-Chapter Box 4.3, Table 2: A comparison of disaster resilience strategies for three Caribbean territories.

Cuba	United Kingdom Outer Territories (UKOT)	Jamaica
Over the last five decades, Cuba has developed and implemented a highly effective civil defense system for emergency preparedness and disaster response, especially for hurricanes, centered around community mobilisation around preparedness (Kirk, 2017; Thompson and Gaviria, 2004). Civil defense committees at block, neighborhood, and community levels working in conjunction with the centralised governmental authority successfully reduce loss of life (IPCC, 2012), even though total losses and economic damages may be high. Legislation for managing disasters, an efficient and robust early warning system that is understood and adhered to by the general population, emergency stockpiles, adequate shelter system and continuous training and education of the population in risk consciousness and disaster management, also create a “culture of risk” (Isayama and Ono, 2015; Lizarralde et al., 2015). Cuba’s success in risk reduction and disaster management is also strongly tied to the country’s investment in its physical infrastructure and human resource base (Kirk, 2017).	The United Kingdom Outer Territories (UKOT), which include Turks and Caicos, Anguilla, British Virgin Islands, Montserrat, Bermuda, and Cayman Islands, have all developed National Disaster Preparedness Plans (PAHO, 2015). The territories are also part of the Caribbean Disaster Risk Management Program (CDRMP) 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 in general (Forster et al., 2011). Despite the 'benefits' of having an overseas territory status through access to funds, there is low-scale management for environmental issues, which increases the vulnerability of these islands. The main adaptation barrier identified is institutional limitations, coupled with lack of human and financial resources, and long-term planning (Forster et al., 2011).	Disaster management is coordinated through a hierarchy of disaster committees at the national, parish and community levels under the leadership of the Office of Disaster Preparedness and Emergency Management (ODPEM). ODPEM is a statutory body operating out of the Office of the Prime Minister, whose mandate is to coordinate disaster preparedness and risk reduction efforts among key state and non-state agencies (Grove, 2013). A National Disaster Committee provides technical and policy oversight to the ODPEM and is comprised of representatives from government and non-government agencies including local parish councils, utility companies, international donor agencies and search and rescue organizations (Osei, 2007).While this disaster management framework has been credited for the relatively low numbers of death linked to natural disasters in recent decades, risk reduction efforts are still affected by a combination of human resources, programmatic and funding limitations (Grove, 2013; Jones, 2011; Osei, 2007). Currently, the majority of adaptation and disaster risk management initiatives are primarily funded through a mix of multi-lateral and bi-lateral loan and grant funding instruments with a focus on strengthening the technical and institutional capacities of state and research-based institutions and supporting the integration of climate

		change considerations into national and sectoral development plans (Robinson, 2017).

Adaptation in the Amazon

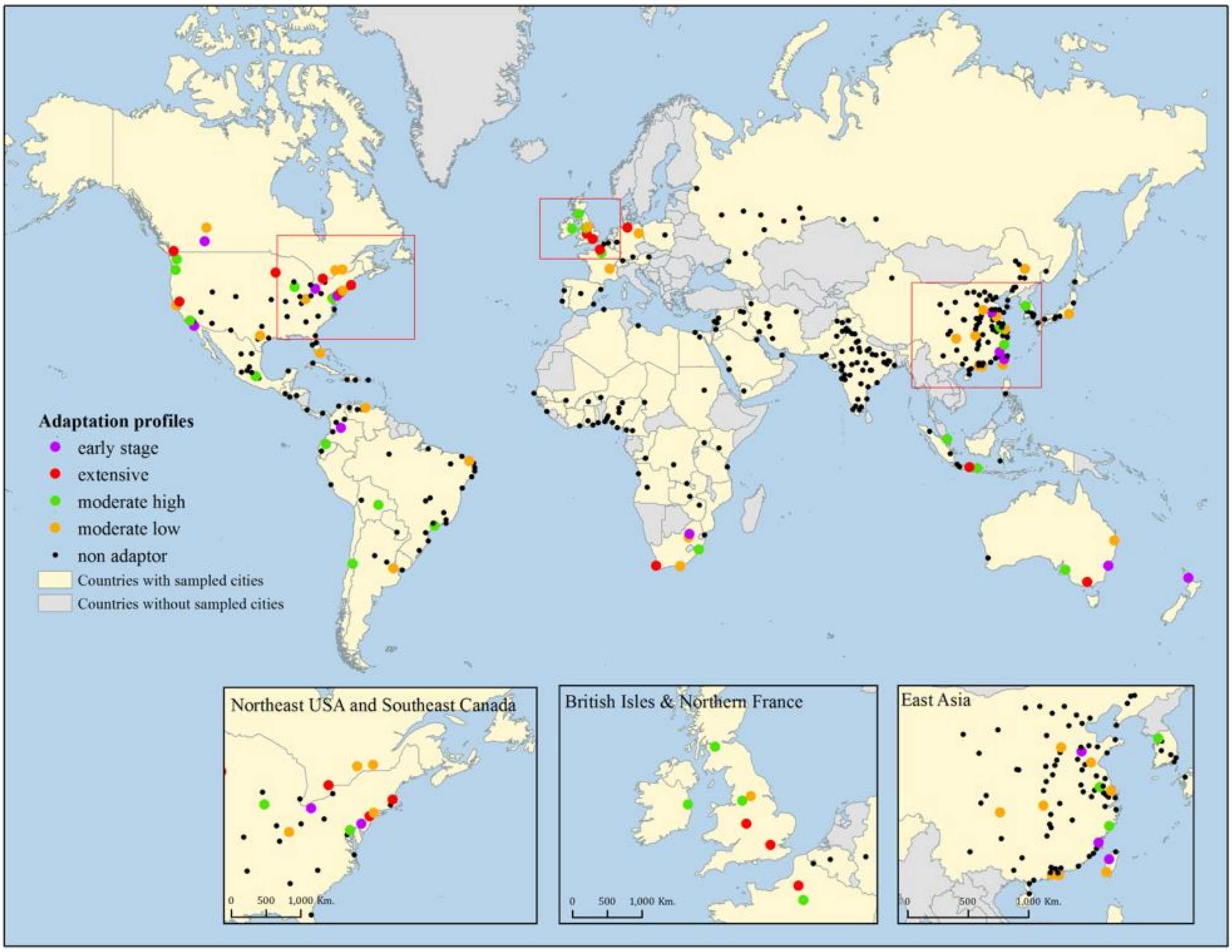
The highest terrestrial carbon dioxide uptake on Earth is due to tropical forests (Beer et al., 2010), including The Amazon, which is quite sensitive to changes in the climate, especially to drought (Laurance and Williamson, 2001). There are two “tipping points” that should not be transgressed: 4C warming or 40% or total deforested area (Nobre et al., 2016). The danger of crossing these come from two directions: human activities, mainly related to land use change for food production, and global warming.

The Amazon is thought to play a critical role in future strategies to avoid global warming. Its devastation, advancing slowly as it is today, would increase CO_2 emissions, preventing most of the actions that could be taken towards a 1.5°C (Nobre et al., 2016). Consequences of deforestation include loss of habitats and biodiversity, loss of indigenous people and culture, and climate change (Fearnside, 1985; Malhi et al., 2008; Nobre et al., 2016; Shukla et al., 1990). Consequences of human activity through burning with the purpose of freeing land for agriculture has been quite drastic, leading to loss of biodiversity, reducing evapotranspiration and increasing CO_2 emissions (de Oliveira et al., 2017; Numata et al., 2017; Tasker and Arima, 2016).
The Amazon is key for climate equilibrium at regional and global levels, thus, its potential effects would be felt not only by local biodiversity and people, but also produce teleconnections that may influence the world in many ways (Bonan, 2008). The complete arrest of forest burning and clearing along with restoration of part of the biodiversity would be an important action to help stay within 1.5°C pathway. The governance and finance mechanisms to implement such a coalition hardly exist, but one agreement made in 2008 between Norway and Brazil generated investment of USUSD 1 billion in projects (REDD+) for reforestation. The investment is generating successful results, but there are challenges and lessons learned that can be used as guides for other agreements.

Adaptation in cities

Cities are acutely vulnerable to climate change. Around 360 million people reside in urban coastal areas that are less than ten meters above the sea level. Precipitation intensity and variability are exposing inadequacies of urban infrastructure and burdening regional ecological systems with floods in some cities and droughts in others. The poor are especially vulnerable, often settling in high-risk areas including in coastal or low-lying areas of urban ecosystems (Revi et al., 2014b).

Across ten megacities of the world, (Georgeson et al., 2016) find that adaptation funds represent a maximum of 0.33% of a city’s gross domestic product with significant variability in total spending between cities (from £15 million to £1,600 million). High-income regions report higher levels of engagement with adaptation than developing regions, yet within industrialised regions less than half of large and medium-sized cities have a plan (Reckien et al., 2014). 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 behind in emerging economies which are major centres of population growth facing complex interrelated pressures for investment in health, housing and education (Georgeson et al., 2016). However, cities are scaling up adaptation across a spectrum of social, economic, and biophysical factors. There are substantive examples of governments taking leadership regardless of income levels and institutional barriers.



Cross-Chapter Box 4.3 Figure 1: Adaptation profiles of cities around the world. Source: (Araos et al., 2016a)

Cross-Chapter Box 4.3 Table 3 exemplifies three cities of different scales.

Cross-Chapter box 4.3, Table 3: Adaptation actions in multi-scalar cities

New York	Adaptation plans and initiatives emanate from different levels of government and have been addressed across sectors by different departments (NYC Parks, 2010; Planning, 2008; The City of New York, 2013; Vision 2020 Project Team, 2011). The adaptation planning effort has been significantly advanced by an expert science panel that is now obligated by local city law to provide regular updates on climate policy relevant science (NPCC, 2015). Federal initiatives include 2013's Rebuild By Design competition, a USD930 million multi-stage planning and design competition to promote resilience through infrastructural projects (U.S. Department of Housing and Urban Development, 2013). In 2013 the Mayor's office in direct response to Hurricane Sandy published the city's climate adaptation strategy in the *Stronger, More Resilient New York* Plan (The City of New York, 2013). In 2015, the Mayor's office published the OneNYC Plan for a Strong and Just City (OneNYC Team, 2015). The Plan lays out a strategy for general urban planning in the city and re-reports the initiatives from the 2013 plan, with a re-framing of adaptation initiatives through a justice and equity lens. City planning and sponsored development begun to actively include elements of climate non-stationarity (Solecki and Rosenzweig, 2014). In Spring of 2017, proposed a series of new climate resiliency guidelines that new City of New York construction must include climate change sea level rise projection into planning and development (The City of New York, 2017).
Kampala	Kampala Capital City Authority (KCCA) has the statutory responsibility for managing the city and the on-going Kampala Climate Change Action Strategy (KCCAS) is responding to climatic impacts of elevated temperature and more intense, erratic rainy days. In addition to direct climatic impacts (Isunju et al., 2016), KCCAS has considered multi-scale and temporal aspects of response

	(Chelleri et al., 2015; Douglas, 2017; Fraser et al., 2017), strengthened community adaptation and other partnership forms (Dobson, 2017; Lwasa, 2010), is responding to differential adaptive capacities across the city(Waters and Adger, 2017) and believes in participatory processes and bridging of citywide linkages(KCCA, 2016). The city's ecosystems and its restoration (Güneralp et al., 2017) is regarded to be a strong foundation for achieving sustainability goals.
Rotterdam	The Rotterdam Climate Initiative (RCI) was launched in 2006to address the current and impending challenges of climate change, with the objective of reducing GHG emissions and climate-proofing (Rotterdam Climate Intitiative, 2017). Rotterdam has an integrated climate change adaptation strategy, built on five themes: flood management, accessibility, adaptive building, urban water systems and urban climate, defined through the Rotterdam Climate Proof in 2008 and the Rotterdam Climate Change Adaptation Strategy in 2013. Early assessments indicate that a strong governance mechanism that enabled integration of flood risk management plans with other policies, along with citizen participation, institutional eco-innovation and dominance of green infrastructure in the response strategy (Albers et al., 2015; de Boer et al., 2016a; Dircke and Molenaar, 2015; Huang-Lachmann and Lovett, 2016), have significantly contributed to the success of the adaptation strategy (Ward et al., 2013)but dominant institutional characteristics constrain the response framework (Francesch-Huidobro et al., 2017a).

Conclusion

The case studies present climate impacts that are being felt in key regions, along with the array of adaptation options and strategies and the multiple challenges that remain to be met. It is not yet possible to determine how effective these efforts have been as there is a lack of medium to long-term empirical studies and monitoring and evaluation of current efforts to generalise across regions and themes. Determining the appropriate adaptation strategy also depends on having the proper data at the local level, appropriate governance and institutional capacity and ensuring citizen participation.

[END CROSS-CHAPTER BOX 4.3 HERE]

[START CROSS-CHAPTER BOX 4.4 HERE]

Cross-Chapter Box 4.4: Residual risks, limits to adaptation and loss and damage

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Introduction and framing

Residual climate-related risks and any limits to adaptation are of increasing relevance for climate change research as well as national and international policy. Chapter 1 provides overall framing including on impacts, risks and adaptation pathways. With 1.5°C mitigation pathways the subject of Chapter 2, Chapter 3 presents projections of impacts and risks at 1.5°C, alongside risks which might be avoided by mitigating to 1.5°C (and 2°C). Chapter 4 reports that adaptation options associated with 1.5°C pathways need to be strengthened across the local, national and global continuum. Chapter 5 links climate mitigation and adaptation pathways to delivering sustainable development, poverty reduction and reducing inequality.

As a point of departure, the AR5 (IPCC, 2014) projected increasing climate-related risks with continued global warming, suggesting that not all risks will be avoided (*unavoided*) and some cannot be avoided at higher levels of warming (*unavoidable*). It recognised that the efficacy of adaptation is constrained by biophysical, institutional, financial, social, and cultural factors, and that the interaction of these factors with climate change can lead to hard and soft adaptation limits (Klein et al., 2014b). There is now a policy mechanism under the United Nations Framework on Climate Change (UNFCCC) to address "Loss and Damage" (L&D) from climate change impacts, including that which cannot be reduced by adaptation

(UNFCCC, 2013a). This box reports on the emerging research and policy discourse on L&D, and considers evidence on potential limits to adaptation at 1.5°C, alongside limits to adaptation avoided by reaching 1.5°C.

Loss and damage-definitions and implications

"Loss and Damage" (L&D) has been discussed in international climate negotiations since the early 1990s (Calliari, 2016; INC, 1991; Vanhala and Hestbaek, 2016). In 2010 at COP16 in Cancun, a work programme on L&D was established as part of the broader Cancun Adaptation Framework in support of developing countries particularly vulnerable to the adverse effects of climate change (UNFCCC, 2010). COP19 in 2013 established the Warsaw International Mechanism for Loss and Damage (WIM) as a formal part of the UNFCCC architecture (UNFCCC, 2013a).The Paris Agreement also recognised "the importance of averting, minimising and addressing loss and damage" through Article 8 (UNFCCC, 2015b).

There is no official definition of L&D in climate policy. The UNFCCC does not explicitly distinguish between loss and damage and has used the two terms largely as synonymous, as well referring to both impacts from extreme events and slow onset processes. Also, economic and non-economic losses are mentioned throughout (UNFCCC, 2013b). L&D policy documents specifically refer to "permanent losses" (UNFCCC, 2015b).

Analysis of L&D policy discussions and stakeholder views (Boyd et al., 2017; Vanhala and Hestbaek, 2016) suggest that many view L&D as climate change impacts which cannot be avoided by mitigation and/or adaptation, also drawing on the notion of limits. For these stakeholders, loss and damage at 1.5°C might refer to projected climate change impacts at 1.5°C which cannot be adapted to, suggesting all climate impacts and risks are to be considered (Boyd et al., 2017), consistent with some working definitions (UNEP, 2016a). Loss and damage from climate extremes associated with natural climate variability would thus need to be considered as well.

Lines of research: residual risks and limits to adaptation

Loss & Damage remains a political concept developed during the UNFCCC negotiations, but with its technical roots in climate adaptation and disaster risk reduction. An emergent topic, disciplines such as climate science, physical and human geography, psychology, philosophy, economics, ecology and law have made contributions over the last few years (Tschakert et al., 2017). AR5 has shown that climate-related risk is multifactorial with hazard, exposure and vulnerability as key drivers (Oppenheimer et al., 2014). Attribution research has been making progress in terms of trend, and, lately, also event attribution (Otto et al., 2015). Attribution science is aimed at better understanding drivers of change and informing actions to avert, minimise and address impacts and risks (James et al., 2014). Scholarship on justice and equity has provided insight on compensatory, distributive and procedural justice considerations (Huggel et al., 2016; Roser et al., 2015; Wallimann-Helmer, 2015)).

Conceptual work since the AR5 has considered the potential and constraints for climate change adaptation (and disaster risk reduction) to comprehensively manage risk, and the challenge of addressing residual risks touching on adaptation limits (Mechler and Schinko, 2016) (also see Supplementary Material 4.A).Adaptation limits are points beyond which actors' objectives are compromised by intolerable risks threatening key objectives such as good health or broad levels of well-being, thus requiring transformative adaptation (Dow et al., 2013; Klein et al., 2014b). An emerging, tentative consensus in research consequently sees the L&D debate focus on climate-related sudden and slow-onset residual risks that have the potential to push human and natural systems beyond soft and hard adaptation limits. What constitutes loss and limits is context-dependent and often requires place-based research into risk perceptions and experience (Tschakert et al., 2017).

Evidence about the implications of a 1.5°C world for limits to adaptation, residual risks, and loss and damage

Empirical evidence to identify limits to adaptation was largely lacking in AR5 (Klein et al., 2014b). This report presents an opportunity to review evidence about limits to adaptation to be avoided at 1.5°C, yet there is a limited literature on risks at 1.5°C (versus higher degrees of warming), and less still on the potential for adaptation at 1.5°C (and other specific warming levels). An assessment of limits to adaptation, residual risks, and loss and damage is therefore very challenging.

In the AR5, the climate risk assessment presented risks at 2°C and 4°C including the potential for and limits of additional adaptation to reduce risk. This assessment draws on other chapters, particularly Chapter 3, to identify examples at 1.5°C, which could be considered examples of limits to adaptation, residual risks or loss and damage.

Exemplary evidence [further integration of findings across chapters to occur after the SOD]
Natural systems

Tropical coral reefs at 2°C of global warming would likely experience a total loss (a biophysical system with limited adaptation options leading to a hard limit). 1.5°C would still mean substantial loss and damage, but the loss of the final 10% of rebuilding corals could be avoided (see Section 3.4.4.2 and Box 3.6).

Constraining warming to 1.5°C, compared to 2°C, is projected to halve the climate change related increase in risk of species extinction. Extinctions are clear examples of permanent losses (high confidence) (see Section 3.4.3.3 and Section 3.5.2.4).

Human systems

At 1.5°C SIDS will see compounding impacts from changes in rainfall and temperature patterns, frequency of extremes, more intense tropical cyclones and higher sea levels cutting across multiple natural and human systems. Impacts likely to occur include loss of or change in critical ecosystems, freshwater resources and associated livelihoods, economic stability, coastal settlements and infrastructure. There are benefits in terms of avoided impacts and risks for 1.5°C versus 2.°C, particularly when (transformational) adaptation efforts are considered (soft limit in human system) (see Box 3.7).

Retreat and human migration has increasingly become an element of responses to impacts and risks, in particular for SIDS. Affected people have migrated internally in the aftermath of inundation. International migration is seeing attention for those at climate-related risk as evidenced through land purchases or migration arrangements with other nations in the Pacific (soft limit in human system). (Section 3.4.5.2.4)

Risks from large-scale changes in oceanic systems (temperature, acidification) for dependent coastal communities (estimated at hundreds of millions of people), experienced as reduced income, damage to livelihoods, cultural identity, coastal protection, and health, are much lower with 1.5°C of global warming vs. 2°C (soft limit in human system) (see Section 3.4.4.2.4).

Risks to food production imply large risks to food security regionally and globally, particularly in low latitude areas. Risk to crop production in Sub-Saharan Africa, West Africa, SE Asia, and Central and South America are significantly reduced at 1.5°C compared to 2°C of warming. In regions where agriculture is increasingly unsustainable, such as in parts of the Middle East, risks for food production and extreme poverty, however, are already substantial at 1.5°C (soft limit in human system) (see Section 3.4.6)

Global warming very likely increases mortality from heat and ozone exposure, if precursor emissions are constant, as well as likely increases in undernutrition. While regional patterns are complex, limiting warming to 1.5°C vs. 2°C will reduce risks to human health (soft/hard limit in human system) (see Section 3.4.7.3).

Disaster related displacement is projected to increase over the 21st century, with over 90% of displacement between 2001 to 2015 related to climate and weather disasters (medium confidence). Human conflict and violence may be exacerbated due to climatic factors (low confidence) (soft limit in human system)(see Section 3.4.10.2)

Options and actions to address residual risk and loss and damage

The L&D policy debate has been diffuse and lacking a principled, mutually agreed understanding of the rationale for Loss and Damage. The debate includes, policy proposals for compensation for the implementation of regional public insurance systems to address climate displacement (Mechler and Schinko, 2016).

Legal scholars have started to consider the legal implications of attribution science and projections of future impacts and risks (Mace and Verheyen, 2016; Mayer, 2016). Legal cases have been filed seeking to hold governments and private actors to account, for alleged failure to address climate change through mitigation or adaptation as well as seeking remuneration for actions to avoid high-level risks (such as from glacial lake outbursts) (Juliana v United States, 2016; Lliuya v RWE AG, 2017; Urgenda v The Netherlands, 2015). Litigation risks for governments and business may increase with improved understanding of impacts and risks as climate science evolves (Banda and Fulton, 2017).

[END CROSS-CHAPTER BOX 4.4 HERE]

Frequently Asked Questions

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

Few cities, regions, countries, businesses or communities are currently in line with limiting global warming to 1.5°C. To meet this goal would require raising ambition and accelerating transitions in four key areas: energy efficiency, carbon intensity of fuels, electrification and land use. Transitional change is already underway in the first three of these areas, but limiting warming to 1.5°C would require a rapid rise in the scale and pace. Land use change, on the other hand, remains a growing source of greenhouse gas emissions. Achieving such transitions at the speed required to limit warming to 1.5°C over the course of the century would require support across all levels of governance and through institutions, together with changes in behaviour and lifestyles that lower energy demand. If there are remaining emissions by mid-century, or if temperature is allowed to temporarily 'overshoot' the 1.5°C mark, they will need to be balanced out by taking carbon out of the air. The means to do this at scale remains untested, however.

When the Paris Agreement was signed in 2015, individual countries pledged various actions to adapt and mitigate against climate change. These included reducing CO_2 and non-CO_2 emissions, setting targets for afforestation or reforestation, and generating a proportion of electricity from renewables by a given date, for example. While the pledges signalled a collective global commitment to reducing the impacts of climate change, they are not enough to limit global warming to 1.5°C.

This Special Report explains how the world's response to climate change would need to be strengthened in order to limit warming to 1.5°C. This involves four main transitions: improvements in energy efficiency; reductions in the carbon intensity of electricity, electrification across all sectors, especially transport, buildings and industry; and changes in land use that enable the world to meet demands for food, feed, fibre and energy, while at the same time reducing greenhouse gas emissions.

To limit global warming to 1.5°C, these transitions would need to be rapid, particularly in the coming decades. Compared to pathways that could keep warming below 2°C, the speed of change is much faster, with equivalent changes happening 10–20 years earlier.

This pace of change has been seen in the past and is sometimes called 'disruptive innovation', meaning the change happens exponentially as the demand for it grows. Introducing LED lighting, in part, was a disruptive innovation, the high demand for which made more energy-intensive, incandescent lighting obsolete. But the actions that would be required now to limit warming to 1.5°C are larger than those that have happened before. They will also require more planning and more coordination.

Energy efficiency is improving due to smart technology that eliminates waste and the regeneration of cities, which is reducing the need for high energy transport. Carbon intensity is declining rapidly as solar, wind and battery storage technologies are becoming quick to deploy, mass produced and more cost effective. The electrification of household, commercial and transport energy, is becoming more cost effective, a trend that is likely to accelerate over the next decade through mass production. Land use change is still a growing source of greenhouse gas emissions. Deforestation and forest degradation would need to be reduced or stopped for this trend to be reversed and the growing demand for food, fibre, energy, and carbon sequestration balanced by raising the efficiency of livestock and agriculture, reducing food waste, shifting diets, and other measures that can be implemented on short time scales.

Models shows that in order to limit warming to 1.5°C, transitions in all these areas would have to happen quickly enough such that 'net' greenhouse gas emissions fall to zero by the middle of the century. In most pathways, this requires renewables to become the dominant source of energy by 2050 and net CO_2 emissions from the energy sector to decline to zero between 2030 and 2060, with remaining emissions compensated by removing CO_2 from the atmosphere. Carbon Dioxide Removal (CDR) techniques have not been tested at scale or have only a limited capacity to lower global emissions, however. They also have implications for sustainable development, which must be balanced responsibly against demand. Another characteristic of pathways that are keep warming below 1.5°C is that coal is phased out as a fuel source at a rate of 4-5% until mid-century, or the emissions are captured and stored underground, a process known as carbon capture and storage.

All of these transformative changes require governance and institutional change at all levels (international, national and local), with particular focus on the local dimension. Citizen-based power systems, or ‘Citizen utilities’, that work out the best local combinations of the four transformations is an important governance innovation for 1.5°C. The extent to which emerging cities and regions can accelerate the use of these four transformative changes will depend on how rapidly aid and climate finance can be delivered, especially in slum upgrading and village scale projects. If successful, such projects can complement progress towards sustainable development.

The costs of these transformative changes vary across regions but are becoming less likely to be a barrier as nations, cities and businesses are recognising their multiple advantages. Other barriers exist to achieving ambitious temperature stabilisation goals, however, including: current patterns of resource consumption, public attitudes, social values, institutional capacity to strategically deploy available knowledge, and finance. There is a pressing need to redirect financing towards low carbon technologies and, in the absence of carbon pricing, economic incentives are insufficient to achieve the pace and scale of mitigation needed to keep global average warming below 1.5°C.

The role of the individual, as well as governance and institutional change, can be vitally important in transitioning to a 1.5°C compatible world. Actions that reduce energy demand, such as a shift toward sustainable healthy diets and reduction of food waste together with more efficient appliances and better insulation can enhance future mitigation. It should be noted, however, that while demand-side measures are important for meeting stringent climate targets, such as 1.5°C and 2°C, they are not sufficient on their own.

*[**Figure Suggestion:** Schematic emphasising and illustrating the 4 areas of transition, it could include a simple scale showing the relative associated costs or amount of governance that may be required]*

FAQ 4.2: What are negative emissions and solar radiation management?

Negative emissions, or carbon dioxide removal (CDR), and solar radiation management (SRM) are two techniques that aim to cool global temperatures in a different way to conventional mitigation techniques. CDR directly removes carbon from the atmosphere, while SRM reduces the amount of solar radiation reaching Earth’s atmosphere. Neither technique is a sole substitute for reducing GHG emissions, and there are substantial risks and uncertainties around both techniques.

The world would need to transform extremely rapidly to limit global warming to 1.5°C above preindustrial levels. If change doesn’t happen quickly enough, however, other methods have been proposed in addition to traditional mitigation options that could, in theory, offset remaining carbon emissions.

One is removing CO_2 directly from the atmosphere, a concept known as carbon dioxide removal (CDR). If the amount of CO_2 taken out of the atmosphere is more than the amount being put in, this achieves ‘negative emissions’. Another technique that has been proposed involves modifying the amount of radiation that reaches Earth from the sun. This is known as solar radiation management (SRM). Both approaches are unproven and carry with them substantial, although very different, risks.

Climate modelling pathways feature CDR techniques in two main ways: either to limit temperatures rising above 1.5°C or to bring emissions down after a temporary overshoot. The greater the overshoot, the greater the reliance on CDR to bring CO_2 back down to within the allowable 'carbon budget' for 1.5°C. But issues concerning feasibility, cost and ethics make deploying CDR at the scale that would be required to limit warming to 1.5°C far from straightforward.

Examples of CDR include bioenergy with carbon capture and storage (BECCS), in which atmospheric CO_2 is removed by growing trees and crops and then used as bioenergy. The resulting CO_2 is then captured and stored underground in rock formations. Another CDR technique is direct air capture and storage (DACS) of CO_2 using chemical processes to store the CO_2 in geological formations. Afforestation and reforestation (planting and replanting trees) can also be considered forms of CDR.

Among the CDR options, BECCS, afforestation and reforestation may be thought of as technically feasible, in that the technology or processes involved are understood. But they have significant environmental, economic and social constraints. For example, deploying BECCs at the scale required to limit warming to 1.5°C would require large amounts of land. This could raise sustainability issues if the land is in competition with food production to support a growing population. A constraint of DACs is its high costs and energy requirements. Other CDR options exist. Some are relatively cheap to do and have extra benefits for biodiversity and ecosystems, such as restoring mangroves. But the extent to which such natural methods of CDR could store CO_2 permanently and play a role in limiting warming to 1.5°C is not well understood, and are currently not included in climate models.

Unlike CDR, the process behind SRM is to regulate Earth's temperature by directly interfering with the amount of solar energy reaching Earth, rather than removing any carbon from the atmosphere. The idea of SRM is discussed in the scientific literature, but exists only conceptually and has never been tested outside of laboratories or in computer modelling experiments.

Two main conceptual types of SRM exist. Both aim to modify the amount of cloud covering the Earth, which increases the amount of solar radiation that gets reflected back into space. In theory, this would result in a cooling effect since less energy being absorbed by the Earth. One proposed method, stratospheric aerosol injection (SAI), shoots tiny sulphate particles high into the Earth's atmosphere to stimulate clouds to form. This process essentially mimics the effect of volcanic eruptions, which can temporarily reduce global average temperatures. A different method, known as marine cloud brightening (MCB), could create denser and brighter clouds over the ocean by adding sea-water particles, which act in a similar way to enhance the concentration of cloud droplets.

But SRM is controversial for many reasons, including justice, equity and ethics. Model experiments suggest impacts are not limited to the region that SRM is deployed. Deploying SRM in one region could lead to impacts in several other areas, raising issues around governance. Moreover, instigating SRM will not alleviate other risks that are associated with rising GHG emissions such as ocean acidification and its resulting impacts on marine ecosystems.

Neither CDR nor SRM are considered a substitute for reducing emissions in the scientific literature or in this Special Report. While CDR could be used in addition to traditional mitigation and adaptation strategies, if current concerns can be resolved, there is considerable uncertainty and concern around any level of SRM deployment.

*[**Figure Suggestion**: a schematic showing the main process of SRM and negative emissions, in an illustrative form.]*

FAQ 4.3: Can we adapt to global warming of 1.5°C?

[Placeholder text – this FAQ will be drafted for the final draft review of the Special Report on Global Warming of 1.5°C]

- *Adaptation needs at 1.5°C are lower than at 2°C, but higher than at 1°C*
- *What are current adaptation needs?*
- *Explanation of adaptation pathways, one example*
- *Explanation of transformational adaptation, one example*
- *Synergies between mitigation and adaptation options. How have current options responded?*
- *Identified areas to avoid trade-offs between mitigation and adaptation options. How can policy support this?*
- *Integration of mitigation, adaptation, and sustainable development (avoid overlap with Chapter 5 FAQs)*
- *Roles of enabling environment (governance, institutions, etc.)*

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