Chapter 4: Strengthening and implementing the global response

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Executive Summary

Accelerating and upscaling the implementation of far-reaching, multi-level, cross-sectoral climate mitigation and adaptation actions, integrated with sustainable development initiatives, can facilitate the transition to a 1.5°C world. Current national pledges on mitigation and adaptation are inadequate to achieve the temperature targets of the Paris Agreement {4.4.3, Box 4.12}. To strengthen the global response, national governments would need to significantly raise their level of ambition and strengthen capacities to implement their commitments. For many developing countries, achieving this will require 'financial, technological, and other forms of support' to build capacity for effective climate governance and implementation, for which currently both local and international resources are insufficient. {4.4.4; 4.4.6}

Adaptation imperatives will be lower in a 1.5°C as compared to a 2°C world, yet transformative adaptation is necessary to address impacts on vulnerable systems and regions across the world. Adaptation is necessary under current (1°C) warming conditions {Chapters 1, 3}. Learning from current adaptation and strengthening by mainstreaming within sustainable development, adaptive governance {4.4} and behavioural shifts {4.4.5}, as well as drawing on community participation and indigenous knowledge {Box 4.15} are important. While adaptation finance volumes have increased, gaps in current adaptation finance and ineffective monitoring mechanisms undermine action. {4.5.1}

The rates of change in energy technology deployment found in the modelling of emission pathways for 1.5°C are consistent with those observed historically. But the scale of the required energy, land and urban transitions, is larger. Such transitions require more planning and coordination across actors than the spontaneous or coincidental changes we have observed in the past. 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 energy, land and urban transitions jointly succeed depends on behaviour and lifestyle changes, faster innovation and effective policies and governance. {4.2; 4.3.1; 4.4.3; 4.4.7}

The energy transition is taking place in many sectors and jurisdictions around the world, but follows a slower pace in energy-intensive industry, waste management and international transport. In solar energy, wind energy and energy storage systems, a transformation seems to be underway. The political, economic, social and technical feasibility of solar and wind energy has improved dramatically over the past few years. In industry, the options that lead to deep emissions reductions consistent with 1.5°C are limited by political, economic and technical constraints. Buildings offer an enormous potential for emission reduction, but barriers prevent this transformation. Transport and waste management improvements in many jurisdictions face economic and institutional barriers. {4.3.2; 4.3.4}

Global land use transitions, in combination with changes in behaviour, could enhance future mitigation. But, if not managed carefully, such transitions could be associated with significant changes in agriculture and forest systems that risk weakening ecosystem health, potentially leading to critical food, water and livelihood security challenges. Adaptation options such as ecosystem-based adaptation and community-based adaptation, and mitigation options such as emissions reductions from agriculture and livestock, afforestation and reforestation programmes, need continued governance, financial and policy support to be effective, and to be socially acceptable {4.3.3}. Behavioural change around meat consumption would reduce the pressure on land and emissions {4.4.5}.

Rapid, systemic transitions in urban areas will be a defining element in an accelerated transition to a 1.5°C world. These will be enabled by an integrated mix of feasible mitigation and adaptation measures, led by local and regional governments that are aligned with sustainable development and support economic development. They include sustainable land use, planning and urban design to alter urban form, de-motorization and decarbonisation of transportation systems, and lowering and decarbonizing energy use in the built environment, especially buildings. In addition, strengthening ecosystem services and building green infrastructure to deliver sustainable water and environmental services and support urban agriculture and forestry are an economically feasible and a socially acceptable option, although institutional barriers need to be overcome. {4.3.4}

Options that lead to a net removal of CO_2 from the atmosphere are affected by multiple feasibility constraints. Therefore, the scale of deployment required in the 1.5°C pathways in Chapter 2 may be challenging to implement. Measures to reduce short-lived climate pollutants (SLCPs) will be implemented if the land, energy and urban transitions succeed. Options to reduce SLCPs, methane, black carbon and short-lived HFCs, can provide fast emissions reductions and unrivalled co-benefits in terms of health due to prevention of air pollution, which enhances political feasibility. However, 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 {4.3.5}. Among the carbon dioxide removal (CDR) options, bioenergy with carbon capture and storage (BECCS) and afforestation and reforestation (AR) are technically feasible but face environmental, economic and social feasibility constraints. The energy requirements and costs of direct air capture and storage (DACS) seem high, so far. Other options, including soil carbon sequestration (SCS) and biochar, enhanced (ocean and terrestrial) weathering, blue carbon enhancement, ocean iron fertilization, and other greenhouse gas removal (GGR) techniques need to be considered. {4.3.6}

Uncertainty and concern surrounds any level of deployment of solar radiation management. It is uncertain whether global solar radiation management (SRM) technologies, in particular stratospheric aerosols injection (SAI) and marine cloud brightening (MCB), could compensate for even part of the temperature rise, and certainly not for all of it. Planned research on SRM is raising concerns about diverting political attention away from conventional mitigation, and the consequent moral hazard around accelerating implementation of mitigation options. Wide implementation of SRM would be controversial for reasons of justice, equity and ethics. A single country or other stakeholder could act out of self-interest and potentially inflict harmful impacts on other geographies, making it socially infeasible.

Governance in a 1.5°C consistent world must be able to create an enabling environment for policy and technology options, behavioural changes and innovation. To forge 1.5°C action, a range of innovations should be enabled including: accountable multi-level governance, coordinated sectoral policies to create collaborative multi-stakeholder partnerships, greater public awareness and improved education and facilitating conditions. Other synergistic approaches that leverage mitigation and adaptation potential should also be realised, including mechanisms that forge international agreements and targets {4.4.1; 4.4.3}. Non-state actors play a key role in the governance mechanisms.

Numerous examples from around the world illustrate that 1.5°C -compatible, inclusive, prosperous and healthy societies are possible. At the same time, very few cities, countries, businesses or communities are truly in line with 1.5°C. Increased ambition, connecting emission reduction options via interconnected value chains and governance, and enhanced capabilities are necessary. Key 1.5°C transition-enhancing institutional arrangements include: robust legal and regulatory frameworks, trustworthy and equity-enhancing financial institutions, transparent and accountable monitoring processes, and collaborative networks across scale and region. Practically everywhere around the world, but particularly in developing countries, institutional and innovation capabilities are currently falling short in implementing far-reaching measures at scale, and by a multitude of actors. Multinational networks supporting multi-level climate action are growing, but challenges in scaling-up remain. {4.4.3; 4.4.4; case studies in 4.4}

Changing behaviour and lifestyles is a necessary part of a strategy to enable a transition to 1.5°C. Measures include: enhancing public responsiveness to climate policy and systemic change, reducing wasteful consumption, enabling end-use efficiency, decarbonising production and consumption, and dealing with psycho-social barriers to effective and timely adaptation and mitigation options. 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 mitigation and adaptation, promoting further action on climate change, creating a virtuous circle. {4.4.3; 4.4.5}

Packages of policy instruments, working across governance levels and promoting innovation, are needed to implement a rapid and far-reaching response. Policy instruments, both price and non-price, are needed to accelerate the deployment of carbon-neutral technologies before they can be more cost-effective than fossil fuels, using a mix of regulation, grants, standards, subsidies, loans and feed-in tariffs, information and social influence strategies to trigger innovation and align a low-carbon transition with equitable access to sustainable development opportunities to address on-going challenges, like poverty, unemployment and debt. {4.4.6; 4.4.7}.

1.5°C -compatible worlds will require active intervention to reduce investment risks in low carbon technologies and to redirect world savings. This implies the involvement of the financial sector including central and multilateral banks. Public guarantees and appropriate financial intermediation to improve the quantity of bankable projects at a given carbon price and reduce risk-weighted capital costs could make low-carbon assets attractive for investors. Public guarantees, development assistance and support of non-state actors could facilitate enhanced adaptation investment. {4.4.8}

Gaps in knowledge for implementing and strengthening the global response need to be resolved to facilitate the transition to a 1.5°C world. They include the questions of how much can be realistically expected from innovation, behaviour and systemic political and economic changes in improving resilience and reducing emissions; whether generalisable and practical principles of climate resilient governance can be identified; and how the political incentives for climate action and the associated financial and socio-cultural systems can be changed to make climate action happen. {4.5.1}

4.1 Accelerating the global response to climate change

This chapter discusses the implementation opportunities and challenges associated with a 1.5°C warmer world, from both mitigation and adaptation perspectives. From an adaptation perspective, impacts in a 1.5°C warmer world are still significant, but can be alleviated by adaptation and development responses. Expected impacts at 1.5°C pose lesser challenges for sustainable development than those at higher levels of warming (see Chapters 3 and 5). From a mitigation perspective, staying below 1.5°C means the global response needs to be more far-reaching and more rapid. This chapter is about how to implement and strengthen adaptation and mitigation responses in a 1.5°C context, where possible in a synergetic manner with the goals of sustainable development, equity and justice.

Previous IPCC reports examined ways of maximizing economic efficiency in staying below temperature limits by varying temporal and spatial distribution of various adaptation and mitigation actions. AR5 has shown that the social costs of meeting temperature limits depend critically on: (1) the mobilization of existing and future low-carbon and adaptation technologies; (2) creating the appropriate governance, finance and institutional enabling conditions; (3) reducing differential vulnerability and enabling the building of adaptive capacity, before adaptation limits are crossed; (4) mediating the economic impact (e.g., employment, consumptions, savings and investment) of diverting resources towards the decarbonisation of production and consumption. AR5 has also shown the importance of addressing the 'equity dilemma': the quantity of avoided emissions reductions required from the developing countries will need to be larger than that from developed countries over the rest of the century, while the cumulated per capita emissions remain far higher in developed countries.

The AR5 has not assessed temperature limits lower than 2°C, but most of its messages remain valid for 1.5°C. One main change, from a mitigation perspective, is that the transition to a 1.5°C world by 2050 leaves almost no temporal flexibility for lags in implementation, unless massive penetration of cheap carbon dioxide removal technologies becomes possible. The second significant difference is that a 1.5°C transition requires structural changes from the global- to the local-level in development pathways and governance, and in economic, financial, institutional, social and technical systems.

In the context of the Paris Agreement, the global response therefore implies the need to focus on: (1) accelerating the realization of 'no-regret' and 'negative costs' options to deliver short-term development, mitigation and adaptation co-benefits; (2) enabling environments that help address institutional, market and behavioural barriers to this; (3) accelerating the implementation of policy packages apt to deliver long-term development benefits and universal improvements in quality of life; (4) diverting investments from current trends, that can lead to a lock-in into climate-vulnerable and carbon-intensive development pathways; (5) reinforcing innovation processes, changes in lifestyles and spatial dynamics that will allow for further deep reductions in GHG emissions, and (6) enhancing the adaptive capacity of key systems at risk (e.g., water, energy, food, cities and coastal resources) to climate change impacts.

A challenge posed by the absence of temporal flexibility is the rapid reduction of the 'implementation gap' between the aspirational climate policies that have been assessed and tested over the past decades (e.g., carbon pricing, regulatory measures, financial instruments, research and development, capacity building) and their implementation. This includes those announced in the Nationally Determined Contributions (NDCs) at the heart of the Paris Agreement. Reducing this implementation gap cannot be done without considering the current conditions of the world economy, polity and society. 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 trade. It may be hard to accelerate climate action if the loss of economic value of carbon-intensive assets, which appears unavoidable, cannot be minimized.

Therefore, this report examines how a 1.5°C -consistent transition can fulfil the universal implementation of the Sustainable Development Goals by 2030. This implies expanding the space for simultaneous development, adaptation, mitigation and risk reduction measures, as well as 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 2015); consistent growth of global economic output, wealth and trade; a significant reduction in extreme poverty, in spite of local and regional economic crises; and rising inequality, exclusion and social stratification in many regions. 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.

Nevertheless, a 1.5°C -consistent transition will take place in a challenging environment on which leading economists and institutions have issued repeated alerts: from the 'discontents of globalization' (Stiglitz 2002), 'depression economics' (Krugman 2008), the structural 'fault lines' of the world economy and excessive reliance of export-led development strategies (Rajan 2010), rising income inequality (Piketty 2014), risks of 'secular stagnation' (Summers 2016), to 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).

Strengthening climate policies cannot alone resolve, and may even exacerbate, these fault lines. Policymakers could address this by helping reduce 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 go to: stimulate growth and employment over the short-term; and over the medium-term enhance productive, climate-resilient investments in sustainable infrastructures (Arezki et al. 2016); improve resources management, and overcome structural barriers to mitigation and adaptation. Another area of potential, is aligning climate policy with other public policies (fiscal, industrial, urban planning, infrastructure, innovation) and thereby enabling greater access to basic needs and services, defined by the SDGs, which could act as hedges against unstable and dualistic growth, and 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 does not allow for free-riding. Hence, a key governance challenge is how the gain from converging climate and sustainable development policies can contribute to the emergence of a world governance based on reciprocity (Ostrom and Walker 2005) and partnership (United Nations 2016a) and how different actors and processes in climate governance can reinforce each other to enable this (Gupta 2014; Andonova et al. 2017).

4.2 Pathways compatible with 1.5°C

4.2.1 Pace of the development and deployment of adaptation and mitigation options

This section will assess 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 whether rates of technological and societal change are realistic: expanding historical trends into the future (in both adaptation and mitigation), and matching of 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 (Lamb and Rao 2015; Clarke et al. 2014).

In the field of adaptation, in order to understand how to adapt to a 1.5°C warmer world, past changes and adaptations that have led to transformations can be studied (Fazey et al. 2016; Pelling et al. 2015; Gajjar et al.). Adaptation pathways in the context of sustainable development are more extensively discussed in

Chapter 5 (Section 5.3). For implementation questions, it is important to note that adaptation pathways can help identify maladaptive actions (Juhola et al. 2016; Magnan et al. 2016; Gajjar et al.) and encourage social learning approaches across multiple levels of stakeholders in sectors such as marine biodiversity and fresh water supply (Butler et al. 2015; Bosomworth et al. 2015; van der Brugge and Roosjen 2015).

A second approach analyses how technologies have developed over time and contrasts those patterns against quantitative models to understand how contemporary 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 IAMS, tentatively conclude that, depending on how metrics are normalized, modelled rates of change of emissions are broadly consistent with past trends while for individual technologies this may not be the case, especially on the mid-term. However, Wilson et al. (2013) conclude that for technologies, models are generally more conservative than historic data suggest. A qualitative strand of this is pioneered by Geels and Schot (2007), who have developed a typology of trajectories of technological change, abstracting from the specific speed of change, and emphasizing the possibility and effects of shocks and other types of discontinuous change. Recently, Geels et al. (2016) also illustrate that energy transitions are associated with wider socio-economic transformations, and that models generally don't represent such processes, and Sovacool (2016) indicates that this gives reason to believe that energy transitions could go much faster. Kern and Rogge (2016) contend that indeed there is reason for optimism but that rather based on some 'autonomous' rate of change, the rate is 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.

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 time progresses forward and that we can learn from the past to understand the direction of technological change in the future. 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 emphasizing the slow, difficult process of change (Fouquet 2016) and fitting studies pointing towards the possible fast speed of (Wilson et al. 2013). Both approaches indicate that the rapidity of changes in the past have not necessarily been slower than the ones that pathways, including those assessed in Chapter 2, indicate.

4.2.2 Implications of climate-resilient pathways consistent with 1.5°C

[The assessment of the pathways towards 1.5°C worlds currently relies on the 1.5°C scenarios published in Rogelj et al. (2015) and the comparison of 1.5°C vis-à-vis 2°C pathways. The quantitative assessement will be adapted as the new ensemble of scenarios becomes available. Additionally, the delay scenarios for 2°C (Luderer et al. 2016) *will be considered for orientation]*

The main characteristics of 1.5°C pathways can be summarized as follows: they are below the emissions pathways of RCP2.6 in AR5, and all feature temperature overshoot. Global GHG emissions will need to change from the current ca. 50 $GtCO_2eq\ yr^{-1}$ to become net zero by mid-century and net negative thereafter. Under some burden sharing assumptions, this implies that large emitters, and regions and cities with high emissions, will need to achieve net-zero emissions by the 2030s. These additional emissions reductions required to move from a 2°C pathway to a 1.5°C world, according to IAMs, would largely be achieved by (a) accelerated reduction of fossil CO_2 emissions by demand reductions and electrification of end-use sectors in combination with decreases of carbon intensity of electricity, and (b) BECCS and management of land-use sinks and the use of emergent technologies in new currently undefined scenarios.

Almost the entire assumed abatement potential for non-CO_2 GHGs is already exhausted in 2°C scenarios, so few additional reductions are possible in the 1.5°C pathways. There is almost no room for growth in energy demand: from 350 EJ yr^{-1} today to an upper bound of 450 EJ yr^{-1} by 2100 (compared to on average 600 EJ yr^{-1} for 2°C). If left unmanaged, this could have significant implications for the achievement of SDG7 on universal affordable access to clean energy by 2030, with potential limits to the reduction in poverty in fossil fuel intense economies and regions.

Fossil-based electricity generation needs to be phased out earlier than for 2°C, carbon-free technologies must be ramped up faster, and the share of electricity in final energy will need to rise more rapidly in 1.5°C -consistent scenarios. This paragraph will thus first discuss the incremental changes for fossil phase out, renewables, nuclear, carbon capture and storage for electricity, and the electricity share in final energy. Furthermore, there will be a massive increase in electricity for transport, though this does not necessarily exceed 2°C by much. Incremental mitigation in transport compared to 2°C mainly comes from demand reductions (e.g. modal shift) and an increased use of biofuels in liquid energy carriers (cf. discussion on potential for land use competition in the context of bioenergy in general below). Concerning industrial and buildings emissions, 1.5°C scenarios feature reduction rates of 25% and 50% lower than for 2°C, respectively.

[A figure will be added depicting a set of global graphs showing emissions reduction by GHG/end-use as stacked area graphs along with scales measuring the difference between 1.5°C and 2°C]

4.2.2.1 Climate-resilient pathways that reach or are consistent with 1.5°C.

[This section will provide a stocktake based on the pathways discussed in Chapter 2 plus any specific adaptation or/and non-IAM pathways from Chapter 3 and any specific pathways provided by Chapter 5.]

Climate-resilient pathways are pathways that combine mitigation and adaptation measures to achieve climate objectives with the lowest possible trade-offs and the least negative side-effects. Note the difference with 'climate-resilient development pathways', which are explained in Section 5.7. Denton et al. (2014) identifies three key aspects of climate-resilient pathways within the context of global and regional environmental limits: enhanced adaptation, reduced vulnerabilities and stringent emissions reductions. In the context of sustainable development these pathways should not only be economically, technically and institutionally feasible but also socio-culturally acceptable by addressing sustainable development concerns of addressing poverty, employment, equity, fairness, and justice, in their regional contexts.

The emissions pathways from the IAM literature discussed above are mostly based on the Shared Socio-economic Pathways (SSPs). Among the five SSPs (O'Neill et al. 2015) only SSP1 and SSP2 are consistent with meeting a stronger mitigation target such as 1.5°C. SSP1 emphasises sustainable development and hence is closest to the broader climate-resilient characterisation. The SSP2 includes a number of the same social considerations in SSP1 but the literature suggests that mitigation requirements and costs along the SSP2 pathway are significantly higher than along the SSP1 pathway (Riahi et al. 2015a).

[Emissions pathways at global, regional, and national levels based on the non-IAM literature will be assessed based on the relevant literature from Chapters 2 and 3 and the outcomes will be summarized and contrasted to those from the IAM literature.]

4.2.2.2 What are the implications of these pathways?

Some of the dimensions of interest to assess, based on the availability of the literature, include the scale of the transformation needed, implications for adaptation and implications for policy and policy decision-making.

4.2.2.2.1 Scale of transformations required

[Discussion of the scale of social and technical innovation required based on details provided by Chapter 2.]

The literature agrees that staying below 1.5°C would entail significantly greater transformation in terms of energy systems and lifestyles compared to the 2°C temperature target. Chapter 2 indicates that this would entail 40% more investments on the shorter term compared to a situation without a temperature target, requiring larger deployment of resources and investments.

4.2.2.2.2 Implications for adaptation

Warming of 0.5°C (from 1.5°C to 2°C) leads to significant increases in temperature and precipitation extremes in most regions. However, the projected changes in climate extremes under both warming levels depend on the emission pathways, with different greenhouse gas (GHG)/aerosol forcing ratio and GHG levels (Wang et al. 2017b).

The avoided climate impacts of moving from 2°C to 1.5°C warming are difficult to define from existing IAM literature (which are typically based on model inter-comparison projects) and are complicated by the uncertainties in climate model responses and internal climate variability (Mitchell et al. 2017; James et al. 2017). Hence, limited available evidence tends to be case and model-specific and mostly from non-IAM literature.

[This will be linked to the Chapter 3 on specific impacts, such as sea level, temperature and precipitation extremes, etc.]

One such study reported that a lower global mean temperature is likely to be decisive for the future of tropical coral reefs, a key system at risk defined by AR5 (Schleussner et al. 2016; IPCC 2014a). A 1.5°C scenario reduces the risk of severe degradation due to temperature-induced bleaching from virtually all coral reefs with an end-of-century 2°C warming, to 90 % in 2050 and projected to decline to 70% by 2100.

In contrast, the analysis of precipitation-related impacts in Schleussner et al. (2016) reveals distinct regional differences and hot-spots of change. Regional reduction in median water availability for the Mediterranean is found to nearly double from 9% to 17% between 1.5°C and 2°C, and the projected lengthening of regional dry spells increases from 7% to 11%, which would have negative implications for agricultural yields depending on crop types as well as world regions. Schleussner et al. (2016) have also reported about 10 cm lower levels for a 1.5°C scenario sea level rise projections, compared to an estimated 50 cm rise by 2100 for a 2°C scenario.

4.2.2.2.3 Policy and decision-making implications

1.5°C pathways raise the bar on the design and coordination of the policy responses and sustainable development actions needed to effectively deal with the scale and pace of mitigation and finance, and which address distributional implications as well as adaptation to climate impacts. Some literature seems to suggest that the level of resources, cost and efforts needed to get to 1.5°C is high. For example, Su et al. (2017) showed that achieving 1.5°C will require tripling the carbon price and doubling the mitigation cost compared to with the 2°C case, though this does not account for the cost of avoided impacts with lower warming.

This report considers policy instruments and targets, alongside mitigation and adaptation options. Policy instruments, such as a carbon tax or regulation for ecosystem resilience, are discussed in Section 4.4.7. Mitigation options, such as solar energy, or adaptation options, such as water management, are assessed for feasibility in Section 4.3. Policy targets can be used by policymakers for orientation purposes. Examples consistent with 1.5°C include a fully renewable electricity system by 2035 (a policy target by Denmark) or a low-carbon steel industry by 2050. The assessment presented in Chapter 2 implies regional policy targets in different sectors. In this section, these will be assessed as to what this means for generic policy instrumentation and other approaches (Section 4.4) such as innovation, behaviour and lifestyle, and finance.

Managing costs and distributional implications require a policy mix approach that takes account of unintended cross-sector, cross-nation, and cross-policy trade-offs essential to manage the transition to low GHGs economies (Droste et al. 2016).

4.2.3 Framing systemic issues: resilient economic systems, social systems, innovation systems, leadership and lifestyles

Chapter 2 has indicated that limiting global warming to well below 2°C or 1.5°C requires a radical transition through deep decarbonisation starting immediately, not merely a fine tuning of current trends. The goal of the Paris Agreement (UNFCCC 2015) of staying well below a 2°C temperature rise, or below 1.5°C, cannot be achieved using climate mitigation policy alone, and expands the scope of this assessment to disruptive technological and social innovation along with economic, institutional, governance, social and behavioural change that will enable 'global peaking of greenhouse gases as soon as possible' (UNFCCC 2015 Article 4.1) and fast emission declines after that (Rogelj et al. 2015).

4.2.3.1 Disruptive Innovation

Disruptive innovation is a form of technological change that leads to significant system change. It was first framed by Christensen (1997) around digital technologies that changed the micro-economy of firms and then impacted the whole economy. It has since been applied at the level of the firm to a range of other sectors including the transformation of power and transport fuels (Christensen et al. 2015; Seba 2014; Green and Newman 2017a).

The demand for a new product or service is unpredictable unless firms can see the broader appeal that the market is looking for. The rapid adoption of a product leads to a whole system change such as with laptop computers (Sampire 2016). Disruptive innovations are very hard to predict by economists and modellers as the innovations can be adopted much faster than models predict as being economic feasible (Green and Newman 2017b).

The increase in roof-top solar and energy storage technology may be such a disruptive innovation in several countries (Green and Newman 2017b). One feature of disruptive innovation is that firms and utilities can be left with stranded assets as the transition created by the disruption happens very quickly (Kossoy et al. 2015; IPCC 2014b). The idea of stranded assets is mostly applied to 'unburnable oil' (McGlade and Ekins 2015) as well as coal-fired power plant assets (Caldecott 2017; Farfan and Breyer 2017).

4.2.3.2 Socio-Technical Innovation

The idea of technological transitions has been advanced by economists since Schumpeter and Kondratief who talked about industrial change coming in waves (Šmihula 2009; Adams and Mouatt 2010). In more recent times this has been developed into a theoretical framework for understanding how technological change is associated with social change such as different business models and governance systems as well as some areas of cultural change (Freeman and Perez 2000; Perez 2002, 2009a,b) and into what is now known as Socio-Technical Innovation Theory (Geels and Schot 2007, 2010). This is now being applied to explain how energy transitions are happening and are showing how significant the socio-technical aspects of change are and will be in driving the transition to 1.5°C (Geels et al. 2016b; Geels 2014). In addition, elements of 'transition theory' and innovation systems theory, such as strategic niche management (Kemp et al. 1998) and functional approaches through technological innovation systems (Hekkert et al. 2007; Bergek et al. 2008) are applied in practice to develop policy responses to innovation challenges.

4.2.3.3 Decoupling

The socio-technical innovation changes associated with fossil fuels underpin the approach taken by a range of people and by the OECD and UNEP called *decoupling* (von Weizsäcker et al. 2014; Newman 2017). This suggests that although wealth has in the past been completely coupled to the use of fossil fuels, there are changes in technology and the economy that can enable the decoupling of wealth from a range of environmental issues, including the consumption of fossil fuels. One of the critiques of decoupling theory is that it will always be only a relative decoupling due to feedback like rebound effects (Gillingham et al. 2013; Jackson and Senker 2011). Recent data suggests that greenhouse emissions have decoupled absolutely over the past two years (International Energy Agency and OECD 2017; Peters et al. 2017). Newman (2017) shows that this has been driven by declines in both coal and oil and this has been happening since the early 2000s in Europe, in the past seven years in the US and Australia, and has begun in China. The rate of decoupling appears to depend on the 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). It is also relevant at the city level (Swilling et al. 2013).

4.2.3.4 Financial Systems

As investment profiles of projects in energy, land and urban systems consistent with limiting global temperature rise to 1.5°C differ considerably from current practice in financial systems, more capital needs to become available on a shorter term for remaining below 1.5°C than would be needed if the energy system was to remain fossil-based (Miller 2008). For renewable energy options such as wind and solar, investments are frontloaded and operational costs are relatively small, and also for energy efficiency, large investments need to be made early on, and the revenues are generated later.

Current financial systems are not prepared to stress-test for climate change (Battiston et al. 2017b). Multilateral climate finance flows are starting to warm up to climate change mitigation and adaptation and are influencing other investments (Buchner et al. 2015), including in the Green Climate Fund and the Global Environment Facility, but also the World Bank, regional development banks, and the Climate Investment Funds. The financial literature is practically silent on climate change (Diaz-Rainey et al. 2017) and central banks only recently started addressing climate change (Bank of England 2015; De Nederlandsche Bank 2016). Pension funds face challenges when electing to invest in climate-friendly activities (Sievänen 2013) and the market provides insufficient signals to institutional investors (Haigh 2011). The literature suggests that potential could still be materialised by engagement of the financial sector, but that this depends on political signals that affect the bankability of climate-friendly investments.

4.2.3.5 Institutional Change and Political Leadership

Institutions, understood as the ‘rules of the game’ not organisations (North 1990), exert both direct and indirect influence over the viability of transformation pathways required to remain below 1.5°C. Individual behaviours are embedded in social institutions, institutional contexts and cultural norms and behaviours emerge from socio-technical contexts made of specific material arrangements, competences and associated meanings (Shove 2010). Institutions and cultural transformations are needed to support wide-scale adoption of climate change mitigation and adaption options. Considerable work remains to align the incentives, aspiration, policies and finance to support the shifts required to remain below the 1.5°C threshold and the level of national state and between nation states in the form of trade, finance and knowledge sharing agreements (Rode et al. 2014).

Off the back of growing urban populations and the recognition that cities account for a majority portion of greenhouse gas emissions, cities have emerged as the locus of institutional and infrastructural climate innovation. 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 nation states (Rode et al. 2014). Work remains in aligning the efforts and reporting of cities with UNFCCC goals, but the growing networks of mayors and cities sharing experiences on how to cope with climate change and how to draw economic and development benefit from climate change responses, represent an important institutional innovation. Mayors and city managers have begun to show significant leadership in driving proactive responses to climate change (Roberts 2016a). In the US, emissions are lower in states that elect legislators with strong environmental records (Dietz et al. 2015).

Definitive leadership in China has given impetus to the combined transitions around urbanisation and sustainability (Bai et al. 2014), and also contributed to the rise of China’s renewable energy sector. It remains to be seen whether decoupling of emissions and growth in China (Newman 2017) can be sustained.

In African countries, the case for climate resilient growth has been slow to gain political traction, in part because it requires perceived adjustment costs in the short-term, in expectation of future gains (Resnick et al.

2012). This may be changing since the Paris Agreement where developing countries view a climate resilient economy as offering new competitive advantage (Cartwright 2015).

4.2.3.6 Behavioural Change

Humans are at the centre of global climate change: human actions cause anthropogenic climate change, and social transformations are key to effectively respond to climate change (Hackmann et al. 2014a). To stay below 1.5°C temperature rise, substantial modification of a wide range of climate change mitigation actions by many different people in different domains is needed. Such actions include the adoption of renewable resources (e.g., solar power), the implementation of resource efficiency measures in buildings (e.g., insulation, weatherising), and the adoption and use of low carbon innovations (e.g., electric vehicles) and energy-efficient appliances. Changes in user behaviour can relate directly to energy use (e.g., walk, cycle, or use public transport rather than drive or fly; reduce room temperature) as well as to the embedded energy needed to produce, transport and dispose of products and services (e.g., reduce meat consumption or buy local seasonal food; Steg 2016; Dietz et al. 2009). Other GHG emissions can be affected via behaviour changes, such as the reduction of methane by reducing meat consumption.

Likewise, many populations already engage in climate change adaptation behaviours to protect themselves from climate change risks occurring now, or those expected to occur in the near future. These include: growing different crops or animal varieties; protecting oneself from risks due to flooding, for example, by elevating barriers between rooms, building elevated storage spaces, building drainage channels outside the home (Jabeen 2014); and protecting oneself from heat waves by staying hydrated, travelling to cool places or installing green roofs (Araos et al. 2016a; Taylor et al. 2014).

Besides changes in adoption and use of products and services, it is important to promote citizenship behaviour and behaviour in companies and other organisations that can support emissions reductions at various levels and enable pre-emptive adaptation action (Stern 2000; Stern et al. 2016). These actions can influence the implementation of climate mitigation and adaptation policies as well as decision-making that is committed to climate action. In addition to active policy choices, public expressions of acceptability of or resistance to projects and policies aimed to promote climate change mitigation and adaptation will increase the likelihood that such policies, programmes and projects will be implemented (Steg et al. 2017).

Given the urgency of meeting the 1.5°C target, options with a substantial potential for carbon emission reduction and adaptation and with a high behavioural plasticity could be prioritised, such as the adoption and use of sustainable technologies (i.e., fuel efficient vehicles, home heating and ventilation, appliances, and weatherization (Dietz et al. 2009)). These are associated with relatively low behavioural costs and can demonstrate to users that their efforts are effective. This, in turn, can strengthen environmental self-identity of users, which is likely to motivate them to engage in further mitigation actions that are consistent with those already undertaken (van der Werff et al. 2016; Lauren et al. 2016). Meanwhile, new technologies, policies and institutions can be developed that promote and facilitate further changes (see Section 4.4.5). Notably, the changes in lifestyles and behaviour needed to limit global warming within 1.5°C will be more likely when supported by changes in economic systems, social systems, infrastructure, institutions and cultural change (see Section 4.4.5).

4.3 Assessment of current and emerging (adaptation and mitigation) options

4.3.1 Assessing accelerated transitions (environmental & geophysical, technological, economic, socio-cultural, institutional)

Both the goal of remaining within a 1.5°C warming limit and the adaptation and mitigation interventions that will help achieve this target must be scrutinised for feasibility.

AR5 identified both technologically and economically feasible pathways for limiting warming to well-below 2°C. Pathways limiting warming to 1.5°C by the end of the century are also feasible, but require more immediate and greater scaled initiatives than those for 2°C, including zero emissions by the 2060-2080 period, roughly 20 years earlier than for a 2°C pathway (see Chapter 2).

In its essence, feasibility in this Special Report is about the cost and speed at which options comprising the 1.5°C pathway can be introduced. In practice, however, feasibility is almost always multi-dimensional, more complicated and more political than narrow definitions of cost, benefit and speed. Moreover, there are profound difficulties in including the full extent of benefits at the local scale in conventional climate change cost-benefit analyses and in identifying the distribution of benefits and costs between income groups and across regions (Cartwright et al. 2013). In discussing feasibility, AR5 recognised both physical constraints to carbon dioxide removal and the social, technical and economic dimensions of feasibility that are linked to subjective desires and human ability (Clarke et al. 2014).

In Section 4.4, options for adaptation, mitigation and SRM cited in the literature on energy systems, land and ecosystems, cities, infrastructure and industrial systems, are reviewed in the context of the three high-level 'dimensions' of feasibility identified in Chapter 1 and shown in Table 4.1. These are: 'economic and technological', 'environmental and geophysical' and 'social and institutional'. Chapter 1 disaggregates these dimensions into 'characteristics' and a non-exhaustive list of 'empirical measures' for which some data are available or being collected. Empirical measures enable a more detailed, and in some instances, a more objective, assessment of options. Recognising the multiple dimensions of feasibility becomes particularly important in the context of 'net negative emissions' options, such as BECCS, that are understood to be an important part of 1.5°C pathways (Smith et al. 2015).

Table 4.1: Dimensions and characteristics for assessing the feasibility of a 1.5°C world and options that lead to this world.

Dimensions	Characteristics	Examples of empirical measures
Environmental and Geophysical	Geophysical	- Proportion of the change required - Rate of land use change
	Environmental	- Capacity of ecological systems - Limits of mitigation/adaptation in ecosystems - Risks of responsive options - Tipping points - reversibility of ecosystem change - Risks associated to irreversible changes
Technological and Economic	Technological	- How quickly different types of technologies can be implemented? - Are there technical resources available?
	Economic	- Required investment flows - Costs of response options - Financial mechanisms to enable transitions - Risks and unforeseen impacts - Differential effects of competitiveness - Benefits and trade-offs, e.g.: economic development, GDP, poverty alleviation, employment impacts
Social and Institutional	Social/cultural	- Behavioural responses (communities and private sector) - Equity, social inclusion and distributional impact - Inter-generational justice - Speed of changes in behaviour and lifestyles - Health benefits and risks - Public support for policy and changes
	Institutional	- Political support - Market structures, market failure and missing markets - Rate of institutional change - Interaction between multi-levels of governance

It is not the purpose of this chapter to apply a universal feasibility assessment or to select the projects or programmes that will ensure warming remains below 1.5°C. Rather, the literature assessment identifies important principles when accelerating change so as to remain below the 1.5°C threshold. The relative feasibility of different adaptation, mitigation and SRM options is contingent upon the availability of money, information, capacity and an enabling environment. As such, feasibility is likely to be location and context specific. However, decision-making can be improved, and rendered more accountable and defensible, by recognising principles of feasibility that tend to apply across contexts. Drawing on the literature, examples of these principles are described below.

Interventions on mitigation, adaptation and SRM are not discrete and feasibility can be enhanced by options that complement each other via feedback loops. Mutually enforcing responses to climate change can not only accelerate transitions, but also generate self-perpetuating change through systemic influences and cost reduction (Bergek et al. 2008; Hekkert et al. 2007; Geels et al. 2016b).

The feasibility of climate change responses is supported when adaptation and mitigation interventions deliver simultaneously non-climate benefits that can off-set the cost of mitigation and adaptation (Schaeffer et al. 2015b). There are many opportunities to align climate interventions with efforts that support livelihoods (Shaw et al. 2014; Ürge-Vorsatz et al. 2014), the economy (GCEC 2014), social progress (Steg et al. 2015a; Hallegatte and Mach 2016a; Ziervogel et al. 2016), and the local environment. These include improving air quality, reducing the impact of flooding and reducing the effects of heat stress. This is particularly true where interventions remove underlying causes of climate vulnerability such as poverty and the lack of services.

Interventions presenting benefits on multiple scales are most likely to enable the transformative change, especially when benefits are aligned through multi-level governance or are mutually enforcing via positive feedback loops (Peters et al. 2017; Hallegatte and Mach 2016a; Geels et al. 2016b).

Feasibility has a distinct temporal component. Clarity on the timing of interventions and benefits is not only critical to feasibility analysis, but also enables co-ordination and sequencing that itself can enhance feasibility. Attitudes towards the future, and associated accounting for the time-lags between the short-term cost of adaptation and mitigation efforts and longer-term benefits, tends to vary based on socio-economic status and risk aversion (Hof 2014; Resnick et al. 2012). Unless the influence of time, and different perceptions of the future is acknowledged and addressed it can lead to highly variable assessments of feasibility.

Recognising that the impact of atmospheric warming is mediated through complex local contexts introduces both new considerations for feasibility assessments and new possibilities for transformative change that are important for the fundamental and rapid change required to remain within the 1.5°C warming threshold (Ziervogel et al. 2016).

In the context of uncertainty, preventing lock-in, monitoring and adapting to technological innovation and other changes (Torvanger and Meadowcroft 2011) and creating the capacity to respond to a wide range of difficult to predict climate change contingencies, comprise important components of feasibility (Kowarsch et al. 2017; Kalra et al. 2014). The risk and uncertainty inherent in any rapid and systemic change process (Daron and Stainforth 2013) creates a premium for options that retain flexibility and reversibility (Hallegatte et al. 2012).

The systemic approach implicit in this characterisation of feasibility introduces analytical complexity to the need for prioritisation (Reyers et al. 2017). It is also however essential to create the potential in accelerating transitions (Sovacool 2016) and in reducing unforeseen consequences and is essential in avoiding the misallocation of scarce resources in the effort to limit warming to 1.5°C (Geels et al. 2016b). The means of assessing and monitoring highly interconnected systems is still evolving (Markusson et al. 2012; Kowarsch et al. 2017), but useful in anticipating crises, mobilizing pre-emptive responses (Battiston et al. 2017a) and identifying interventions that address 'root causes' (Pelling et al.). The importance of these elements to the transition to a 1.5°C world presents a case for their consideration in feasibility analyses. Whilst IAMs offer many analytical strengths, they do not completely capture the dynamics and scope of these elements of the required transition (Daron et al. 2015). The inference drawn from IAMs can be complemented by multi-criteria analyses that include the guidelines considerations.

4.3.2 Energy system transitions

This section discusses the feasibility, based on the empirical measures discussed in 4.3.1 and Chapter 1, for 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 the IPCC Fifth Assessment Report are discussed. This means that for options like nuclear energy (the capacity additions of which continue to fluctuate (IEA 2017)), hydropower and biomass, we refer to AR5 for an assessment of their feasibility. Demand-side options in the energy sector, including energy efficiency in buildings, transportation and industry, are discussed in Section 4.3.4.

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 according to the IEA (2017), only solar energy and onshore wind energy are on track to reach a 2°C pathway. Ocean energy, hydropower, concentrated solar power, bio-energy, offshore wind and geothermal energy would all need to show faster growth rates. This applies even more strongly to a 1.5°C scenario.

The largest growth factor since AR5 has been the dramatic reduction in the cost of solar PV to 0,41 USD Wp^{-1} (REN21 2017), leading to costs of rooftop solar in combination with battery storage to be almost competitive in sunny areas such as Australia (Green and Newman 2017b). 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 energy independence, allowing them to bypass the need for a transmission network and therefore remove the associated costs of installing and maintaining a network (Nature 2004). Strategies for small-scale distributed energy projects are now being implemented around the world (Aguiar 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 make renewable energy options increasingly attractive also in areas where one would not expect it; e.g. solar energy in north-western Europe. Another important factor is public acceptance, in particular for wind energy, though research indicates that financial participation and serious community engagement can be effective in mitigating resistance.

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, also excluding biomass, is possible (Jacobson et al. 2015) or not (Heard et al. 2017; Clack 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. 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 by e.g. 2035 (Denmark).

4.3.2.2 Electricity storage

Most current electricity storage is done by pumped hydro (150 GW), but grid-connected battery storage is growing fast; by 50% between 2015 to 2016 to 1,7 GW (REN21 2017). Battery storage has been the main growth feature in energy storage since AR5. The cost of battery storage has decreased significantly.

Although costs and technical maturity look increasingly positive, the feasibility of battery storage may be negatively affected by the availability of resources and the environmental impacts of its production (Peters et al. 2017). The production of lithium, a crustal element, does not appear to be restricted and large increases in production have happened in recent years (Government of Western Australia 2016). One study suggests that the environmental impacts of the combination of solar PV with hydrogen fuel cells as energy storage would result in lower life-cycle greenhouse gas emissions (Belmonte et al. 2016).

4.3.2.3 Carbon dioxide capture and storage in the power sector

The IPCC Special Report on CCS (IPCC 2005)and the IPCC Working Group III Fifth Assessment Report (IPCC 2014) assign great potential for mitigation 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 4.3.4; for a discussion of bio-energy with CCS (BECCS), see 4.3.6). CCS in the power sector has seen significant developments over the past years. The technological maturity of CO_2 capture options in the power sectors has improved considerably (Abanades et al. 2015), but costs have risen over the past ten years (Rubin et al. 2015). Storage capacity estimates vary greatly, but there is high agreement that on the order of thousands, perhaps ten thousand, $GtCO_2$ could be stored in underground reservoirs, of which about one thousand in well-characterised oil and gas reservoirs, and the vast majority in saline formations, which are generally poorly characterised (Coninck and Benson 2014). Insights on communication of CCS projects to the general public and inhabitants of the area around the CO_2 storage sites (in order to prevent public resistance and increase social acceptance) have been documented over the years, but not all decision-makers have taken notice (Ashworth et al. 2015).

CCS in the power sector is not being realised at scale, mainly because the incremental costs are not compensated by incentives (IEA 2017). One full-scale demonstration project in the power sector has come online over the past years, whereby part of the capture costs were compensated with revenues from Enhanced Oil Recovery (Global CCS Institute 2015), a technique that uses CO_2 to mobilise more oil out of depleting oil fields. In addition, several planned CCS projects have been cancelled over the years, mainly because of economic reasons (Global CCS Institute, 2017). Coninck and Benson (2014)indicate that political leaders, communities and investors are key actors to provide climate change action, robust policy support, favourable costs and market conditions, storage security and ensuing community support in order to make CCS feasible.

4.3.2.4 International transport options

International (or intercontinental) transport is notoriously difficult to decarbonize (Sims et al. 2014). Aviation emissions could be reduced by about a third by energy efficiency measures (Dahlmann et al. 2016), and on shorter distances be replaced by low-carbon electricity-based high-speed trains. 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 can be considerable (Budsberg et al. 2016; Cox et al. 2014), depending on their location (Elshout et al. 2014).

[International shipping yet to be included]

4.3.2.5 Options for adapting electricity systems to 1.5°C

For hydroelectric plants, one of the main concerns is the decrease in reservoir reliability (Jahandideh-Tehrani et al. 2014; Goytia et al. 2016; Minville et al. 2009). Hybrid renewable-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 (Jahandideh-Tehrani et al. 2014; van Vliet et al. 2016; Bartos and Chester 2015; Kraucunas et al. 2015), if climate change adaptation options are not considered, both to secure vulnerable infrastructure and to ensure the necessary generation capacity (Eisenack and Stecker 2012; Schaeffer et al. 2012; Cortekar and Groth 2015; Murrant et al. 2015; Goytia et al. 2016; Panteli and Mancarella 2015; Minville et al. 2009). 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 (Almeida Prado et al. 2016) are in place.

Water scarcity patterns and electricity disruptions will differ across regions. There is high agreement that mitigation and adaptation options for thermoelectric 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 are insufficient to limit temperature rise to 1.5°C.

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 (Eisenack and Stecker 2012; van Vliet et al. 2016; Murrant et al. 2015; Bartos and Chester 2015; Bustamante et al. 2016; Chandel et al. 2011). 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), and other thermal generation sources (Fricko et al. 2016; Doll et al. 2012; Kyle et al. 2013; Tidwell et al. 2014).

It is expected that more options for water management and other combinations of mitigation and adaptation challenges will be developed in the coming years 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).

4.3.3 Land and ecosystem transitions

Land-use transitions are driven by agriculture, deforestation, and urbanisation. Agriculture is currently responsible for more than one-fourth of anthropogenic GHG emissions (Smith et al. 2014a). There is broad agreement in the literature that mitigating emissions from agriculture has limits, as it will require a concurrent shift in farming practices and food systems in order to simultaneously meet food security needs for a growing global population (Bennetzen et al. 2016a,b). Deforestation has increased substantially in the post-industrial era, driven by food production imperatives and growing demand for renewable and non-renewable natural resources (Nakicenovic et al. 2000). Recent global trends show a convergence of institutional arrangements, including improved protection and effective monitoring, have led to a deceleration and stabilisation in deforestation in many regions, most notably in the Brazilian Amazon which has seen an 80% reduction in deforestation (Aguiar et al. 2016). Studies indicate two tipping points that should not be transgressed: 4°C warming or 40% deforestation (Nobre et al. 2016). This section examines possible adaptation and mitigation options related to land-use and ecosystem transitions that could play a role in the transition to a 1.5°C world.

4.3.3.1 Agriculture and food

Recent 1.5°C -specific scenarios depict a mixed picture for agriculture. While certain high-latitude regions may benefit, local yields in tropical regions like West Africa, South-East Asia, and Central and northern South America, which are main food growing regions of the world and support a high number of vulnerable populations, are projected to reduce substantially (Schleussner et al. 2016).

The way people produce, process and transport food drives greenhouse gas emissions and is also affected by elevated atmospheric greenhouse gases and higher temperatures. The humanitarian imperative of enhancing global access to sufficient food holds the potential to undermine or contribute to mitigation and adaptation pathways required for a 1.5°C world (Belz 2004).

Increased temperatures, even up to 1.5°C, will affect production of key cereals such as wheat and rice, thus impacting food security (Schleussner et al. 2016), and elevated CO_2 concentration is also expected to change the composition of food (DaMatta et al. 2010). For example, wheat and sorghum grown under elevated CO_2 differ in protein content and composition (Högy et al. 2009; De Souza et al. 2015).

Meta-analyses of experiments studying effects of elevated CO_2, high temperature, and drought conclude that at 2°C local warming, wheat, maize, and rice will see decreased yield, but this could be reduced if adaptation measures are taken (Challinor et al. 2014). As a central principle, climate resilient development pathways, whether socio-economic, socio-technical or socio-ecological, leading to a 1.5°C world need to ensure access to sufficient food of sufficient quality (see also Chapter 5). Three adaptation options can help lead us on this path.

Behavioural shifts towards conservation agriculture refer to small changes in agricultural practices such as changing crop varieties, shifting planting times, and irrigation and residue management to increase wheat and maize yields by 7-12% (Challinor et al. 2014). There is growing empirical evidence that such shifts in farming practices could be a key adaptation strategy (although the efficacy is still debated in the literature) while other analyses show that dietary shift directed to low-impact foods along with increases agriculture efficiency offer more environmental benefits than transforming conventional agricultural into organic agriculture or grass-fed beef (Clark and Tilman 2017). For example, conservation agriculture has been identified as an effective adaptation strategy across regions as varied as southern Africa (Thierfelder et al. 2017), India (Pradhan et al. 2017) and southern Spain (Varela-Ortega et al. 2016). 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). It demonstrated that alone, no-till practices tend to reduce yields. However, when combined with other two conservation agriculture principles (residue retention and crop rotation), crop productivity in rain fed dry conditions increase significantly, suggesting that it may become an important climate-change adaptation strategy in regions projected to face drying in a 1.5°C world.

Efficiency increases will be a key agricultural adaptation option to climate change. The application of computational tools in precision agriculture for example, could avoid waste and increase productivity, helping to cope with the decrease forecasted in production.

There is high agreement that improved climate services can play a critical role in aiding adaptation decision-making (Singh et al. 2017; Wood et al. 2014; Trenberth et al. 2016; Lourenço et al. 2015). However, empirical evidence suggests that there remain several technical, institutional, design-related, financial and capacity barriers to applying climate information for better adaptation decision-making (White et al. 2017; Jones et al. 2016b; Singh et al. 2017; Briley et al. 2015) and to scaling up current successes (Singh et al. 2016b).

A growing number of programs aimed at using climate services for better decisions are showing signs of success: from various actors, at various scales, and using different forms of information delivery and uptake. These involve participatory analysis of seasonal forecasts in East Africa (Dorward et al. 2015), NGO-driven weather advisories in India (Lobo et al. 2017) and innovations in government-led agriculture extension in various countries across sub-Saharan Africa and South Asia (Singh et al. 2016b).

Extreme event forecasts are transferring crop cultures to regions where lower impacts are expected, There is information available about: (1) the most likely regions for extreme events associated with 2°C (Nakicenovic et al. 2000) and (2) how different varieties of food, fibre and bioenergy crops can be adapted to different climates (Challinor et al. 2014). These two data sets could be combined so that the costs of transference could be calculated more precisely.

Improved technology, such as new molecular biology tools, have been developed and can lead to fast and precise genome modification (e.g. CRISPR Cas 9, De Souza et al. 2016; Scheben et al. 2016). Such genome editing tools can assist in adaptation of agriculture to climate change. For example, considering that meta-analyses studying effects of elevated CO_2, high temperature, and drought concluded that at 2°C local warming, wheat, maize, and rice would see decreased yield, though this could be reduced if adaptation measures are taken (Challinor et al. 2014). Adjustments in plant metabolism could be enabled to avoid changes in food quality (e.g. decrease in proteins). Photosynthesis could be modified to improve plant growth and tolerance to drought, (De Souza et al., 2016). However, biosafety concerns and government regulatory systems are likely to be a major barrier to the use of these tools as this increases the time and cost of turning scientific discoveries into ready applicable technologies (Maghari and Ardekani 2011).

There is abundant knowledge on how some key crops used for food, feed and bioenergy, and livestock, might respond to climate change (elevation of temperature combined with elevation of CO_2 and, drought or flooding). Thus, developing new varieties with higher tolerance can minimize adverse impacts during the transition to overshoot pathways to 1.5°C. Some synergy can be expected from the use of technologies to increase efficiency (precision agriculture) and the use of genetics and plant transformation. Together, they should be able to increase productivity to a high level compared to today´s status, helping to produce enough food to cope with population increase and decreasing 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 is attributed to forests. Tropical forests are thought to be particularly important in climate dynamics because of their strong evaporative cooling potential, as compared to temperate and boreal forests with moderate and low potentials, respectively (Bonan 2008). However, the carbon sink of the Amazon is thought to be decreasing slowly due to the combination of increasing mortality with a levelling off in productivity. Although some action has been taken (Aguiar et al. 2016), the Amazonian tropical forests are also disappearing due to direct human action, especially deforestation for agricultural land.

Land not only provides a source and potential sink of CO_2 but is also central to adaptation, for example, in coastal zones (Schleussner et al. 2016) and through agriculture and forestry. Furthermore, a considerable proportion of carbon is stored in soils, peatlands, wetlands and permafrost. This means that land use is important to the prospects of stabilising temperature increase at 1.5°C (Davidson et al. 2006) Options such as afforestation and bio-energy and carbon capture systems (BECCS) need to be carefully analysed with respect to the potential competition for land in achieving the goal of food security for all, safeguarding terrestrial ecosystems (Haberl 2015; Williamson 2016), and the labile nature of carbon sequestrated in plants and soil at higher temperatures (Ågren 2000; Davidson et al. 2006; Wang et al. 2013).

Other complementary approaches such as biochar, soil carbon sequestration and enhanced weathering (see Section 3.2.2) are land-based but do not directly compete with food production and could have substantial co-benefits in terms of raising crop yields (Smith et al. 2014a).

AR5 focused on 2°C stabilization pathways at the lower end of the considered spectrum and found a LULUCF mitigation potential of up to 10.60 $GtCO_2$eq/year in 2030. For mitigation efforts, this was consistent with carbon prices up to 100 USD/tCO_2-equivalent. This included both supply and demand side measures, with the main sources of emissions addressed being deforestation and agricultural emissions from livestock, soil and nutrient management. Demand side measures (e.g. waste reduction, diet shifts) was flagged as under-researched (Smith et al. 2014a). In 1.5°C pathways emissions reductions from the AFOLU sector range from *[xx%-yy%]* depending on the underlying assumptions about population, economic growth and technical change.

The potential for sequestering atmospheric CO_2 in processes that simultaneously restore large swathes of 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 to forest and crop interventions. In the tropics, a technology for Atlantic forest restoration has been developed

(Rodrigues et al. 2009) and its coupling with bioenergy production has been modelled (Buckeridge et al. 2012). These authors concluded if the best genetic technologies for crop improvement, leading to requirement of less land for the same level of production, could be combined with forest regeneration, the high potential of associating both activities could be realised, since forests store 18 times more carbon than sugarcane crops.

Innovations in livestock management, the use of fire regimes in savannah and rangeland ecology offer the potential to remove the assumed trade-off between soil carbon restoration and stocking densities (overgrazing) and 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).

Several adaptation options are currently used in agriculture and associated sectors. Community-based natural resource management (CBNRM) has been highlighted as a potential adaptation strategy (Fernández-Giménez et al. 2015; Fook 2015). Integrated watershed management is one such CBNRM option and it has moved from being restricted to soil and water management to include actions related to maintaining ecosystem services, strengthening and diversifying livelihoods, and meeting food security needs (Zanzanaini et al. 2017; Singh 2017).

However, cases from India demonstrate that, though such initiatives have become more participatory and holistic in nature, they focus disproportionately on building hard adaptation options (check dams, earthen bunds) with lower emphasis on soft options such as behavioural shifts towards reducing water demand (Bharucha et al. 2014; Singh 2017). Moreover, there is high agreement in the literature from Asia that integrated watershed management as it is currently implemented, will need to strengthen institutional mechanisms that do not incentivize exploitative behaviour (Bharucha et al. 2014; Kale 2015; Chaudhari and Mishra 2015), expand its current mandate to emphasize demand management instead of supply augmentation (Bharucha et al. 2014; Singh 2017), and ensure growing irrigation and domestic water needs are met without depleting water supply or causing increased damage to the watershed and the biodiversity and social and economic sources it supports (Gray and Srinidhi 2013; Bharucha et al. 2014). It is also critical to enhance monitoring and evaluation systems in watershed management to move away from numerical assessments of 'hectares of land treated or women in self help groups' to a more complex adaptive systems approach that focuses on forward-looking, flexible, iterative decision-making and evaluation.

Agroforestry designed to couple forest recovery with agriculture is an option providing higher carbon sequestration through growing forests and the agricultural products need for human communities (Ray et al. 2015; Buckeridge et al. 2012).

While it is established that ecosystem restoration is essential, policy-related complexities needed to do this consistently and at scale, present significant planning and management challenges. In many cases, biomes cut across different countries (e.g., Amazon). This will require the development of transnational governance structures and adequate finance to deal with recovery and conservation of very large bio-regions.

Reducing emissions from deforestation, forest degradation, and other forest related activities, known as REDD+, has been a strategy for over two decades. Although REDD+ was designed primarily as a mitigation strategy, its multiple co-benefits have made REDD+ a strategy that also benefits local communities, biodiversity and sustainable landscapes (Turnhout et al. 2017). In some cases, these co-benefits have been the key to the success of projects, beyond carbon pricing (Turnhout et al. 2017; Ngendakumana et al. 2017), as REDD+ projects have been implemented with the joint goal of working with local communities to improve their livelihoods and their sustainable use of natural resources (Dunlop and Corbera 2016). The institutional financial architecture of REDD+ will require strengthened coordination, additional funding sources, and access and disbursement points, especially in order to meet the commitments of the Paris Agreement (Well and Carrapatoso 2016).

Besides financing, REDD+ have faced other challenges, including a lack of coherence with local forestry policies (Ngendakumana et al. 2017), limited involvement of local populations and stakeholder centred consultation processes (Bastakoti and Davidsen 2016), focus on the local rather than the structural causes of deforestation (Ingalls and Dwyer 2016), legal problems related to property rights (especially benefits over avoided or reduced emissions) (Skutsch et al. 2017), top-down distribution of funding and benefits from the project (Skutsch et al. 2017; Chomba et al. 2016), and diverging perceptions of equity and 'willingness to participate' among stakeholders (Pasgaard et al. 2016).

Most of these challenges depend on local context, policies and perceptions (Skutsch et al. 2017; Pasgaard et al. 2016; Chomba et al. 2016; Ingalls and Dwyer 2016) and, as such, are best addressed at the local level to unlock the enormous potential that REDD+ has in achieving a 1.5°C goal.

4.3.3.3 Urban green cover

Urban green spaces provide ecosystem services and associated benefits such as pollination, water retention and infiltration and, in some cases, sustainable food production (Green et al., 2016). They constitute a form of Ecosystem-based Adaptation (EbA) and share five linked components: ecological structures, ecological functions, adaptation benefits, valuation, and ecosystem management practices Brink et al. (2016). Amongst the benefits are flood control, reduction of urban heat island, pollination of numerous areas, and the improvement in health and wellbeing of urban dwellers (Jennings et al. 2016; Lin et al. 2017; Sanesi et al. 2017).

Wellbeing is improved by passive and active means; passive related to the vegetation availability, whilst active relates to the time spent in green areas (Lin et al. 2017). Although active means will bring greater benefits, dense urban areas around the world tend to have smaller green area with less vegetation, meaning that dwellers will benefit more from passive means (Lin et al. 2017). However, vacant lots and other abandoned or degraded areas are being repurposed for green spaces in many cities (Green et al. 2016). Milan in Italy has developed new policies, including the creation of an Urban Forest inventory in response to the 10,000 hectares of new forest and green areas created over the last two decades (Sanesi et al. 2017).

The growth of urban green spaces can lead to the concern over their governance, as they operate as small-scale nodes that form part of a larger array of parks and ecological reserves (Green et al. 2016). Due to the dynamics of cities and green spaces, adaptive governance has been suggested (Green et al. 2016). With the expected growth of urban green areas, issues of equity, stakeholder participation, normative and ethical considerations need to be accounted for. Future scenarios and the creation of new ecological structures need to be thought of (Brink et al. 2016) and the evolving and growing use of 'big-data' can help create a better understanding of the connections between these environmental services and health (Jennings et al. 2016) and of urban green area dynamics and improve decision-making of natural resources management in urban development (Li et al. 2017).

4.3.3.4 Synergisms and the systemic approach

4.3.4 Urban, infrastructure and industrial transitions

IPCC AR5 emphasized that much of the key and emerging climate risks and responses are concentrated in cities and urban areas and the infrastructure and industries associated with those areas. Cities are complex inter-dependent systems that can be leveraged to support climate mitigation and adaptation action to deliver mitigation co-benefits, mainstreaming adaptation as a resource efficient strategy (Revi et al. 2014). The transportation and industrial economic activities happening in urban areas increase both welfare and greenhouse gas emissions. In urban areas, adaptation responses to 1.5°C will need to be integrated with the mitigation transition.

In the context of the 1.5°C challenge, growing literature recognises that any likelihood of achieving a world that stays within the 1.5°C temperature limit will be defined by four critical elements: what happens in cities and other urban centres in the next few decades will be the defining influence on whether or not dangerous climate change is avoided (Roberts 2016a; Satterthwaite and Bartlett 2016), local governments will emerge as the key mediators and drivers of achieving global ambition and local action (Satterthwaite and Bartlett 2016), a new type of city/urban science will be desirable that bridges disciplinary boundaries and practices a mix of approaches to create an evidence base for action (Solecki et al. 2013; McPhearson et al. 2016) and it will be critical that prospective solutions will need to be co-designed and co-produced at the interface of science and policy and these actions will often rely on the boundary roles played by local level champions (Leck and Roberts 2015). Most economic growth is now being driven by urban systems (Glaeser 2012) and there has been a growing awareness of the importance of urban systems as a critical part of the 1.5°C target.

4.3.4.1 Options for 1.5°C transitions in urban areas

The following sections outline the potential for both mitigation and adaptation action in urban areas.

4.3.4.1.1 Sustainable Land Use, Urban Planning & Design

There is strong evidence that indicates that a mix of land management options, such as compact development and infrastructure, focusing on increased accessibility (Berke et al. 2007; Ma and Banister 2006) and practicing mixed land use, create multiple co-benefits like better health outcomes (Su et al. 2016), improved environmental quality and human well-being (Panagopoulos et al. 2016; Stevenson et al. 2016), promotes diversity and vitality (Shi and Yang 2015) that help human and natural systems adapt to the changing climate (Puppim de Oliveira et al. 2013). Some of the key benefits emerging from such a mix of strategies are: improved productivity, efficient resource use and delivery, improved health impacts (Milner et al. 2012; Campbell-Lendrum and Corvalán 2007) and commute savings (Day and Cervero 2010). The biggest efficiencies in urban energy demand are emerging structural change in cities reflected in their urban form (Goodwin and Van Dender 2013; Wee 2015; Newman and Kenworthy 2011).

Urban transitions are linked to industrial transitions (Freeman and Perez 2000; Perez 2002, 2009b,a) and more specifically to transformation of transportation and energy systems (Geels et al. 2016b; Newman 2017). The current structure of cities across the world is very diverse, based on the level of development and established infrastructure, that range from pre-industrial walking cities prevalent in the 19th and early 20th century, transit cities based around trains and trams, to late-20th century automobile-based cities. These city forms were and are associated with different business models, economies and governance systems (Geels and Schot 2010; Hargroves and Smith 2005), with distinct urban fabrics that developed around such transport systems and the economies and governance systems are associated with them (Newman et al. 2016).

The issues now being studied are the options available to change urban form and fabrics in response to the 1.5°C challenge. This is particularly shaped by the transition to new smart technology systems that enable the energy and transport technologies to grow in a disruptive fashion (Adams and Mouatt 2010). There is evidence that knowledge economies using smart ICT systems in cities need the space efficiencies and rapid transit associated with walking and transit urban fabric. This is associated with significant urban regeneration and mass transit agendas (Newman and Kenworthy 2015; Gehl 2010). A range of studies have shown how oil-based greenhouse gas emissions associated with high-density, mixed-use walking city urban fabric are much lower than in a medium-density, partially mixed transit city urban fabric and these are much lower than low-density, highly zoned automobile urban fabric (Ewing et al. 2016; Newman et al. 2016).

4.3.4.1.2 Green infrastructure & Ecosystem services

There is evidence that approaches to urban mitigation and adaptation should be multi-level, multidimensional and multi-sectoral. Green infrastructure and ecosystem services such as biophilic urbanism are shown to reduce the need for energy and to cool the city during potentially damaging periods of hot weather as it reduces the urban heat island effect (UHIE) (Beatley 2011; Newman et al. 2017). Community-based adaptation (CBA) has proven to be successful, particularly in the context of enhancing local-level participation in framing adaptation planning for green infrastructure, with a wider transformative potential for urban governance (Archer et al. 2014). Ecosystem-based adaptation (EbA) has emerged as a potentially cost-efficient, comprehensive, and multifunctional approach, in addition to conventional, 'hard' adaptation measures (Brink et al. 2016).

4.3.4.1.3 Sustainable Water and Environmental services

Integrated and sustainable water resource management continues to be recognised as a promising instrument for exploring mitigation and adaptation to climate change (Xue et al. 2015; Poff et al. 2015). In many cities water is one of the most energy consumptive products. There are however significant barriers to sustainable water management that still exist within the sector, such as lack of human and institutional capacity, lack of financial resources, lack of awareness, lack of communication, inappropriate institutional structures and improper management; particularly those that impede 'participation of and collaboration between stakeholders' (Lemos 2015; Hill Clarvis and Engle 2015; Margerum and Robinson 2015; Bettini et al. 2015). Significant innovation will be required to strike a balance between sustainable water supply and demand (Deng and Zhao 2015).

4.3.4.1.4 Sustainable Urban Agriculture & Forestry

Developing countries need to meet growing demands for food, water and energy, which is further compounded by climate change. Effective adaptation to climate change would require efficient use of land (like zoning for agriculture as in McClintock et al. 2012), water, energy and other vital resources, and coordinated efforts to minimize trade-offs and maximize synergies (Angotti 2015; Biggs et al. 2015; Yang et al. 2016; Bell et al. 2015; Lwasa et al. 2015; Sanesi et al. 2017; Gwedla and Shackleton 2015). Evidence is emerging (Rasul and Sharma 2016) on using a nexus approach for the integrated management of urban agriculture and forestry systems (see 4.4.3 for further details).

4.3.4.1.5 The urban built environment

Improving the performance of buildings and housing in cities, in terms of thermal comfort, end-use service efficiency and embodied energy are significant means of decarbonizing urban systems. In cities in developing countries and emerging markets, the rapid pace of urbanization and new construction can imply considerable emission reduction, cost-efficiency and lower climate impact if these new buildings systems, end-use technologies and standards are put into place.

Climate change impacts the construction and housing sector in multiple ways: first, changing weather conditions leading to delays and increased construction costs *[ref]*; second, climate change and associated extreme weather need buildings systems and building materials to withstand an extended range of weather conditions; third, changed climatic conditions that may induce building failure *[ref]*; fourth, a changing pattern of extreme weather may imply a change in the demand for rebuilding and repair *[ref]* that will need a range of responses around building design, material selection and resilience *[ref]*.

Adaptation of the urban built environment in the face of a range of climate change impacts would require it to protect urban populations, the urban economy, critical assets and infrastructure. Stress has been laid on new emerging knowledge and innovative frameworks to adapt existing and new buildings, using a balance between structural and non-structural measures, with a focus on locations where housing quality is the poorest, climate risks are the greatest and economic and population exposure is the highest (UNISDR 2009, 2011, 2015). Adaptation in the housing sector is enabled by design, policy and implementation responses to extreme weather conditions and attention to access and safety and minimizing displacement. There is strong empirical evidence that poor quality housing erodes adaptive capacities in human systems (UNISDR 2009; UN-HABITAT 2011; Mitlin and Satterthwaite 2013).

4.3.4.1.6 Resilient Urban energy systems

The heavy dependence of the urban economy, infrastructure, services and residents on electricity and fossil fuels means far-reaching consequences, if supplies are unreliable or disrupted, as has been demonstrated in extreme events (UNISDR 2011; IPCC 2012). Urban energy sector adaptation has received limited attention *[ref]*. Key challenges include building redundancy into generation and distribution, negotiating policy and decision-making scales and building adaptive capacity through and around local action *[ref]*.

4.3.4.2 Sustainable and Resilient Transport systems

AR5 emphasized four key aspects of energy transitions in the transport sector (Sims et al. 2014). First, it recognized that reducing global transport GHG emissions will be challenging, owing to the projected growth in passenger and freight activity. Second, it identified key interventions that would enable decoupling of mobility and emissions in the transport sector. This included avoided journeys, modal shifts, uptake of improved vehicle and engine performance technologies, a shift to low-carbon fuels, investments in low-carbon and related infrastructure; and changes in the built environment and urban design that could alter urban form reducing travel needs, using strategies like mixed-use and transit-oriented development (IPCC 2014;Mittal et al. 2016; Li and Loo 2017; Zhang et al. 2016; IEA 2016)

There is evidence of decoupling car use and wealth since AR5, mostly in developed economies though some emerging cities are also showing this (Newman 2017). In rapidly growing cities, largely in developing and emerging economies, good opportunities exist for both structural and technological change around low-carbon transport. Yet, decoupling mobility and emissions faces critical barriers, which differ across regions: financial, institutional, cultural, and legal, particularly constraining wide deployment of low-carbon technology uptake and behavioural change (Bakker et al., 2017). Present urban form, infrastructure and urban design may facilitate or limit options for a modal shift (Geels 2014; Newman et al. 2016)

A recent study (Shi and Yang 2015) assesses the co-relation between socio-economic development, urban form and transport-sector development in China. It found a significant positive effect on per capita CO_2 emissions from transportation. The study recognized the need for planning controls, particularly around urban population density, the size of built-up areas and urban road density, to reduce the per capita CO_2 emissions from the transport sector. It also found public transport helped reduce per capita CO_2 emissions, establishing it as a key driver of altered urban GHG profile.

The major transport trend since AR5 has been towards the electrification of transport (IEA, 2016). Electric railways have been growing rapidly, especially in China, in both cities and between cities (Mittal et al. 2016; Li and Loo 2017; Zhang et al. 2016b; International Energy Agency (IEA) 2016). Electric rail policy was successful in reducing transport sector energy demand and emissions, with significant co-benefits for the oil-importing nations (Chaturvedi and Kim 2015).

Vehicle efficiency for conventional vehicles has been slowly increasing despite rebound effect of larger vehicle sizes, negating most of this improvement (Sivak and Schoettle 2016). Urban passenger vehicles have also shown a consistent growth in electric vehicles as shown in Figure 4.1.

Figure 4.1: Growth in Plug-in Electric Vehicles (PUV's) globally, 2015-16. Source: Carlin, Rader and Rucks, 2015
[Figure 4.1 to be included in the SOD]

Evidence (Mittal et al. 2016; van Vuuren et al. 2017) indicates substantial mitigation potential with electric passenger vehicles, if non-fossil energy resources are used for electricity and hydrogen production. But studies (Bauer et al. 2015; Nanaki and Koroneos 2016) caution against the associated environmental burdens across battery and fuel-electric vehicles, advocate the use of life cycle management in vehicle manufacturing chains as well as energy and transport policies, and emphasise urban planning and design interventions.

Biofuels may emerge as a viable mitigation option in some geographies. In Sao Paulo (Menezes et al. 2017), the highest potential for reducing GHG emissions is found to be via the use of biofuels, particularly ethanol, rather than through the use of public transport. This points to the need for a careful assessment of trade-offs (see also Box 4.3).

Fuel cells have been identified as a potential mitigation option, but concerns have been raised about their large-scale commercial application (Badwal et al. 2015) without adequate hydrogen storage and the almost

non-existence of hydrogen transportation and distribution infrastructure. Trade-offs with respect to biofuels would need consideration.
Decarbonising the transport sector will require a range of measures, particularly in its convergence with long-term climate change and sustainable development (Bakker et al. 2017). Policy co-ordination at multiple scales and of multiple types, including congestion pricing, public transport improvement, pricing strategies, and information and awareness campaigns have also been identified as key drivers of GHG mitigation effectiveness (Menezes et al. 2017). In a recent study (Regmi and Hanaoka 2011; Mittal et al. 2016), a mix of regionally differentiated low-carbon transport strategies were found to be important to India and China, including improving fuel economy, promoting a low-carbon fuel mix including low carbon electricity supply.

Four different transport adaptation strategies broadly define an integrated response framework for urban mobility: maintain and manage; strengthen and protect; enhance redundancy; and, where needed, relocate. Cities that have developed adaptation plans usually include attention to more resilient transport systems (UN-HABITAT 2011).

The biggest efficiencies in transport energy demand have been due to structural change in cities, reflected in the urban form associated with what is now known as 'peak car' (Goodwin and Van Dender 2013; Wee 2015; Newman and Kenworthy 2015). Although this was recognized in AR5 based on the first work by Puentes and Tomer (2008) and Schipper (2011), it was not clear how global the trends would develop. Geels and Schot (2010) explain the trend as a socio-technical innovation and Newman et al (2017) as a disruptive innovation based on demand to reduce travel time by living closer to destinations (a change in urban form) and demand for faster urban transport options (modal shift changes towards faster rail and bus options in mass transit). Global data on these trends are now apparent (Newman and Kenworthy 2015) and even show 'peak car' happening in Shanghai and Beijing (Gao and Kenworthy 2017).

Associated with peak car has been a shift towards walking and cycling in many cities (Gehl 2010; Newman et al. 2016; Pucher and Buehler 2016; Colville-Anderson 2016) . These have been closely associated with changes in infrastructure and amenity enabling these modes.

Transport trends in freight and air travel have not changed significantly and will probably need to be decarbonized by biofuels and renewable gas.

4.3.4.3 Industrial transitions - energy-intensive industry

For global temperatures to remain under 1.5°C, industry will need to fully implement drastic changes in three directions. First, use of bio-based feedstocks, electrification of production processes, and/or capture and storage of all CO_2 emissions by 2050 (Åhman et al. 2016). Second, 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). Third, an increase of the rate of recycling of materials and the development of a circular economy industry (Lewandowski 2016; Linder and Williander 2017).

Dimensions to facilitate deep decarbonisation in energy-intensive industries on the scale to achieve a 1.5°C target include addressing competitiveness, fairness, sustainable development, and technology transfer (Åhman et al. 2016). Both CO_2 capture and storage and bio-based feedstock processes face barriers in public acceptance (Ashworth et al. 2015) and costs (Rubin et al. 2015), but would leave the production process of materials relatively untouched. Electrification of manufacturing processes and material substitutions 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). 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, and environment.

4.3.4.4 Adaptation options in urban areas

4.3.4.4.1 Disaster risk reduction and resilience building

Building urban resilience to both climate change and extreme events, and enabling disaster risk reduction is an important strategy to enable the transition to a 1.5°C world (IPCC 2012; UNISDR 2009, 2011, 2015). It is now reasonably established that climate mitigation is crucial for defining the emergence of future risks and hence, defining adaptation potential (Satterthwaite and Bartlett 2016).

A recent critical debate has been around the potential of integrating climate adaptation, mitigation, disaster risk reduction and urban poverty across strategies at the city level (Revi et al. 2014). An extensive in-depth study (Satterthwaite and Bartlett 2016) examined the challenges of such an integration across multiple city types to enable successful urban adaptation. It recognized multiple barriers and enablers from: measuring socio-economic co-benefits to encourage and sustain local climate action (Durban), coherence between environmental and development concerns to lay a strong foundation for adaptation (Manizales, Rosario), fragmented governance and lack of institutional coherence that inhibits positive synergies (Bangalore) and active partnership of marginalized urban residents in the process of developing adaptation strategies (Uganda). Urban plans and actions in Manizales (and in Colombia more generally) look for coherence between disaster risk reduction and climate change adaptation and assume that capacity to adapt to future changes will increase if disaster risk and emergencies are handled well, enables by a supportive national government.

The long history of urban environmental innovation includes engaging communities and publicly monitoring environmental performance and has helped get attention to urban mitigation and to the idea of a lower carbon future. The coherence between environmental and development concerns, along with a history of disaster preparedness, has laid a durable foundation for adaptation (Satterthwaite and Bartlett 2016).

Building of local capacity and innovative institutional structures are effective measures to enable urban climate resilience (Dodman et al. 2016; Archer et al. 2017). The most meaningful outcomes emerged through interventions that emphasized knowledge, networks, information, and greater engagement of citizens with the state. This emphasis on the capacity to learn and reorganize provides a counterpoint to ideas around ‘implementation’ and ‘mainstreaming’ normally promoted within climate change adaptation practice (Reed et al. 2015).

There is enough evidence that significant overlaps between the agendas of climate adaptation, disaster risk reduction and urban poverty (Mitlin and Satterthwaite 2013; Satterthwaite and Bartlett 2016); which is critical to address sustainable development, but equally important to improve adaptation effectiveness.

4.3.4.4.2 Migration

4.3.5 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 a number of hydrofluorocarbons (HFCs) (Schmale et al. 2014). SLCFs thus can be gases as well as aerosols, and are defined as substances that remain in the atmosphere for between a couple of days and roughly a decade. SLCFs also include emissions that lead to cooling, such as sulphur and nitrogen dioxide, organic carbon and ammonia. Here, we focus on the primary warming agents, black carbon, HFCs and methane, often referred to as short-lived climate pollutants (SLCPs).

Box 1.2 provides a discussion of the emission metrics around SLCPs and their long-lived counterparts. Modelling indicates that implementing full SLCP mitigation would delay crossing the 2°C threshold in an RCP 4.5 scenario by 68 years, in an RCP 6 scenario by 17 years and in RCP 8.5 by nine years

(Pierrehumbert 2014) and could increase the CO_2 budget for a >66% chance of staying below 2°C by 25% compared to a case without dedicated SLCP mitigation (Rogelj et al. 2015). We note that BC is rarely emitted alone, and so mitigation strategies target BC-rich sectors and consider the impacts of all co-emitted SLCFs.

The AR5 concluded that SLCPs have comparable contributions to CO_2 for short-term time horizons and that the atmospheric lifetimes of SLCPs are better matched with the political lifetime of decision-makers than those of long-lived GHG, thus potentially resolving intergenerational barriers to interventions to reduce the emission of SLCPs.

Table 4.2: Overview of main characteristics of SLCPs (based on Pierrehumbert (2014) and Schmale et al. (2014)

SLCP compound	Atmospheric lifetime	Annual global emission	Main anthropogenic emission sources	Options to reduce emissions consistent with 1.5°C
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	See Sections 4.3.2 and 4.3.3 managing manure from livestock; Intermittent irrigation of rice; Capture and usage of fugitive methane; Dietary change
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
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	See Section 4.3.4: Fewer and cleaner vehicles; Cleaner cook stoves, gas-based or electric cooking; Replacing brick and coke ovens; Solar lamps

Mitigating SLCPs leads to a cooler climate more quickly (because of the front-loaded warming effect; Myhre et al. (2013)) and more permanently as compared to scenarios where SLCPs are not reduced, but if CO_2 emissions are not reduced in parallel to SLCPs, rapidly accumulating warming due to CO_2 will overwhelm any SLCPs mitigation benefits over a time span of a couple of decades.

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, biomass burning and landfill (Schmale et al. 2014; Finn et al. 2015). As such, the options to reduce emissions of SLCPs are also many and varied. This was extensively discussed in various sections in AR5 (IPCC 2014b).

Reducing black carbon and co-emissions from vehicles has numerous co-benefits, in particular for health, avoiding premature deaths and increasing crop yields (Scovronick et al. 2015; Peng et al. 2016). A consequence of this is that interventions to reduce black carbon offer tangible local benefits, increasing the likelihood of local public support (Venkataraman et al. 2016; Eliasson 2014). 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 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. 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 to agricultural practices using deep-sowing and mulching technologies.
HFC emissions are currently small, but growing rapidly (Myhre et al. 2013). Mitigation options are to transition to climate-friendly alternatives, ideally in combination with improved energy efficiency so as to simultaneously reduce both CO_2 and co-emitted air pollutants as well (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; the majority of emission reductions can be done below 60 €/tCO_2eq, and the remainder below roughly double that number (Höglund-Isaksson et al. 2017). This indicates that economic feasibility is more limited.

Most very low-carbon emissions pathways include a transition away from use of coal and natural gas in the energy sector and oil in transportation, leading to a substantial overlap with SLCP mitigation strategies in such scenarios. However, SLCP reductions may be achieved later in such scenarios.

Reductions in SLCPs can also provide large benefits towards sustainable development. These have been well characterized in terms of improvements in air quality (e.g. Schmale et al. 2014) and crop yields (e.g. Shindell et al. 2012). Benefits would also be realized in terms of energy access, gender equality, and poverty eradication (e.g. Shindell et al. 2017). There is an information deficit, however, 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).

4.3.6 Carbon dioxide from the atmosphere and CO_2 capture, utilisation and storage

While there are some 2°C pathways that manage to achieve their emissions reductions targets without relying on negative emissions (Clarke et al. 2014; Rogelj et al. 2015), 1.5°C pathways typically feature removal of carbon dioxide from the atmosphere (CDR) to either limit overshoot or to bring emissions down again from a temporary overshoot.

Complementing the analysis of the pathways assessed in Chapter 2 (Section 2.2.2), this section provides a bottom-up assessment of the different CDR options already embedded in the pathways (bioenergy with carbon capture and storage, i.e. BECCS), direct air capture and storage (DACS) and afforestation & reforestation). Other options that have not yet been integrated in the assessment models, but could also contribute towards augmenting the mitigation potential, include enhanced (ocean and terrestrial) weathering, soil carbon sequestration (SCS), biochar, blue carbon, ocean iron fertilization, and other greenhouse gas removal (GGR) techniques (e.g. of methane). Exponential growth in the literature since the IPCC's last assessment cycle (Minx et al. 2017) demonstrates that the knowledge landscape has significantly expanded in recent years and needs to be assessed and synthesized to serve as input for the development of 1.5°C strategies.

Another strand of options assessed here concerns carbon capture, utilization and storage (CCUS). In the absence of carbon pricing, the argument is that regarding the captured CO_2 as a resource (e.g. for usage in greenhouses; to produce synfuels or enhanced oil recovery (EOR) can be an entry point for negative emissions, fostering learning and eventually upscaling, even though the technology does not *per se* lead to negative emissions.

4.3.6.1 Bioenergy with carbon capture and storage

There have been bottom-up assessments of BECCS components in previous IPCC reports (IPCC 2005; Smith et al. 2014) and different BECCS technologies have been incorporated into integrated assessment models (IAMs) for a long time (Clarke et al. 2014; Fuss et al. 2016). The 1.5°C pathways assessed in Chapter 2 remove about 5 (median, 1-16 full range) Gt CO_2 per year by mid-century and 15 (median, 3-32 full range) Gt CO_2 per year by 2100 through BECCS, which corresponds to 68 (median, 19-296 full range) and 175 (median, 54-404 full range) EJ per year of bioenergy for CCS, respectively. Note that bioenergy (Section 4.3) can play an even larger role when BECCS use is constrained, as biofuels are then needed at larger scale to decarbonize the transport sector.

There is now large agreement that bioenergy potentials in 2050 are restricted to 100 EJ per year (Creutzig et al. 2015; Slade et al. 2014), which is less than what is usually assumed to be available in the scenarios (Chapter 2). While bioenergy potentials depend very much on assumptions about future yields, the type of technology deployed, the land available for the cultivation of biomass and grazing intensity and diets (Klein et al. 2014), these restrictions appear to be mostly due to sustainability concerns, with respect to the requirements for land that would also be needed for food production for a growing population, to safeguard ecosystems and biodiversity and potential limitations with respect to other inputs such as water and nutrients (Williamson 2016; Haberl 2015; Smith et al. 2013).

Synthesizing bottom-up literature to perform an ex-post assessment of the implications of BECCS deployment consistent with the aim of limiting global warming to below 2°C, Smith et al. (2016) estimate a land use intensity of BECCS between 1–1.7 ha per ton of C-eq. per year when forest residues are used as feedstock, about 0.6 ha of C-eq. per year for agricultural residues, and 0.1–0.4 ha of C-eq. per year when purpose-grown energy crops are used. Putting this into perspective, the average amount of BECCS deployed in 2°C pathways would thus require an area of land amounting to 25–46% of arable plus permanent crop area in 2100. Other assumptions can, however, lead to a percentage of up to 80% (Monfreda et al. 2008).

There is low agreement on the exact land areas required for BECCS deployment, which is also reflected in the ranges across models (Chapter 2). Importantly, the area of land is not necessarily a good indicator for competition with food production or threats to ecosystems. On the contrary, requiring a large area of land for the same potential could indicate that low-productivity marginal land is used to avoid such potential conflicts (Schueler et al. 2016). It is thus important to complement global assessments with regional, geographically explicit bottom-up studies of biomass potentials to get more precise insights into the implications of large-scale biomass cultivation. Other implications are the energy that would on average be produced by the BECCS infrastructure in a 2°C pathway (170 EJ per year by 2100) and the water footprint (720 km^3 per year by 2100). Smith et al. (2016) find low agreement on global impacts on nutrients and albedo.

Combined 2050 bioenergy and CCS potentials are found to be of the order of magnitude of 10 Gt CO_2 per year (Kemper 2015), 18 Gt CO_2 per year (NAS 2015)and 20 Gt CO_2 per year (combined with ocean liming and DACS, Caldecott et al. 2015), which partially exceeds pre-AR5 estimates. As these potentials are not homogenously distributed across regions, pertinent knowledge gaps around distributional impacts and governance mechanisms need to be addressed more systematically in the future literature (Fuss 2017).

On the CCS side, large technological advances have been made over the last years (see Bui et al.) for an extensive assessment: there is now injection of CO_2 at rates exceeding 1 Mt CO_2 per year at individual sites with 14 currently operating industrial scale projects, including three injecting into saline aquifer systems (Global CCS Institute 2015). Coninck and Benson (2014) and (Bui et al.) provide an in-depth review of the latest CCS literature identifying a better characterisation and prediction of plume migration, lowering of uncertainty around and managing the risks of leakage, and evaluation of the global role of CO_2 storage in energy systems as the current cutting-edge research activities addressing knowledge gaps in the field. They furthermore find large agreement in the literature that pore space exceeds the amounts of CO_2 that are stored for climate change mitigation in below 2°C pathways by far. The capture rate ranges reported by the model inter-comparison presented in Koelbl et al. (2014) are 5–23 Gt CO_2 per year in 2050 and 8–50 Gt CO_2 per year in 2100. Recent assessments (Cook and Zakkour 2015) reconfirm this conclusion from previous assessments (e.g. Benson et al. 2012).

There is lower agreement on whether this storage capacity can also be exploited to achieve ambitious climate targets. For example, Scott et al. (2015) assess permanent (>100,000 years) storage potential for CO_2. While they also find that overall capacity is adequate to *technically* match current fossil fuel reserves, they emphasize that *rates of storage creation* cannot balance current and expected rates of fossil fuel extraction and CO_2 consequences. Coninck and Benson (2014) point out that not only the availability of storage capacity, but also the required infrastructure of the size of the oil industry poses an obstacle to the rapid upscaling.

This uncertainty about feasibility of timely upscaling is exacerbated by CCS being largely absent from the Nationally Determined Contributions (Spencer et al. 2015) and CCS deployment having lagged significantly behind roadmaps in line with a 2°C or even 1.5°C target (Peters et al. 2017; IEA 2016). Furthermore, economic incentives for ramping up a large BECCS infrastructure are weak in the absence of carbon pricing or other policies that could support an accelerated uptake of the technology. Smith et al. (2016) cite US$138 billion and $123 billion per year by 2050 as the average investment costs for a BECCS infrastructure compliant with keeping temperature increase below 2°C by 2100 for bio-electricity and biofuels respectively. However, BECCS unit costs vary widely in the literature, ranging between US$ 60–250 per ton of CO_2 according to Kemper (2015) and McLaren (2012). The latter further specify the range of US $70-250 per ton of CO_2 to apply to BECCS from combustion and co-firing and provide an estimate of only US $45 per ton of CO_2 for BECCS from ethanol fermentation. Kemper (2015) also discusses different policy instruments and gives an overview of negative emissions and CCS in different GHG accounting frameworks finding relatively little agreement in the literature on the appropriate policies for rapid upscaling of BECCS, but identifying important interactions across sectors (e.g. by affecting the wood price, incentive schemes targeted at the energy sector could then affect the pulp and paper industry).

Limited public acceptance is one barrier related to large-scale BECCS deployment. Indeed, BECCS is affected by this challenge on two fronts. First, CCS is problematic (Benson et al. 2012) as there is concern that it is a strategy in favour of prolonging the profitability of the fossil fuel industry (Shackley et al. 2009; Upham and Roberts 2011; Wallquist et al. 2012). Further factors lowering acceptance relate to safety and environmental issues (de Best-Waldhober et al. 2009; Ha-Duong et al. 2009; Reiner et al. 2006). On the other hand, bioenergy has come under scrutiny in the aftermath of the food price hikes in 2007 and 2008 with concerns relating to competition for resources like land and water (see above). Most importantly, the assumption that bioenergy can be carbon-neutral has been under special scrutiny. Studies raising concern over the carbon-neutrality assumption can inter alia be found in the literature on indirect land use change, site-specific barriers, and challenges of implementing at scale without impacts on the environment (Plevin et al. 2010; Fargione et al. 2008; Searchinger et al. 2009; Havlík et al. 2011; Popp et al. 2014). While policies have tried to account for indirect land use change by formulating sustainability criteria, for example in the European Union, these have been found to be insufficient (Frank et al. 2013).

4.3.6.2 *Direct air capture and storage*

Direct air capture from ambient air through chemical processes with subsequent storage of the CO_2 in geological formations is another option to remove CO_2 from the atmosphere. Alternatively, the captured CO_2 could be disposed of in carbonate minerals (Lackner et al. 1995). Compared to BECCS, DACS has the advantage of being independent of source and timing of point emissions, but can capture CO_2 independently of these factors and thus also offset emissions from aviation, for example. On the other hand, this is also the main challenge. While the maximum theoretical potential for DACS is probably only limited by the availability of safe and accessible storage, the concentration of CO_2 in ambient air is 100-300 times lower than at gas- or coal-fired power plants (Keith et al. 2016) and thus still requires about three times more energy than flue gas capture (Pritchard et al. 2015), for which the agreement in the literature appears to be relatively high, with the most extreme range given by NAS (2015) as two to ten times as much.

Newer studies therefore explore alternative techniques, which can help to reduce the parasitic load (van der Giesen et al. 2017). In their ex-post assessment of DAC energy requirements based on previous bottom-up technology studies (Socolow et al. 2011), Smith et al. (2016) estimate that energy consumption could be up to 45 GJ per ton C-eq. This translates into an average of 156 EJ per year by 2100 corresponding to an average 2°C pathway. Water requirements are estimated to average 10–300 km^3 per ton C-eq. per year. Nutrients and albedo would not be affected.

However, as Broehm et al. (2015) point out in their DAC review, the body of literature is extremely fragmented without a frame of reference or system of analysis for the different studies in the field, which makes assessment difficult. This fragmentation is also reflected in a large variety of cost estimates, which range from US$ 20 to US$ 1000 per ton of CO_2 (Goeppert et al. 2012; Sanz-Pérez et al. 2016). This includes both the range by Socolow (2011) of US$ 600–800 per ton of CO_2 and at the upper end the US$ 1000 per ton of CO_2 estimate by House et al. (2011). Many of the lower estimates come from commercialisation projects, cover different systems designs or only parts of the system (Ishimoto et al. 2017; National Academy of Sciences 2015; Lackner et al. 2012). For example, Holmes and Keith (2012) only consider capture costs and provide an estimate of US$ 60 per ton of CO_2. Mazzotti et al. (2013) also include regeneration and arrive at an estimated range of US$ 376-600 per ton of CO_2. We can thus establish that there is lower agreement in the literature at the lower end of the cost range assessed here, higher agreement for the higher cost estimates and strong support for the conclusion that DACS is significantly more expensive than conventional CCS (Bui et al.).

While the same barriers to implementation that apply for capture and storage combined with bioenergy apply to DACS in terms of public opposition to storage and lack of an incentive scheme, DACS obviously suffers less from concerns about competition for scarce land resources and negative side effects on ecosystems and biodiversity compared to BECCS, as it can be flexibly placed.

Current research and efforts by small-scale commercialization projects are focused on overcoming the lack of incentives by considering the captured CO_2 as a resource (see Section 4.3.6.7). Other priorities should include the incorporation of DACS into IAM scenarios alongside BECCS, which has so far only rarely been done (Chen and Tavoni 2013).

4.3.6.3 Afforestation and reforestation

The potential for mitigation in the forest sector was evaluated to be up to 9.5 Gt CO_2-eq per year in 2030 at a CO_2 price of US$ 50 per ton and up to 13.8 Gt CO_2eq per year at US$ 50 per ton of CO_2 in AR5 based on post-AR4 literature (Smith et al. 2014b). More than 60% of this potential is provided by forest management options and avoided deforestation, which do not lead to a removal of CO_2 from the atmosphere and are thus assessed in Section 4.3.3. The remainder of the forest mitigation potential can be attributed to afforestation, the share of which is relatively stable across escalating carbon prices, but differs by region: while reduced deforestation dominates the forestry mitigation potential in Latin America and Caribbean and Middle East and Africa, there is very little potential in the OECD-1990 and Economies in Transition (Eastern Europe and part of former Soviet Union), which on the other hand have higher potentials in forest management and afforestation with (non-OECD) Asia featuring a more even distribution (Smith et al. 2014b).

New literature since AR5 includes e.g. Houghton et al. (2015), note that afforestation is more challenging than avoiding deforestation and relying on natural regrowth because of higher costs per hectare, but they estimate that about 500 Mha could be available (low to medium agreement, see e.g. Dinerstein et al., 2014) for the re-establishment of forests on lands previously forested but not currently used productively. This would sequester at least 3.7 Gt CO_2 per year for decades. Smith et al. (2016) find that it is possible to reach the 12 Gt CO_2 that are on average removed in the 2°C pathways by 2100 with afforestation and reforestation. However, even though the unit costs are estimated to be low compared to other CDR options, US $18–29 per ton of CO_2-eq, realizing such large potentials comes at an even larger land and water footprint than BECCS – up to 970 Mha and 1000 km^3 of water per year, respectively. The nutrient impact would be at 16.8 kt N per year, while the energy requirement would be negligible.

Many caveats apply when comparing afforestation and reforestation to BECCS and DACS because the biogenic storage has typically much shorter permanence, as forest sinks saturate, a process which typically occurs on the scale of decades to centuries compared to the thousands of years of residence time of CO_2 stored in geological formations (Smith et al. 2016) and is subject to disturbances, for example to drought, forest fires and pests that can be exacerbated by climate change (Chapter 3). These issues require careful forest management also after the actual afforestation process and make afforestation and reforestation less effective as a CDR option over time. In the context of reaching the 1.5°C target, it also needs to be stressed that even though there is a lot of practical experience with afforestation and reforestation, which also does not involve ramping up large infrastructures like BECCS and DACS, the pace at which removal will be taking place will still be slow, as forests need to grow to their full potential. Further issues arise from the heterogeneous geographical distribution of afforestation and reforestation potentials, where CDR effectiveness of afforestation and reforestation is limited by its impact on the albedo in higher latitudes

(Jones et al. 2015; Bright et al. 2015), and the lack of governance structures and monitoring capacities to protect forests in the first place (Wehkamp et al. 2015), which is not considered when modelling baselines. Finally, even though forest mitigation options appear to be more accepted than options that involve geological storage, there is relatively low agreement in the literature whether avoiding deforestation and pursuing afforestation and reforestation necessarily have a positive impact on ecosystems and biodiversity, in particular (Phelps et al. 2012). Such co-benefits would need to be actively considered in the design of incentive schemes.

Moving from trade-offs to opportunities, current research is also focusing on exploiting synergies with other policy goals. For example, Röös et al. (2017) explore how much land would be spared by shifting to healthier diets in Western Europe, which could then be afforested, finding that the yearly carbon storage potential arising from spared agricultural land ranges from 90 to 700 Mt CO_2 in 2050. More research like this will be needed by countries seeking to ratchet up their climate change mitigation ambitions in the context of other policy goals.

4.3.6.4 Soil carbon sequestration and biochar

Mitigation through SCS has been included in AR5 AFOLU mitigation potentials and the option of biochar – both for replacing fossil fuels and for sequestering CO_2 - has been presented in AR5 as well (Smith et al. 2014b). However, the full potential to extract CO_2 from the atmosphere to meet ambitious temperature targets has not been assessed for these options. A bottom-up analysis such as that conducted in Smith et al. (2016) finds that 2.6-4.8 Gt CO_2 could be removed each year using either of the two options. The mitigation potential of biochar is, therefore, less than that assessed for BECCS, DACS and afforestation and reforestation, but could make a substantial contribution. For biochar, this range is less than previous estimates e.g. by Woolf et al. (2010) because earlier studies also consider the displacement of fossil fuels through biochar, which is not considered as carbon-negative here. In their review, McGlashan et al. (2012) quote a range of 5.5–9.5 Gt CO_2 per year by 2100 (Gaunt and Lehmann 2008). Caldecott et al. (2015) report a yearly sequestration potential of biochar of 2.2 Gt CO_2 by 2100, under the assumption that any additional biomass would be used for BECCS, and 1.3-3.9 Gt CO_2 for SCS, under the assumption of ongoing restoration. Despite the wide range, there is high agreement in the literature on the magnitude of these potentials, also considering pre-AR5 studies.

Total costs of exploiting the full biochar potential estimated by Smith (2016) would amount to US$ 130 billion, while SCS is cost-negative on average: it is estimated that much of the negative emissions could be delivered at negative cost (US$ -16.9 billion per year), and the rest at low (US$ 9.2 billion per year) cost, with an overall saving of US$ 7.7 billion per year. This is connected to the multiple co-benefits of SCS, for example 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 per year. Both options affect nutrients favourably, but the disadvantage of biochar is that it affects the albedo if applied at large scale: 14 Mha are needed for implementation at 2.6 Gt CO_2-eq. per year, which could reduce the albedo by up to 12% thus partially offsetting the mitigation benefit. Concerning land requirements, biochar would consume less than 3.67 ha per ton of CO_2 (Smith 2016). However, since SCS and biochar addition can be applied to all managed land without changing its current use, there are no problems with respect to competition for land. Still, not all land is suitable for SCS and biochar (Caldecott, B.; Lomax, G.; Workman 2015) and there is also a constraint for biochar in the maximum safe holding capacity of soils (Lenton 2010). The disadvantage of SCS is similar as for AR: saturation will eventually diminish its effect, thus also requiring subsequent management.

4.3.6.5 Ocean Alkalinisation (OA), marine and terrestrial Enhanced Weathering (EW)

Many recent assessments have highlighted the substantial uncertainty about the potential storage capacity, environmental impact, and cost of sequestration of inorganic carbon in the ocean (NAS 2015; IPCC 2014a). More recent literature (Renforth and Henderson 2017) provides a thorough review of the state-of-the-art knowledge on OA for large-scale carbon removal to fill this knowledge gap. Ocean alkalinity increases due to rock weathering, thereby naturally sequestering about half a billion tons of CO_2 each year. The idea behind OA is to enhance this natural process e.g. by accelerated weathering of limestone, enhanced weathering, electrochemical promoted weathering, ocean liming, potentially sequestering hundreds of billions of tons of carbon according to Renforth and Henderson (2017) at cost ranges like those of other CDR options. Hartmann et al. (2013) specifically examine enhanced weathering based on ground olivine applied to the ocean or land. The latter would not only help to sequester large amounts of carbon, but would have significant co-benefits amongst which higher agricultural productivity due to the fertilization effect and increased alkalinity of natural waters which decreases ocean acidification if performed at large scale. Taylor et al. (2016) use simulations and find that distributing pulverised silicate rocks throughout the tropics has the potential of sequestering hundreds of Gt of CO2 by 2100 with significant negative impacts on ocean acidification. Another important advantage is that – at smaller scales – it could be started relatively quickly and thus complement other CDR options without the downside of raising competition for land for other policy goals such as ensuring food security. Yet, exploiting more of the large potentials cited above would require an enormous upscaling of mining, transportation and monitoring that could imply prohibitive costs. In addition, terrestrial EW could also have negative side effects such as an increase in air-borne dust that could impair health (Hartmann et al. 2013). Finally, terrestrial EW potentials are concentrated in the tropics and so huge investments would be needed in less developed regions posing distributional and governance challenges. Smith et al. (2016) estimate more conservatively that between 0.7 and 3.7 Gt CO_2 per year could be sequestered by terrestrial EW, spreading ground olivine on 2-10 Mha of agricultural land and requiring 46 EJ of energy per year, mainly for the grinding of the minerals. The corresponding water use is 0.3-1.5 km^3 per year. These potentials compare to the NAS (2015) number of 2 Gt CO_2 per year for the US only at US$ 20-1,000 and are very dependent on the underlying assumptions about the applied technology (cf. (Renforth and Henderson 2017)).

4.3.6.6 Ocean Fertilization

Another option to remove CO_2 from the atmosphere involving the oceans is by adding iron or other nutrients to them, either from external sources or via enhanced ocean mixing. However, there is currently low confidence on the amount of carbon that could be removed from circulation on a long-term basis (Williamson et al. 2012). This is because so far, only small-scale field experiments and theoretical modelling have been conducted to assess this question, thereby also resulting in low confidence concerning the readiness of this technology to contribute substantially to rapid decarbonisation (e.g. (McLaren 2012), who also makes this point for mineralization techniques). There is broad agreement that OF as a negative emissions technique is likely to play a modest role in offsetting current or future climate forcing (Williamson et al. 2012). Williamson et al. (2012) also assess the literature on unintended impacts of large-scale OF, which represent considerable bottlenecks to its rapid and effective implementation: (a) an increase in upper ocean concentrations of a range of climate-relevant gases associated with phytoplankton growth; (b) potential impacts on subsurface waters and sediments into which the fertilized biomass sinks; (c) a decrease oxygen levels in the ocean interior; (d) unclear impact of an increased carbon flux on ecosystems at the sea floor; and (e) in spite of reduced ocean acidification in the upper ocean, an increased rate of acidification of ocean interior waters.

The implications of these findings are that impacts would need to be adequately monitored over large space and time-scales. Along with the fact that the greatest theoretical potential for the application of ocean fertilization is the Southern Ocean, this would pose grand challenges for governance, especially when considering the oceans as global commons. Williamson et al. (2012) therefore recommend international governance of further field-based research on ocean fertilization.

Previous assessments have nevertheless provided estimates for potentials. NAS (2015) bases its range of 1-4 Gt CO_2 per year (through ocean iron fertilization) at US$ 500 per ton of CO_2 on the work of Aumont and Bopp (2006) and Harrison (2013). McLaren (2012) considers fertilization with nitrogen (0.2-0.5 Gt CO_2 per year) and phosphate (0.5 Gt CO_2 per year), with the caveat of resource limitations. For ocean iron fertilization, he quotes a potential of up to 1 Gt CO_2 per year.

4.3.6.7 Carbon capture utilization & storage

Carbon dioxide has large potential as synthetic feedstock for chemical material because of its abundance, non-toxicity, and low cost. Among CO_2, the chemical utilization for producing Poly Propylene Carbonate (PPC) has been assessed to represent the best opportunity for rapid scale-up and commercialization (Qin et al. 2015). Other applications include carbon mineralization, Enhanced Oil Recovery (EOR), biodiesel and synfuel production and other chemical applications. These have varying potentials and limitations and more research and piloting are needed to demonstrate their large-scale viability (Cuéllar-Franca and Azapagic 2015). However, von der Assen et al. (2013) warn that most Life Cycle Analyses (LCA) suffer from at least one of the three following pitfalls shedding doubt on whether CCUS can really contribute much to achieving large-scale CDR: 1) utilized CO_2 might intuitively be considered as carbon-negative without actually being so; 2) accounting problems with respect to the allocation of emissions to the individual products and 3) negligence of CO_2 storage duration. There is now more critical research, lowering the confidence of CCUS as an entry point for negative emissions. In particular, MacDowell et al. (2017) voice serious concern about scale issues: comparing the scale and rate of CO_2 production to that of utilization allowing long-term sequestration, they assess it to be highly improbable the chemical conversion of CO_2 will contribute more than 1% to the mitigation needed to achieve the Paris goals. Even scaled-up EOR will account for 4–8% only according to their estimates. So while they agree that EOR may be an economic incentive for early CCS projects, CCU may prove to be a costly distraction from the real task of mitigation.

4.3.6.8 *Removal of non-CO_2 greenhouse gases*

Another recent strand of literature discusses the possibilities of not only removing CO_2 from the atmosphere, but to also consider the removal of non-CO_2 GHGs (GGR) such as methane. This is very relevant for the 1.5°C target, as the remaining carbon budget is already almost exhausted (see Chapters 1 and 2) and methane is a much more potent GHG than CO_2 (Montzka et al. 2011), which is associated with difficult-to-abate emissions in the food sector, but also outgassing from lakes, wetlands, and oceans (Stolaroff et al. 2012), two processes for which there are no quick solutions at sufficiently large scale in the next few years. Enhancing processes that naturally remove methane, either by chemical or biological decomposition (Sundqvist et al. 2012), has been proposed to lead to negative emissions. Boucher and Folberth (2010) review several existing technologies for methane removal (cryogenic separation, molecular sieves or gates, and adsorption filters based on zeolite minerals) and find low confidence that any of these are currently economically or energetically suitable for large-scale air capture. Further, their review highlights several co-benefits of methane removal: reduced tropospheric ozone production, decreased stratospheric forcing, energy recycling by exploiting the methane chemical energy, and a possible further reduction in atmospheric CO_2 (during the methane oxidation process). Still, they consider it only part of a larger negative emissions portfolio, mainly because of the very small concentration of methane in the atmosphere and its low chemical reactivity at ambient conditions, which would require more research. Current work (e.g. (de Richter et al. 2017)) examines other technologies that go beyond methane and also consider non-CO_2 GHGs like N_2O. More literature is needed, however, to arrive at more robust global GGR potentials.

4.3.6.9 Blue Carbon

There have been some publications hitherto left out from assessments that can be summarized under the label of, which refers to the carbon stored in sea grasses, mangroves, and salt marshes along coasts. Enhancing seagrass meadows has been suggested to remove CO_2 from the atmosphere. Macreadie et al. (2017) assess the literature for three different routes of BC and find that reducing nutrient inputs, avoiding unnaturally high levels of bioturbation, and restoring natural hydrology will maximize carbon sequestration and minimize carbon losses – with the latter featuring the highest confidence in the scientific literature. While there are no quantifications of what a global CDR potential from BC could look like, all three options are found to reduce human and environmental impacts on coastal ecosystems and the ecosystem benefits go beyond the pure benefit of carbon sequestration. Johannessen and Macdonald (2016) report the BC sink at 0.4-0.8% of global anthropogenic emissions and point out that protocols have been developed to quantify BC potentials to include BC credits into the Verified Carbon Standard. However, they warn that these do not adequately account for post-depositional processes and therefore significantly overestimate BC CDR. Seagrass beds will likely not contribute significantly to the meeting the 1.5°C target, according to the review by Johannessen and Macdonald (2016), even though they acknowledge that seagrass meadows provide valuable habitat, are disappearing rapidly and thus warrant intervention for other ecosystems services than carbon storage. There is thus general agreement in the literature that the main knowledge gap is to further investigate the contribution and costs of BC in reaching the 1.5°C target. Otherwise, overestimated carbon offsets could lead to a net increase in CO_2 emissions Johannessen and Macdonald (2016).

Finally, there are knowledge gaps affecting any technique removing CO_2 at large scale (Section 4.5.1) Jones et al. (2016a) show, for example, that on sufficiently long time scales, natural sinks could even reverse. However, much more research is needed to be able to make robust quantitative statements about this.

[Table (or figure) giving a systematic overview of potentials, costs, side effects, governance implications planned either here or in synthesis section]

4.3.7 Solar Radiation Management

Several recent papers have asserted that SRM could reduce some of the global risks of climate change related to temperature rise (Keith and Irvine 2016; Keith et al. 2016; Irvine et al. 2016; Izrael et al. 2014; Heutel et al. 2016; Lloyd and Oppenheimer 2014; Moreno-Cruz and Smulders 2017; Tilmes et al. 2016). However, SRM also presents a number of risks and concerns (Robock 2016; Visioni et al. 2016; Smith et al. 2017; Pitari et al. 2014; Suarez and van Aalst 2017; Svoboda 2017). If SRM is employed, it will have implications for geophysical characteristics (precipitation, cloudiness, ozone, etc.) that are key for livelihoods and economies.

Those impacts, as well as a full discussion of all SRM options currently proposed, and their implications for sustainable development, are discussed in Chapter 3 and in Box 4.13. In this section, we assess the feasibility, mainly from a governance, economic and ethical viewpoint, of two SRM options: stratospheric aerosols injection (SAI) and marine cloud brightening (MCB). Amongst the SRM options that have been proposed, SAI and MCB at the moment appear to be the technologies that could become most effective.

Although SRM is sometimes considered alongside CDR (see Section 4.3.6) under the header 'geoengineering', this report separates the two. This is because their technical characteristics, risks, governance and even their classification as a mitigation, adaptation or another category, are different. In this report, we consider CDR as mitigation. SRM is neither adaptation nor mitigation.

4.3.7.1 Governance and institutional feasibility

SRM governance and incentives differ from governance commonly proposed for climate change mitigation or adaptation (Sandler 2017; Ricke et al. 2013). If risks of negative effects and trade-offs are ignored, SAI and MCB may be relatively cheap compared to carbon emission reduction (Crutzen 2006). This makes unilateral deployment by one or several countries or even non-state actors possible (Lloyd and Oppenheimer 2014; Sandler 2017; Rabitz 2016; Weitzman 2015). Governance of field experimentation to help clarify the many uncertainties surrounding SRM is also needed (US National Academy of Sciences 2015; Long and Shepherd 2014; Lawrence and Crutzen 2017; Caldeira and Bala 2017).

In addition to global SRM, regional radiation management has potential since marine cloud brightening and thinning or dissolution of cirrus clouds could be operated at a local scale (Quaas et al. 2016). From a governance perspective, it is desirable to avoid any substantial climate effects of regional SRM outside the target region (Quaas et al. 2016).

Preventing unilateral action, so as to avoid international conflict, may be the most difficult SRM governance issue (Sandler 2017). 'Predatory geoengineering' may emerge if self-concerned actions to manage climate change through SRM result in harmful consequences to others (Suarez and van Aalst 2017). Any international governance instrument would have to reflect views of different countries, because it is likely that SRM implementation will create winners and losers (Izrael et al. 2014; Heyen et al. 2015; Robock

2016). Different countries view SRM differently (Harnisch et al. 2015; Huttunen et al. 2015) making the formulation of an international governance instrument for SRM difficult to formulate and follow (Sandler 2017).
Several possible institutional arrangements have been mentioned for governance in regards to SRM: through the United Nations, by a single state, or through a consortium of states (Sandler 2017; Bodansky 2013). Agreements through the United Nations can be very time consuming, governance by a single country is rapid, but the interests of the pivotal country are favoured, a third structure – coalition governance – involves a small number of countries that include those capable of SRM and those most affected by such modification (Sandler 2017).

4.3.7.2 Economics and cost

Cost estimates of SRM deployment (not taking into account indirect and social costs) are mostly focussed on stratospheric aerosols injection (SAI), and have varied over the years and between studies. Robock et al. (2009) and The Royal Society (2009) put the costs of injecting 1-5 megatons of sulphur per year into the stratosphere between $0.225-30 billion depending on the implementation method. McClellan et al. (2012) arrive at a cost range of $1-8 billion depending on the delivery system. Ryaboshapko and Revokatova (2015) estimate a capital cost of SAI implementation at $ 3.8 billion and annual cost at $ 3.2 billion. According to Moriyama et al. (2016), the annual cost of SAI to achieve cooling of 2 W m^{-2} (with injection of 10 Mt H_2S) could reach $10 billion. Authors also noted that it is important to recognize that costs could increase rapidly as cooling exceeds 2 W m^{-2}.

Only a single cost study exists for marine cloud brightening (Salter et al. 2008). According to this research, MCB need $32 million for more research and development. Once there is operational experience and MCB technology has matured, it would cost approximately $38 million annually.

However, the true economic cost of SRM must incorporate not just deployment expenses but also any externalities or a social cost in addition to just engineering costs (Mackerron 2014; Moreno-Cruz and Keith 2013). Recently economists began to delve deeper and discover the various risks, uncertainties, and problems with international politics of implementation (Harding and Moreno-Cruz 2016; Heutel et al. 2016).

Most of the studies examined benefits and costs of SRM by using integrated assessment models (Metcalf and Stock 2015; Heutel et al. 2016; Bickel and Agrawal 2013; Kosugi 2013; Manoussi and Xepapadeas 2015). Depending on the criteria used, SRM could be economically optimal or suboptimal (Sugiyama et al. 2017). Recent studies examined game-theoretic, strategic interactions of states under heterogeneous climatic impacts of SRM (Ricke et al. 2013; Weitzman 2015; Manoussi and Xepapadeas 2015; Moreno-Cruz 2015). Manoussi and Xepapadeas (2015) attribute asymmetries between countries to two main sources: differences in the impacts of climate change and SRM activities across countries, and differences in the prevailing economic conditions. When the asymmetry is in the cost of global warming to each country, the country with the lower costs substantially increases emissions and reduces SRM (Manoussi and Xepapadeas 2015).

A recent paper (Aaheim et al. 2015) addresses the economic impacts of implementing two SRM technologies: SAI and MCB. It was found that economic benefits of SRM under a moderate emission pathway (RCP4.5) can be questioned. In particular, under the set of assumed conditions and processes, the economic impacts of SRM are clearly positive for Sub-Saharan Africa, Latin America and Former Soviet Union, while East Asia would lose out. However, authors concluded that usage of RCP8.5 could change their results significantly (Aaheim et al. 2015).

There is no literature supporting the complete substitution of mitigation by SRM. This suggests that SRM would be used sparingly, which would decrease the potential side-effects, including the termination effect, and could address some of the societal issues (Sugiyama et al. 2017). Some studies indicate for how much forcing or temperature reduction goal they prefer to use SRM; for example Kosugi (2013) for 1 W/m^2 and Keith & MacMartin (2015) for half the temperature rise. A small amount of deployment could make economic sense (Keith and MacMartin 2015) assuming climate change remains gradual, and no run-away, tipping point climate impacts are happening – a risk that Crutzen (2006) warned could happen.

4.3.7.2.1 Social acceptability and ethics

SRM research and deployment is connected with variety of ethical issues (Preston 2013), and literature seems polarised (Linnér and Wibeck 2015). The so-called ‘moral hazard’, sometimes described as ‘mitigation obstruction’, asserts that SRM research (preceding SRM implementation) might lead policy-makers to reduce mitigation efforts (Klepper and Rickels 2014; Morrow 2014a; McLaren 2016; Lin 2013).

Klepper and Rickels (2014) indicate that any successful SRM application would significantly reduce the chances of ever reversing the impacts of anthropogenic interventions and reverting Earth back to its natural state. Reynolds (2015) argues that, so far, the consideration of SRM has meant that more mitigation is done, and that SRM may lead to mitigation because of income effects, if uncertainties about the impacts and risks of SRM are addressed. Some of these conclusions are supported by Moreno-Cruz (2015), who in a game-theoretic exercise finds that in asymmetric interests between countries (i.e., reality), the prospect of SRM may lead to inefficiently high levels of mitigation. Chen and Xin (2017) argue that the Paris Agreement means that SRM research must be done and propose guidance for China to engage in SRM (and CDR) research, as well to integrate natural and social sciences in SRM research. Preston (2013) discusses the ambiguity on the moral hazard and calls attention to ‘moral corruption’, basing himself on Gardiner (2010), who contests that considering SRM an alternative to mitigation is ‘culpable self-deception’ and shows ‘just how far we are prepared to go to avoid confronting climate change directly’ (Gardiner 2010 as quoted in Preston (2013)). Other ethical concerns include those of intergenerational equity, the rights of women and those concerned with the rights of non-human species (Burns 2010; Morrow 2014a; Buck et al. 2014).

To address ethical concerns for SRM researchers, frameworks have been proposed, including the Oxford principles (Rayner et al. 2013) and a ‘Draft Code of Conduct’ (Hubert and Reichwein 2015) for researchers in the field of SRM. An investigation into public perception of SRM research indicates that the perception of controllability is key to legitimacy and public acceptability of SRM experiments (Bellamy et al. 2017).

More ethical concerns are connected with maintenance of SRM. Even if SRM would be effective and morally permissible, and all distributive and compensatory issues associated with costs, risks, harms and benefits connected with implementation have been satisfactorily addressed, the normative questions related to maintenance of SRM would remain (Wong 2014). Other researchers argue that while it is technically possible for SRM to reduce unjust harms from climate change, its side-effects and unevenly distributed benefits and costs make it unlikely that any particular SRM policy would be both morally permissible and politically feasible (Morrow and Svoboda 2016). Compensation schemes for SRM could be constructed in order to addresses injustices, in instances where a party has experienced disproportionate harm (Lambini 2016; Svoboda and Irvine 2014).

A final issue of SRM is connected with concerns about who gets to participate in decisions about SRM. Illustrated by a case of coastal management by a large city that severely harmed a small coastal community, Suarez and van Aalst (2017) worry that voices of vulnerable populations will not be heard, and that insufficient weight is given to affected communities in decision-making around SRM. Whyte (2012) argues that the concerns, sovereignties, and experiences of indigenous peoples must be addressed in SRM governance.

Despite the growing literature on the concerns and considerations around SRM (Lawrence and Crutzen 2017), more research is needed to understand a morally permissible decision on whether, when, where, and how SRM might be done, to construct compensation system of SRM and to be able to take precautions against objectionable mitigation obstruction (McLaren 2016; Svoboda and Irvine 2014; Morrow 2014b).

4.4 Implementing far-reaching and rapid change

4.4.1 Enabling environments

The far-reaching and rapid change required to remain below 1.5°C and allow societies to cope with the associated climate changes will depend on circumstances that enable and cohere innovations in technology (Creutzig et al. 2015), buildings and infrastructure (most obviously in urban areas) (Rode et al. 2014; Roberts 2016b), finance (Campiglio 2016; Pauw 2017; Diaz-Rainey et al. 2017) and human behaviour (Steg 2016; Moloney et al. 2010).

An enabling environment is the product of these circumstances and describes the institutional context as the 'rules of the game' (North 1990) that incentivise and support change. This section describes in some detail the sustainable development (Section 4.4.2), governance (Section 4.4.3), institutional capacity (Section 4.4.4), behaviour and lifestyle (Section 4.4.5), innovation (Section 4.4.6), policy instruments (Section 4.4.7) and finance (Section 4.4.8) components that are key to implement the actions needed for the transition to a 1.5°C world.

While enabling environments show considerable variation across regions, sectors and contexts (Creutzig et al. 2015), there are also common features to contexts that are capable of rapid change. Recognising and establishing the preconditions of rapid and far reaching change forms an important part of efforts to limit warming and adapt effectively to a warmer world. Infrastructure, governance, information and finance are clearly important inputs to any innovation process, but the sections below draw on the literature to synthesise across these inputs and identify the dynamic features of an environment that will enable the transition to a 1.5°C world.

4.4.1.1 Dynamic features of enabling environments

Transformative change is seldom an insular or discrete pursuit. Aligning incentives, regulations and relationships at different spatial and temporal scales is critical to accelerated and substantive change (Daron et al. 2015; Ostrom 2009). We briefly discuss accountable governance, policy instrumentation, partnerships, inclusivity and education.

Accountable governance is a prerequisite for policies and programmes that will drive the transition to a 1.5°C world. Beyond this prosaic point, it is important that governments and corporations at various scales begin providing the information that will enable them to account for their progress against the 1.5°C threshold (James et al. 2017; Diaz-Rainey et al. 2017).

Guiding policies and policy instruments, of which carbon pricing is currently most discussed, can be applied at various scales, but ultimately requires a global consensus as part of an enabling environment. Pricing instruments are unlikely to succeed on their own (Campiglio et al. 2014), but stronger carbon pricing signals hold the potential to internalise the negative externality of greenhouse gas emissions and contribute to a useful reallocation of resources (Schaeffer et al. 2015a).

Partnerships, characterised by a shared vision and trust, between different spheres of government and between the public and private sector, enable collaboration, shared investment and a sharing of risks during ambitious innovation (Mazzucato and Semieniuk 2017; Geels et al. 2016b). For example, National Urban Policies that bring coherence to the business of nation states, cities and state-owned enterprises create the type of environment in which ambitious change can be undertaken. The example of Manizales below (Box 4.4.1.2) illustrates the importance of a national farming of the development-climate interface that empowers local individuals and action. Similarly, Shenzen's decarbonisation is enabled by local incentives and the national context. Important in the national context is China's swing in coal consumption from 3.7% growth in 2013 to 3.7% decline in 2015 (Hsu et al. 2017; BP Global 2016; Zhang 2010). The local context involves a New-type Urbanisation Plan that seeks to resolve difficult connections between ecological progress, urbanisation quality, expanding domestic demand and rural-urban coordination across scales (Cheshmehzangi 2016).

The Manizales example further suggests that enabling environments function better when they are inclusive. Aligned household, community and city interactions within the global policy regime can enable rapid innovation and change (Ziervogel et al. 2016; Blanchet 2015). Given the tenacity with which poor and vulnerable people hold onto their hard-won livelihoods, the ability to partner and enfranchise these communities in climate programmes is important in establishing the type of enabling environment that is also inclusive. Seen through this lens, informal settlements in the cities of the developing world that are characterised by rapid growth in consumption and population growth become important loci for climate action and the capacity to engage these settlements with governments programmes becomes critical (Freire et al. 2014).

Education does not explain all views on climate change. It does, however, support resilience and increase the efficacy of climate policies (Wamsler 2009). As such, education and female education, in particular, form a key component of an enabling environment for a 1.5°C world. There are strong two-way links between female education and climate risk. These links manifest through decisions on fertility, ability to access information and other resources, and the vulnerability to climate change that arises from multiple deprivation (Wamsler et al. 2012). Better educated communities are more enabled to adapt and take long-term decisions regarding their futures.

4.4.1.2 Systemic elements of enabling environments

Public awareness and support are important in creating pressure for socio-technological change (Blanchet 2015). The decoupling of emissions and economic growth in select economies (Newman 2017) is enabled by a growing social concern around climate change that generates incentives for policy and technological change (Geels et al. 2016b). It is, however, the alignment of public awareness, policy driven change, technological efficiencies and economic and finance factors that holds the greatest potential (Peters et al. 2017).

Systemic approaches that combine adaptation and mitigation can unlock synergies, avoid side-effects and accelerate change by mainstreaming and integrating climate policy (Locatelli et al. 2015), keeping in mind the differences between mainstreaming and integration (Abeygunawardena et al. 2003) (see Box 4.4). Switching generation sources in the energy sector, for example, can be strengthened by a consideration of the energy-water-food nexus (van Vliet et al. 2016; Rasul and Sharma 2016). Studies highlight the growing importance of geothermal energy sources, both to generate clean energy and as a cleaner source for desalination, especially in areas that are water constrained (Manju and Sagar 2017; Loutatidou and Arafat 2015; Chandrasekharam et al. 2015). Policies that recognise and deal with spill-over effects can form an important part of an enabling environment (Cosbey and Tarasofsky 2007; Higham et al. 2016; Åhman et al. 2016).

Bold political leadership and a clear vision, as is illustrated by Bhutan (see Box 4.1) can give direction to innovation efforts and accelerate the pace of change through appropriate regulation, the allocation of public money and associated mobilisation of investment (Roberts 2016b). Appropriate and targeted government spending can send a clear signal to investors, particularly when aligned to taxes (Mazzucato and Semieniuk 2017). Committing to the removal of perverse subsidies and to 'sun-rise' and 'sun-set' sectors industrial policies can assist the smooth reallocation of assets (Battiston et al. 2017b; Hallegatte et al. 2013).

Harnessing mega-trends can provide momentum. Enabling environments draw on, rather than resist, the global mega-trends such as ICT, financialisation and urbanisation, so as to harness and direct behaviour change trends. It is, for example, 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, given the scale of the urbanisation trend (Revi 2016), or without major reforms in the global financial system (Pauw 2017).

Knowledge partnerships and science-policy interactions provide the information, skill and technologies required for the challenging and complex transition to a 1.5°C world (Figueres et al. 2017; Roberts 2016b). An enabling environment for a 1.5°C world will not only encourage research that describes pathways to this world, but will align national commitments and economic policies with the science of how to remain within the 1.5°C warming threshold (Rockström et al. 2017).

A durable rights framework is a necessary, if insufficient, precondition for navigating the difficult trade-offs between interest groups and avoiding perverse outcomes in the context of rapid change (Ziervogel et al. 2016) and can enable inclusive and more durable change (Annecke and Swilling 2012).

Integrated climate and development planning. The ability to anticipate and prepare for extreme weather events can greatly enhance a community's ability to cope with climate risks, as can effective disaster relief efforts when these risks manifest. Effective enabling environments will combine weather forecasting and communication with programmes that alleviate the underlying causes of climate vulnerability, such as poverty (Pelling et al.) and inadequate access to employment, food, mobility, energy and housing (Hallegatte and Mach 2016b).

Box 4.1: Case Study: Bhutan - mutually enforcing economic growth, carbon neutrality and happiness

Bhutan has three national goals: Gross National Happiness index (GNH), economic growth (GDP) and carbon neutrality (NEC 2015). These goals clearly interact. Whether they can all be maintained into the future depends on the creation of a suitable enabling environment. This case study gives a cursory discussion of how Bhutan integrates and pursues 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 SDG's (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). Like most emerging countries, Bhutan wants to increase its wealth to become a middle-income country by 2020 (RGoB 2013, 2016) and aims to remain carbon-neutral, which was reiterated in its INDC (NEC 2015). Bhutan achieves its current carbon-neutral status though 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 *[ref]* 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 challenge involves electrifying the transport system. Plans are being developed to electrify both freight and passenger transport (ADB 2013). If this succeeds, Bhutan would be a model for achieving economic growth consistent with limiting climate change to 1.5°C and improving its Gross National Happiness. In this case it will point to the importance of an enabling macro-environment for balancing the difficult trade-offs involved in realising a national contribution to a 1.5°C world.

Box 4.2: Case study: Manizales, Colombia - Supportive national government and localised planning and integration as an enabling condition for managing climate and development risks

The case on the city of Manizales, Colombia assists in identifying 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; 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. The city is widely recognized for its longstanding urban environmental policy

(Biomanizales) and local environmental action plan (Bioplan), and has been integrating environmental planning in its development agenda for nearly two decades (Velasquez and Stella 1998; Hardoy and Velasquez Barrero 2014). When the city's environmental agenda was updated in 2014 to reflect climate change risks, assessments were conducted in a participatory manner at the street and neighbourhood level (Hardoy and Velasquez 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 Velasquez 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 the 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 Velasquez Barrero 2016).

4.4.2 Implementing SD and the SDGs

One of the questions emerging from the Paris Agreement is whether the transition to a 1.5°C world is compatible with the UN commitment to end poverty and meet the 17 Sustainable Development Goals by 2030 (United Nations 2016b). Endogenous to this SDG set is one on climate change (SDG13), which provides direct linkage between the Paris Agreement and 2030 Sustainable Development Agenda.

Another important related goal is SDG7 on universal access to affordable and clean energy, which has a strong convergence with the climate SDG and the transition pathway to a 1.5°C world. In principle, the expansion of renewables, energy efficiency, and fuel switching - all implicit in the achievement of SDG7 - could be made compatible with 1.5°C pathways. This also holds true for the achievement of other SDGs for which energy is an enabler.

There are however, other implicit challenges. These exist especially around the imperatives of achieving decent work and economic growth (SDG8) with expanding populations; the implicit drive towards industrialisation and infrastructure development (SDG9) without decoupling of energy intensity and decarbonisation; and simultaneous movement towards sustainable production and consumption (SDG12). Additionally, the universal commitment of the SDGs to 'leave no one behind' (United Nations 2016b) could challenge the triggering and feasibility of market-based instruments and innovation in introducing new emission reduction or carbon dioxide removal technologies, as Box 4.3 on bio-ethanol in Brazil illustrates.

Strengthening the implementation of the Sustainable Development Goals requires governments, communities, and businesses to address synergies, trade-offs, and spill-over effects inherent within the goals (Barbier et al. 2017; Åhman et al. 2016). This not only requires coordinated policy interventions, but needs to address considerations of equity and access. The Addis Ababa slum clean energy provision case (Box 4.4) highlights the complexity of simultaneously meeting multiple goals and delivering sustainable outcomes to poor and vulnerable people.

The case studies and literature shows that there is no simple answer to the question of what can be done to strengthen implementation of the 1.5°C transition and the SDGs simultaneously. Responses for both 1.5°C and the SDGs need to be locally appropriate. If initiatives emerge from communities, this aspect is generally covered. But neither the 1.5°C challenge nor the world's poverty problems will be resolved by community action alone.

Box 4.3: Case Study: Bio ethanol in Brazil

The use of sugarcane as a bioenergy source started in Brazil in the 1970s. Government and multinational car factories modified engines nationwide so that pure ethanol running cars could be produced while making production and distribution systems more efficient to meet the growing demand (de Souza et al. 2014).

After a transition period in which ethanol only and gasoline only cars were used across the whole country, the flex-fuel era started in the 1990s, when all gasoline became E25%, that is, with blend of 25% ethanol. Brazil became the first country in the world where pure gasoline was no further available for transportation. Over the next two decades, around 80% of the light car fleet in Brazil was converted to use flex-fuel (Goldemberg 2011).

Despite the intensive use of sugarcane as a bioenergy crop, no significant effects on food production or forests was observed, although some adverse effects of bioenergy production were reported, related to debts created by forest substitution by croplands (Searchinger et al. 2008). More recently, Searchinger and Heimlich (2015) examined the impact of the competition between bioenergy and food production, and claimed that bioenergy feedstocks potentially undercut efforts to minimize the climate change impact in Brazil. This was not observed by other studies, which show that the energy matrix had become more sustainable, both economically and environmentally (Smeets et al. 2008; Macedo et al. 2008; Buckeridge et al. 2012).

More than 40 years of R&D 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). Pollution reduction was an important co-benefit, leading to a 30% decrease in the emission of ultrafine particles (Salvo et al. 2017).

Brazil's bioethanol potential is high. Some modelling exercises have indicated the potential to reduce up to 6% of net emissions by 2045 without a reduction in forest area or food production *[ref]*. 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).

One 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 met with little success (Afionis et al. 2014; Favretto et al. 2017). Nevertheless, lessons learned from these experiences, could perhaps be applied in the future expansion of bioenergy production and use in land-surplus tropical countries.

Box 4.4: Case Study: Slum Regeneration in Addis Ababa: Can Carbon Reduction Work with SDGs?

Addis Ababa, like many developing country cities, has a high level of informal settlements, perhaps up to 80% (Assefa and Newman 2014; EMUDC 2014). The question facing many such cities is how these informal settlements can be upgraded to achieve a reduction in GHG emissions (SDG 13) while enabling economic and social goals to be achieved as set out in the other SDGs (United Nations 2016b).

Two approaches are in play in Addis Ababa. One is urban renewal based on slum clearance and transfer to high rise dwellings; the other is urban regeneration based on *in situ* upgrading of infrastructure using solar energy and other community-based distributed infrastructure (Satterthwaite 2016; OECD 2011). Data from three existing slums have been compared to two urban renewal high rise complexes in Addis Ababa, where residents were transferred from slums (Teferi).

Communities in the informal settlements before in situ upgrade are exposed to physical, socio-economic, and health hazards because of poor quality housing, poor environmental sanitation, and inadequate social services. This situation is improved for relocated apartment dwellers, who have better housing and living environments (SDG11), and better sanitation and water supply (SDG6). Yet, they have lost the all-important community cohesion that is a hallmark of informal settlements that provides the social safety net that underpins access to other SDGs, and the end of extreme poverty (SDG1).

Small-scale distributed infrastructure like roof-top solar PV not only enables access to clean and modern energy (SDG7) but also enables the achievement of climate goals (SDG13) and maintains the strength of informal community life (Teferi). Governance of these informal settlements is currently maintained by *Idir*, a community-led self-help system. The *Idir* are elected by the residents and provide support for people in need through a local fund based on a monthly contribution. Giving *Idir* more responsibility to manage community-based infrastructure through training and job creation can not only improve the quality of life meeting several SDGs, but also facilitate required emission reduction that will contribute to 1.5°C agenda.

AR5 outlined the development of climate resilient pathways for sustainable development (IPCC 2014a), in advance of the full definition of the SDGs that emerged a year later. In addition, transitions to a 1.5°C world could involve considerable overshoot, not only of the temperature goal but also of linked precipitation and extreme events (IPCC 2012). This has a direct bearing on two issues: First, is the delivery of core SDGs on extreme poverty reduction (SDG1) and food security (SDG2) as an outcome of either rapid decarbonisation or the impacts of overshoot. Second, is that lack of long-term scenarios outside of IAMs for mid- or late-century sustainable development, that define in a consistent manner the interaction between economic and social development and environmental protection.

The next case study on bioethanol production for transport in Brazil explores the non-trivial challenge of assessing the long-term feasibility of a proven biofuel-led emission reduction at scale, keeping into consideration its consonance with food security (SDG2), forest protection (SDG15), and health co-benefits due to lower air pollution (SDG3). Chapter 5 and the feasibility screening of both mitigation and adaptation options (see Section 4.5.3) explore these questions in more detail.

4.4.3 Enhancing multi-level governance

Addressing climate change and implementing sound responses for 1.5°C transitions will need to engage with various levels of governance – local, regional, national and supranational – in a mutually reinforcing effort to curb emissions and to increase resilience to the unavoidable impacts of climate change (Betsill and Bulkeley 2006; Kern and Alber 2009; Christoforidis et al. 2013). The effectiveness of these outcomes also depends on innovative, effective and strengthened governance structures, that work along with other policy and financial instruments, lifestyle and behaviour change

AR5 highlighted the significance of governance as a means of strengthening climate change adaptation and mitigation responses 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. It goes beyond notions of formal government or political authority and integrates other actors, networks, informal institutions, and incentive structures operating at various levels of social organization' (Fleurbaey et al. 2014, p. 297).

This section will discuss what dimensions of governance are relevant for 1.5°C transitions from both a mitigation and an adaptation perspective, and how governance at multiple levels can be enhanced to strengthen the implementation of responses to 1.5°C.

Section 4.4.3.1 will discuss institutions and their capacity for change. Section 4.4.3.2 will discuss recent findings on the roles of different governance levels for staying below, and adapting to, 1.5°C. Section 4.4.3.3 will discuss findings on what interactions between actors in governance structures work and what effective approaches to enhancing multi-level governance can be identified.

4.4.3.1 Institutions and their capacity to invoke far-reaching and rapid change

Institutions, the rules and norms that guide human interactions (analysed in more detail in Section 4.4.4), play a key role within governance by enabling the structures, mechanisms and measures that guide climate change mitigation and adaptation. Institutions and governance structures are strengthened when the principle of 'commons', under which the global climate system falls, are explored as a way of sharing management and responsibilities (Chaffin et al. 2014; Ostrom et al. 1999; Young 2016a).

Institutions need to be strengthened to interact amongst themselves, and to share responsibilities for the development and implementation of rules, regulations, and policies that will more likely ensure their compliance (Craig et al. 2017; Wejs et al. 2014; Ostrom et al. 1999). The goal for strengthening implementation is to ensure that these policies, rules and regulations embrace poverty alleviation and sustainable development, enabling a 1.5°C world through mitigation and building adaptive capacity (Wood et al. 2017; Reckien et al. 2017). Literature also suggests building a synergy between sustainable development and climate change goals within each institutional mandate and within each policy domain (e.g. clean energy, sustainable transportation and cities, education and health) will be a step forward (Eizenberg and Jabareen 2017; Wood et al. 2016).

Capacity for change will have to be strengthened across multiple scales: from the individual and household; communities and at the local level; in organisations and business; and at national and global level. Multi-level governance in climate change has emerged as a key enabler for systemic transformation and effective governance, combining decisions at global (i.e. UNFCCC), regional (e.g. EU), national, subnational (e.g. state/region) and local (i.e. cities, municipalities and communities) levels in a productive way, as well as a cross-sectorally and across various types of institutions, at the same level. For example networks of cities like C-40 or ICLEI, that are attempting to accelerate a climate response (Ringel 2017; Hsu et al. 2017; Kemp et al. 2005).

Several authors have identified different modes of cross-stakeholder interaction in climate policy. Horizontal and vertical interaction across state levels and between public and non-public actors requires considerable policy coordination (Ingold and Fischer 2014; Kern and Alber 2009). Kern and Alber (2009) recognise different forms of collaboration relevant to successful climate policies beyond the local level. Horizontal collaboration (e.g. national and transnational city networks learning from others and sharing best practices) and vertical collaboration within nation-states can play an enabling role with national governments and funding schemes. Hsu et al. (2017) affirm that vertical and horizontal alignment require synergistic relationships between stakeholders.

4.4.3.2 Multiple levels of governance: from global to local

Strengthening solutions and policy change requires both a bottom-up approach to engaging citizens, businesses, municipalities and local communities and a more traditional top-down approach, enacted by national or supranational governmental institutions. A bottom-up approach provides information and a local perspective on what are viable actions and targets, and can respond to short-term political interest linked to electoral cycles (Maor et al. 2017). A 1.5°C transition needs long-term planning, solutions and instruments such as legislation and international cooperation (Oberthür and Groen 2017), which are often better enacted from the top down. Actions by nation states are discussed in Section 4.4.7 on policy instruments.

4.4.3.2.1 Global governance

Governance models or 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 *[ref]*. Global governance is organized via many mechanisms, including international treaties and conventions. Climate change is governed by the UNFCCC, through the Kyoto Protocol and the Paris Agreement, with an important contribution on HFCs coming from the Montreal Protocol that operates under the Vienna Convention.

While binding targets are seen by some as the strongest and most effective form of global climate governance, the failure to negotiate binding targets in the Paris Agreement (Patt 2017) is because a new temperature target does not only need emission reductions. It ideally needs the elimination of all GHG emissions and 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 enable a transition to a 1.5°C world. Emerging literature suggests the Paris Agreement will be strengthened under conditions that enable effective monitoring and timely reporting on national contributions, international scrutiny and persistent efforts of civil society to encourage greater and faster action (Allan and Hadden 2017; Bäckstrand and Kuyper 2017; Höhne et al. 2017; Maor et al. 2017). International climate governance also includes multi-actor engagement. Recently, the importance of non-state actors, such as civil society and citizens, business and environmental organisations, has been recognized (Hsu et al. 2017; Hale 2016).

International climate governance has some profound differences between governance of mitigation and adaptation. 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). Hence, emissions can be allocated by country and carbon markets can be established with some international intermediation. Adaptation, which has a local or national dimension, often involves local authorities and stakeholders, with a less central role for international actors. For instance, international treaties bridge the short-term vision of emergency response and disaster reconstruction with longer-term sustainable development goals, which is key as short-term disaster reconstruction programs and risk mitigation. Short to medium-term disaster responses can strengthen climate mitigation and adaptation when embedded within longer term sustainable development processes (de Leon and Pittock 2016).

So far, work on international climate governance at the interface between political science, law, geography, sociology and political economy (Aykut, 2016) focused on the nature of 'climate regimes', coordinating the action of nation-states. Most discussions were on whether this coordination should rely on carbon prices, emissions quotas or pledges and review of policies and measures (Pizer 2002; Newell and Pizer 2003; Grubb 1990; Stavins 1988). Carbon prices and emission quotas were envisaged *via* a top-down approach where the decentralised coordination of efforts was operated through market instruments in view of equating marginal costs of global GHG abatement. This was the basic principle behind the Kyoto Protocol (Aldy and Stavins 2007).

Literature about the failure of the Kyoto Protocol (KP) gives two important insights from a 1.5°C perspective. First, the major cause of failure of the KP was the absence of agreed rules to allocate emissions quotas under the Common but Differentiated Responsibility (Shukla 2005; Winkler et al. 2011; Gupta 2014; Méjean et al. 2015). A burden sharing approach led to an adversarial game among nations to decide who shall be allocated 'how much' of the remainder of the emissions budget. The second is the impasse of a climate-centric vision of a climate regime (Shukla 2005; Winkler et al. 2011; Shukla 2006; Jayaraman et al., 2011) disconnected from development issues.

The paradigm shift enabled at Cancun by fixing the objective of 'equitable access to sustainable development' (Hourcade et al. 2015) now underpins the Paris Agreement. This consolidates the attempts, after COP15 in Copenhagen to define a governance approach that relies on National Determined Contributions (NDCs) and on means for a 'facilitative model' (Bodansky and Diringer 2014, p. 6) to reinforce them. Beyond a general consensus on the necessity of Measuring, Reporting and Verification (MRV) mechanisms as a key element of a climate regime, the literature explores different governance approaches to implement the Paris Agreement. For example, convergence toward a uniform carbon price and the progressive integration of different regional mechanisms (Metcalf and Weisbach 2012; Bodansky et al. 2014) under the Art 6 of the PA (e.g. Internationally transferred mitigation outcomes (ITMOS) (6.3) and joint credit mechanism (JCM) (Art 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.

These two approaches contain useful elements to meet the transition to a 1.5°C world. This objective demands an acceleration of cooperation and action on three key barriers to more ambitious nationally determined policies: evolution of the finance and monetary system; trade organisation to tackle distortions of competitiveness; and intellectual property rights to accelerate access to technology. They expect to expand and revisit the CBDR principle out of a 'sharing the pie' paradigm (Ji and Sha 2015) as a tool to open a world innovation process towards alternative development pathways.

Enabling the 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) where actors can exchange information to avoid the prisoner's dilemma, where the outcome is the worst for all stakeholders.

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 (Nordhaus 2015; Hermwille et al. 2017; Hovi et al. 2016) or club of countries as complement to the UNFCCC (Abbott and Snidal 2009; Biermann 2010; Bulkeley et al. 2012; Zelli 2011). However, these will not replace deep 'top-down' evolution in financial institutions and governance (Hourcade et al. 2015), trade organization (Jegou 2015) and intellectual property rights (Zhuang 2017; Abdel-latif 2015) as preconditions for regimes built on trust and reciprocity.

4.4.3.2.2 Community and local governance

Local governments can play a key role among other actors, influencing climate mitigation and adaptation strategies. It is important to understand how cities, communities and other actors might intervene to reduce climate impact (Bulkeley et al. 2011), either by implementing climate objectives defined at higher government levels or to take initiative autonomously (Aall et al. 2007). Local government are a key to coordination and developing effective local responses and more effective policies around energy and environmental issues (Fudge et al. 2016). Fudge et al. (2016) indicate that policy makers, academics and practitioners recognise that local authorities are well-positioned to involve the wider community in designing and implementing climate policies, engaging with both the technological aspects of energy generation and the delivery of sustainable demand-side energy management strategies. Carney and Shackley (2009) show that in several policy areas excessive centralisation has led to failure and that sustainable policies could be better designed nearer to the intended beneficiaries, hence more focused at the local scale.

Rutherford and Jaglin (2015) acknowledge that 'while cities are often seen as the source of many energy issues and problems […] they may also be part of the 'solution', offering potential, wide-ranging opportunities for contributing to shifting energy policies onto more 'sustainable' pathways'. Several initiatives have been launched to help cities to implement climate change mitigation and adaptation measures at local level, for example the Covenant of Mayors (Melica et al. 2017; Kona et al. 2017). The Covenant of Mayors serves to test new models of governance, including citizens and stakeholders and other neighbouring cities, and on the vertical dimension regions and countries (see Box 4.5). The need to have local context or place in the governance of global problems is illustrated by MacGillivray (2015).

Box 4.5: Multi-level governance in the EU Covenant of Mayors: the example of the Provincia di Foggia

The EU Covenant of Mayors (CoM) is an initiative of the European Union in which municipalities voluntarily commit to CO_2 emission reduction via energy efficiency and renewable energy targets. It has allowed the testing of a model of multi-level governance 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 (Covenant of Mayors 2017).

As a CTC, the Province of Foggia (Italy) enabled 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 Mayors 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) programme (EIB 2015), a joint initiative of the European Investment Bank and the European Commission. ELENA provided the Province with support for preparing an energy baseline study and 1.7 M€ procurement support for the selection of the ESCos. The local Chamber of Commerce had a key role in the implementation of these projects by the municipalities.

The expected results are (Lombardi et al. 2016):

- Energy savings in buildings of about 30 GWh yr^{-1} (almost 55% of the total consumption)
- Energy savings in public lighting of about 21 GWh yr^{-1} (60% of total demand)
- GHG emission reduction of 20,375 $tCO_2eq\ yr^{-1}$
- Investment to be mobilized: 81 M€

Besides contributing to the EU Climate and energy targets and the Paris Agreement, this highlights a new form of collaboration among different actors, both governmental and non-governmental, which could potentially be replicated elsewhere. A wider involvement of Chambers of Commerce could help to bring the business community and local and regional governments, closer together to address the challenge of climate change.

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

Emerging literature since AR5 on governance for a 1.5°C warmer world indicates that achieving this ambition will take leadership, vision and widespread participation in transformative change (Castán Broto and Bulkeley 2013; Wamsler 2017; Fazey et al. 2017). However, authors disagree over the extent to which implementing transformative governance must involve large scale, top-down, fast and far reaching action including reliance on negative emissions (Anderson 2015; Biermann 2014; Busby 2016); incremental yet significant voluntary changes amplified through community networking, poly-centric partnerships and long-term change to governance systems at multiple levels (Termeer et al. 2017; Pichler et al. 2017; Stevenson and Dryzek 2014; Lövbrand et al. 2017); or the allying of “deep and early reductions in energy demand with rapid substitution of fossil fuels by zero-carbon alternatives” and policy initiatives that focus on the highest carbon emitters (Anderson 2015; Knutti et al. 2015).

4.4.3.3 Interactions and processes for multi-level governance

It is still 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). However, Jordan and Huitema (2014) highlight that subnational policy makers are often relatively poorly connected to international climate governance agendas, represented on global fora or on in contact with their counterparts in other countries. Kivimaa et al. (2017) conclude that systematic deliberation of combinations of diverse types of experiments, each contributing to slightly different processes, can facilitate the emergence and diffusion of new technologies, test several types of governance innovations, and change existing policies and institutions.

There is agreement in the literature that national processes to prepare integrated climate and development plans must be leveraged to meet adaptation and mitigation goals. The NDCs have been identified as one such institutional mechanism (Peters et al. 2017; Kato and Ellis 2016; Magnan, A., Ribera, T., Treyer et al. 2015); see also Box 1 on NDCs. In addition, adaptation policy has seen growth: Massey et al. (2014) found that, between 2005 and 2010, the total number recorded adaptation policy measures in the EU grew by 635%. However, current emission reductions pledged in the NDCs are inadequate to remain below the Paris Agreement temperature limits (Höhne et al. 2017). To strengthen responses, national governments must raise their level of ambition and for many developing countries, achieving this will require 'financial, technological and other forms of support' to build capacity for effective climate governance (Höhne et al. 2017), which has been promised in the Paris Agreement but has not been delivered (e.g., de Coninck and Sagar, 2015).

To overcome barriers to policy implementation, local conflict of interests (building of roads and parking space that favour the usage of private vehicles) or vested interests (e.g. construction of buildings in area prone to flooding), strong leadership and agency is needed by political leaders. As shown by the Covenant of Mayors initiative (Box 4.5), 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 (Kona et al. 2017; Rivas et al. 2015; Croci et al. 2017). 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 endorse it is found to increase the likelihood of success (Wamsler 2017; Rivas et al. 2015). Effective plans also describe the financial tools for implementation. However, as described in Nightingale (2017) and Green (2016), struggles over natural resources and adaptation governance both at national and community level need addressing too, 'in politically unstable contexts, where power and politics shape adaptation outcomes'.

Multilevel governance for adaptation 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). Different actors have different responsibilities and interdependencies across administrative levels. National governments, for example, have been associated with enhancing adaptive capacity through building awareness of climate impacts, encouraging economic growth, 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).

Hoppe and Wesselink (2014) propose that multilevel governance can manifest as two different arrangements. One arrangement disperses authority across general-purpose and non-intersecting jurisdictions, where jurisdictional units are arranged around territorial communities and are separated from each other. The second assigns distinct functions to different jurisdictions, so that each level of government deals with a specific policy problem, but with overlapping territorial coverage.

A multilevel approach considers that adaptation planning is affected by scale mismatches between the local manifestation of climate impacts and the diverse scales at which the problem is (Shi et al. 2016). Multilevel approaches are particularly 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. A multilevel approach seeks to determine how different levels of government contribute to or obstruct the process of adaptation planning. National governments or international organizations, 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 4.6: Watershed management in response to drought and El Niño Southern Oscillation (ENSO) in Southern Guatemala.

Central America has suffered from the impacts of hydrometeorological events (Chang et al. 2015; Maggioni et al. 2016), especially of the El Niño Southern Oscillation (Steinhoff et al. 2014). The 2014-2016 ENSO was especially devastating for agriculture and rural communities in Southern Guatemala. The country has experienced a drop in productivity of staple crops, including sugar cane, banana, and palm (Vargas et al. 2017; Sain et al. 2017) and loss of cattle (Shannon and Motha 2015) due to drought. A lack of proper water infrastructure (Vásquez and Aksan 2015; Mekonnen et al. 2015) and water policies and regulations (Vásquez and Aksan 2015; Vásquez and Espaillat 2014; Mekonnen et al. 2015) have created some conflicts amongst watershed users (Hileman et al. 2015). Conflicts over water use have been predominant, especially due to mining and hydroelectrical projects (Aguilar-Støen and Hirsch 2015; Haslam and Ary Tanimoune 2016) and competing agricultural uses (Mingorría 2017).

In February 2016, the Climate Change Institute (ICC, for its acronym in Spanish), together with the government, private and public sectors, communities and human rights organizations, created technical dialogue tables in different watersheds to mitigate the effects of the drought and the social tension it had created. These tables were created by the users of the Achiguate, Madre Vieja, and Ocosito watersheds and led by the respective State Governors. Identification of all water users and the measurements of river levels to ensure availability of the ecological flow, were focal concerns. The goal of these dialogues was to enable better management of water resources, through improved communications, transparency, and coordination amongst users, was met this year when all previously affected rivers didn't run dry and reached the Pacific Ocean with at least their minimum ecological flow (Guerra 2017). This initiative is planned to be expanded to other watersheds at risk.

4.4.4 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 (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 responses based on the jurisdiction, as institutional capacity is highly context-dependent (North 1990; Lustick et al. 2011).

Institutions need to interact with one another and align across scales to ensure that rules and regulations are followed (Chaffin and Gunderson 2016; Young 2016b). 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). 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 (McGranahan et al. 2016; Kaika 2017).

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

4.4.4.1 Capacity for policy design and implementation

The enhancement of institutional capacity for integrated policy design and implementation has long been among the top of the UN agenda to 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 at lower governmental levels and within cities (Romero-Lankao et al. 2013). 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 4.5 and 4.6.

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 urbanization 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. 2014). 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 enhanced the capacity of decision making institutions in many developing countries to support the effective implementation. These efforts are particularly reflected in Article 11 of the Paris Agreement on capacity building, as well as Article 15 on compliance.

4.4.4.2 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 committing countries to provide regular progress reports on national pledges to address climate change (Paris Agreement, Article 13). Many countries will rely on public policies and existing national reporting channels to deliver on their NDCs under the Paris agreement. Scaling up the efforts to be consistent with 1.5°C would put significant pressure on the need to enhance and streamline local, national and international GHGs reporting and monitoring methodologies and institutions (Schoenefeld et al. 2016). Consistent with this direction the Paris Agreement has invented two mechanisms: progression and the global stock, to scale up international efforts (Paris Agreement, Article 14).

4.4.4.3 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-carbon energy and energy efficiency measures may be required through to 2050 (Blanco et al. 2014). Financing of 1.5°C would present even a 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 the public and private financial institutions would be needed to mobilize resources for 1.5°C. Yet, in the ordinary course of business private finance is not expected to be sufficiently forthcoming, given the risks associated with commercialization and scaling up of renewable technologies (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 taxpayers subsidization Hoch (2017) suggest the creation of special institutions that underwrite the value of emission reductions using auctioned price floors.

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).

In addition to the private and public financial institutions, there are the global multilateral financial institutions such as the World Bank, the IMF, IFC, and regional development banks that are currently leading the mobilization of green finance and which need to assume an even greater role during the low-carbon transition. Further, there are the specialized multi-lateral financial intuitions such as the Green Climate Fund and the Global Environmental Fund whose functions and level of operations need upscaling to address the 1.5°C challenge.

4.4.4.4 Co-operative institutions and social safety nets

Effective Co-operative institutions and social safety nets may be useful to address distributional impacts during the transition to low-GHG emissions societies and enabling sustainable development. Social capital (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).

Transitioning economies towards sustainable energy models could impact the livelihoods of large populations. The transition of select EU economies to biofuels, caused anxiety among farmers, who lacked confidence in the biofuel crop market. Contracts between farmers and energy companies, involving local governments were enabled, to 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 (Moffatt 2014) to a more 'rational conception of risk assessment, where risk is noted on a spectrum of tolerability for the party involved.

Compared to traditional social forms where energy technology and resource systems are either owned and administered individually in market settings or via a central authority (e.g. the state), self-governing and self-organized institutional settings where equipment and resource systems are owned and managed in common by people can potentially generate a much higher diversity of administration solutions. 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 (Thi Hong Phuong et al. 2017; Butler et al. 2016).

The strengthening of institutional capacity to accelerate the transition to 1.5°C requires special attention to capacity building efforts, especially in developing countries. Article 11 in the Paris Agreement has made a positive step in this direction through its emphasis on capacity building.

Box 4.7: Institutions for integrated policy design and implementation

The presence of multinational networks and scientific groups help guide local governments in climate policy creation and provide access to knowledge in the urban context. In Mexico, the World Mayors Council on Climate Change helped develop the Mexico City Climate Action Plan for 2008-2012. Climate Adaptation Santiago played integral role in launching 'Climate Adaptation Plan for the Metropolitan Region of Santiago 2012' (Romero-Lankao et al. 2013). In Huambo, Angola, collaboration between Centre for Environment & Human Settlements, Development Workshop, and the City Administration of Huambo in an urban planning project supplemented the weak institutional capacity of the local government in such projects (Smith and Jenkins 2015).

Box 4.8: Case: Indigenous Knowledge

For centuries, indigenous communities have observed the behaviour of flora, fauna, and climate phenomena on their crops and their communities (Mistry and Berardi 2016; Green and Raygorodetsky 2010). This indigenous knowledge can now contribute towards climate research (Reyes-Garcia et al. 2016) and adaptation strategies (Altieri et al. 2015).

Mayan indigenous traditional knowledge has been transferred from one generation to the next, since ancestral times. The changing climate is a growing concern amongst indigenous populations, who depend on their climate knowledge for a livelihood. In Guatemala, the Mayan K'iché population of the Nahualate river basin and the Climate Change Institute (ICC, in Spanish) have systematized traditional and ancestral knowledge and identified indicators used for watershed meteorological forecasts (Yax 2016). These indicators need to be scientifically validated to determine if they are still viable, in an effort to link this indigenous knowledge to current science (Nyong et al. 2007; Alexander et al. 2011; Mistry and Berardi 2016).

For more than ten years, Guatemala has had an Indigenous Table for Climate Change that ensures indigenous concerns are taken into consideration in national policies and, more importantly, that indigenous knowledge play a role in the different disaster management and adaptation policies that take place, as it constitutes a part of their livelihood.

The Arctic is experiencing some of the earliest and most rapid impacts of climate change (Ford et al. 2012; Hinzman et al. 2005; Kirtman et al. 2013), exacerbating pre-existing high health burdens in the region (Ford et al. 2014b). However, Indigenous communities in the Arctic have historically adapted to environmental change, and traditional knowledge systems are recognized as being key to resilience in the region (Arctic Council 2013a; Ford et al. 2015). They have shifted the timing of harvesting activities, and, more recently, adapted and diversified economic systems (Einarsson 2014a; Wenzel 2009). In the present, community and regional capacities are driving adaptation initiatives across the Arctic, with the potential to reduce vulnerability (Arctic Council 2013b). Adaptation initiatives are increasingly observed at local to national scales in the Arctic, with communities responding and reducing current damages and future risks, and capitalizing on new opportunities presented by climate change (Ford et al. 2014a; Labbe et al. 2016; Arctic Council 2013b). Arctic communities have used traditional knowledge to conduct community-based monitoring initiatives and risk assessments centred on the needs and interests of communities (Rosales and Chapman 2015; Johnson et al. 2015; Alessa et al. 2015), and several recent initiatives have combined indigenous knowledge with technology to record and assess the safety of sea ice for hunters and community members (Bell et al. 2015; Eicken et al. 2014).

4.4.5 Enabling lifestyle & behavioural change

Substantial changes in behaviours and lifestyles are needed to stay below 1.5°C. Climate change mitigation and adaption efforts will be more effective when they address key factors influencing climate-related actions, and consider behavioural anomalies that affect how decisions that affect climate change are made. A wide range of policy approaches can be employed to encourage and facilitate climate-related actions. We refer to climate-related action when factors and policies affect both climate change mitigation and adaptation actions; otherwise we refer to mitigation and adaptation actions specifically.

4.4.5.1 Factors related to climate change actions

Individual preferences, choices and behaviour have major implications for anthropogenic climate change and for the effectiveness of mitigation and adaptation strategies (Dietz et al. 2013; Hackmann et al. 2014b; ISSC and UNESCO 2013; Sovacool 2014; Weaver et al. 2014; Vlek and Steg 2007). The likelihood that individuals act on climate change depends on many contextual factors that define their opportunities to engage, influencing motivations and cost and benefits of their actions. These include economic, spatial, institutional, social and cultural factors, and available infrastructure and technology, discussed earlier in this chapter. These factors can both pose serious barriers to action on climate change, or encourage and facilitate them.

Mitigation and adaptation strategies that aim to realise economic, physical or technological change involve behaviour changes. It is important to understand under which conditions these strategies are most likely to realise their potential and what social and psychological factors enhance their effects. Further, individuals need to accept these proposed policies and changes, and use new technologies and infrastructure in the intended way. Hence, it is important to understand which individual and social factors promote action on climate change and the acceptability of climate change policy.

Behaviour is affected by a wide range of factors that shape which behavioural options are feasible and considered by individuals. These include abilities and the motivation to engage in relevant mitigation and adaptation behaviour (Steg et al. 2015a), and behavioural anomalies incentives (Shogren & Taylor 2008).

Abilities depend on, among others, income and knowledge. A higher income is related to higher CO_2 emissions; higher income groups can afford more energy intensive lifestyles (Lamb et al. 2014; Vringer and Blok 1995; Wang et al. 2015; Dietz et al. 2015; Abrahamse and Steg 2009) (Gatersleben, Steg & Vlek 2002). At the same time, low-income groups may lack the financial resources to invest in energy efficient technology, refurbishments (Andrews-Speed and Ma 2016) and climate change adaptation options (Takahashi et al. 2016; Fleming et al. 2015).

Lack of knowledge can inhibit engagement in actions on climate change, even when people would be motivated to do so. Knowledge of the causes and consequences of climate change and ways to reduce greenhouse gas emissions is not always accurate (Bord et al. 2000; Whitmarsh et al. 2011; Tobler et al. 2012). For example, people overestimate savings for low-energy activities, while they underestimate savings for high-energy activities. Besides, people know little about the energy use ‘embedded’ in products and services (Tobler et al. 2011), such as the mitigation potential of limiting meat consumption (de Boer et al. 2016). They also hold misperceptions of the environmental impact of energy sources. For example, some individuals think natural gas is a renewable energy source or think bioenergy is a fossil fuel as it involves burning materials (Butler et al. 2013; Devine-Wright 2003). Similarly, some people conflate risks posed by climate change impacts with different hazards, which may be a barrier to adequate adaptation (Taylor et al. 2014). People may also hold misperceptions of the pros and cons of behaviour options, which may inhibit climate change actions. For example, people tend to overestimate the disadvantages of public transport. Yet, perceptions can become more accurate when people are triggered to try out public transport, which can motivate them to continue using public transport rather than driving a car (Fujii et al. 2001; Fujii and Kitamura 2003).

While knowledge is important, it is seldom sufficient to motivate action (Trenberth et al. 2016). Indeed, climate change knowledge and perceptions are not strongly related to climate change mitigation actions (Hornsey et al. 2016). Similarly, while providing information on climate change and possible mitigation and adaptation actions generally does increase knowledge and awareness, their effects on climate change actions are typically weak (Ünal et al., *submitted;* Abrahamse et al. 2005). Direct experiences of events related to climate change influence climate concerns and actions more than second-hand information (Demski et al 2017; Myers et al. 2012; Spence et al. 2011). Individuals 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 et al. 2010; O'Neill et al 2013), which inhibits support for climate change policy (Ding et al. 2011; McCright et al. 2013). Economic recession can also reduce climate change concerns (Scrugg and Benegal 2012).

Climate change mitigation and adaptation actions are more strongly related to motivational factors such as values, ideology and worldviews than to knowledge (Hornsey et al. 2016). People particularly consider consequences that have implications for their key values (Dietz 2013; Steg 2016). This implies that different individuals consider different types of consequences when making choices. For example, endorsement of a market-friendly perspective is associated with weaker climate change beliefs (Hornsey et al. 2016), and capital-oriented culture tends to promote economic expansion and activity associated with GHG emissions (Kasser et al. 2007). People who strongly value protecting nature, the environment and other people are more likely to act on climate change than those who strongly endorse hedonic and egoistic values (Dietz et al. 2005; Steg, 2016; Taylor et al. 2014). Furthermore, people are more likely to adopt sustainable innovations when they are more open to new experiences and ideas (Jansson 2011; Wolske et al. 2017).

Individuals are more likely to act on climate change when such actions have more individual benefits relative to individual costs (Steg and Vlek 2009; Bamberg and Möser 2007; Wolske et al 2017), including prices, time, convenience, and safety. Yet, many other costs and benefits play a role that are often more predictive of actions than financial costs and convenience. These include social costs and benefits (Farrow et al. 2017). People are more likely to act on climate change when they think others expect them to do so and when others act as well (Bamberg and Möser 2017; 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; Wolske et al. 2017; Singh et al., 2016) and when they discuss about effective actions with their peers (Esham and Garforth 2013), particularly when they strongly identify with the relevant groups (Biddeau et al 2016; Fielding & Hornsey 2016).

Actions on climate change are more likely when individuals think doing so would enhance their reputation and social status, and signals something positive about them to others and self (Kastner and Stern 2015) (Griskevicius et al. 2010; Milinski et al. 2006; Noppers et al. 2014; Schuitema et al 2013). Furthermore, individuals are more likely to act upon climate change when they worry about climate change (Verplanken & Roy 2013), while positive affect associated with a climate related threat may inhibit protection behaviour (Lefevre et al., 2015). People are more likely to act on climate change when they expect to derive positive feelings from such actions (Taufik et al. 2016; Pelletier et al. 1998), either because engagement is pleasurable or because they feel meaningful when engaging in actions that benefits others and the environment (Venhoeven et al. 2013, 2016; Taufik et al. 2015).

Besides individual consequences, collective consequences affect climate change actions (Dóci and Vasileiadou 2015; Bamberg and Möser 2007; Kastner and Stern 2015; Balcombe et al. 2013). Individuals are motivated to see themselves as morally right and to do the right thing, such as protecting the environment, which encourages actions on climate change (Steg et al., 2015), particularly when long-term goals and motives are salient (Zaval et al. 2015). The more individuals are aware of environmental problems caused by their behaviour, the more they think they can reduce these problems by acting responsively, which strengthens their feelings of moral obligation to act accordingly and promotes actions on climate change (De Groot and Steg 2009; Jakovcevic and Steg 2013; Steg and De Groot 2010; Stern 2000; Stern et al 1999; Wolske et al. 2017). Individuals are less likely engage in climate change actions when they believe others are responsible for climate change problems (Fielding and Head 2012). Climate change mitigation actions are more likely among those who see themselves as supportive of the environment (i.e. strong environmental self-identity; Barbarosa et al. 2017; Fielding, McDonald & Louis, 2008; Gatersleben et al. 2014; Kashima et al. 2014; Van der Werff et al. 2013, 2014). Environmental self-identity is strengthened when people realise they engaged in climate mitigation actions, which may in turn promote further actions on climate change (Van der Werff et al. 2014).

Individuals are more likely to engage in climate adaptation and mitigation behaviour when they believe climate change is happening and perceive climate change and variability, when they are aware of threats caused by climate change and the problems caused by their inaction, and when they feel capable to engage in actions that will reduce the relevant threats (Esham and Garforth 2013; Arunrat et al. 2017; Chatrchyan et al. 2017).

Personal experience with climate change hazards strengthens motivation to protect oneself (Jabeen 2014), although this does not always translate into proactive adaptation (Taylor et al. 2014). Adaptive capacity depends on contextual factors and individual abilities, including income, knowledge and technical capacities (Eakin et al. 2016; Feola et al. 2015; Singh et al. 2016), and on gender roles (Jabeen 2014). Individuals are less likely to engage in climate adaptation behaviour when they rely on protection measures undertaken by the government (Burnham and Ma 2017; Armah et al. 2015; Grothmann and Reusswig, 2006) and when they believe 'God' will protect them from any harm (Dang et al. 2014; Mortreux and Barnett, 2009). Moreover, individuals with a strong attachment to their community may be unwilling to migrate to protect themselves from climate change risks as they are reluctant to leaven behind their social and emotional support groups (Adger et al. 2013).

4.4.5.2 Behavioural anomalies

Decisions are not always based on weighing costs and benefits, but are also based on feelings (Taufik et al. 2016; Finucane et al 2000), habit (Aarts and Dijksterhuis 2000; Klöckner et al. 2003), and behavioural anomalies. Behavioural anomalies imply individuals do not have well-defined preferences, do not use all available information, and do not maximize utility with perfect foresight and impeccable optimization skills under budget constraints. Behavioural anomalies challenge theory on rational choice and on how individuals respond to incentives (Shogren and Taylor 2008).

Behavioural anomalies can lead to systematic difference between decision utility (i.e. expected or intended utility at the time of choice) and experienced utility (i.e. utility experienced after the choice) (Kahneman & Thaler 2006). Behavioural anomalies that result in sub-optimal choices in climate change mitigation and energy use include the endowment effect, loss aversion, reference-dependency, status quo bias, heuristics, limited attention, framing effects, procrastination and satisficing (Frederiks et al. 2015; Gillingham & Palmer 2014; Gowdy 2008; Lopes et al. 2012; Steg et al. 2015; Tietenberg 2009). Behavioural anomalies in the context of adaptation are heuristics, such as the availability heuristic that imply that risk perceptions are influenced by recent or recurrent events that are more cognitively available (Preston et al. 2013; Clayton et al. 2015). Besides, biases such as status quo bias, omission bias and action bias play a role. For example, farmers in Mozambique were unwilling to take an action with potentially negative consequences, in order to avoid personal responsibility for the losses (an omission bias), while policymakers displayed action biases, wanting to demonstrate positive action even though it might lead to negative consequences (Patt and Schröter 2008). Another example is around mismatches between perceived and actual risks. For example, farmer adaptation decisions in India were shaped by collectively constructed notions of risk, experiences of past events, and expectations of future variability which often differed from measured shifts in climatic variables, leading to a mismatch between risk and response behaviour (Singh et al. 2016). A brief review of these behavioural anomalies is presented below.

Loss aversion is the tendency to place greater value on relative losses and disadvantages than on gains or advantages (Kahneman 2003). Perceived gains and losses depend on a *status quo* or reference point (Kahneman et al. 1991; Kahneman 2003). Indeed, energy-related information or recommendations 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 (e.g. via performance contracts, dynamic pricing, energy audits)

(Bradley et al. 2016; Gonzales et al. 1988; Wolak 2011). Loss aversion prevents consumers to switch to time-of-use electricity tariffs (Nicolson et al. 2017). Combined with uncertainty, loss aversion also leads consumers to over-discount the value of future energy savings (Greene 2011). Training energy auditors in loss-aversion to recommend efficiency improvements was effective in motivating households to invest in retrofits (Gonzales et al. 1988).

The endowment effect (Thaler 1980) refers to individuals attaching greater value to goods they already own and that the (selling) value is much higher than the buying price. Owned inefficient appliances and fossil fuel-based electricity are likely to act as instant endowments, which increases the value of a default option compared with alternative options (Dinner et al. 2011; Pichert and Katsikopoulos 2008).

Loss aversion also drives individuals to stick to the *status-quo*, as new options are perceived to have more drawbacks than benefits (Samuelson and Zeckhauser 1988).The *status quo* affects households decisions to switch to a new electricity supplier (Ek and Söderholm 2008) and to accept changes in energy systems (Leyten et al. 2014). Field experiments show that consumer inertia towards energy conservation activities or renewable energy can be reduced if participation is set as default 'opt-out' option, rather than as 'opt-in' (Ebeling and Lotz 2015; Ölander and Thøgersen 2014; Pichert and Katsikopoulos 2008).

Procrastination leads to delayed decisions, failure to act or acceptance of the *status quo* (Anderson 2003). Individuals with a higher tendency to procrastinate are less likely to participate in energy saving activities (Lillemo 2014). Uncertainties about the performance of products and illiquidity of investments can also drive consumers to postpone energy efficient investments, even when this would be profitable (Van Soest and Bulte 2001; Sutherland 1991).

People are 'rationally bounded' in problem solving capacities (Simon 1955, 1979). This results in satisficing outcomes ('good enough', a mix of 'satisfying' and 'sufficing' as opposed to 'maximising'; (Gigerenzer and Goldstein 1996), rather than finding the 'best' or 'optimal' solution (Simon 1979). Satisficing often takes over utility maximisation in energy related decisions of individuals and firms (Klotz 2011; Wilson and Dowlatabadi 2007), which can prevent them from investing in energy efficient measures (Decanio 1993; Frederiks et al. 2015). Energy consumers appeal to intuition as balancing all costs and benefits of energy-using products is challenging (Allcott 2013; Frederiks et al. 2015). Heuristics (or 'rules of thumb') are simplified intuitive decision-making rules that often lead to immediate but suboptimal choices and inaccurate perceptions. For example, people tend to think that larger and visible appliances use more energy, which is not always accurate (Steg et al. 2015). They also underestimate the amount of energy used for water heating and overestimate the energy used for lighting (Stern 2014). Relying on heuristics demands less cognitive efforts, knowledge and time. When facing choice overload, heuristics can make people focus on the most important information and drive individuals to choose the easiest or first available option, which can inhibit energy saving behaviour (Frederiks et al. 2015; Stern and Gardner 1981) and drive energy consumers to systematically undervalue the savings from energy efficient technologies (Kolstad et al. 2014). Consumers are also careless about additional delivery costs if they are added to the end of transaction (Hossain and Morgan 2006).

4.4.5.3 Strategies to promote actions on climate change

To encourage wide-scale changes in behaviour and lifestyles, policy and changes need to be implemented that empower and enable people to engage in climate change mitigation and adaptation actions. More rapid and far-reaching implementation efforts are needed to scale-up mitigation and adaption responses.

In both rural and urban areas, adaptation efforts tend to focus on infrastructural and technological solutions with relatively lower emphasis on socio-cognitive and finance aspects involved in adaptation action (Boyd 2017; Mortreux and Barnett 2017). For example, flooding policies in cities currently focus on infrastructure projects and amendments to regulation such as the building code, but do not target the behaviour of households or individuals (Georgeson et al. 2016; Araos et al. 2016a).

Policies can influence mitigation and adaptation behaviour through different instruments: informational or awareness campaigns that rely on voluntary compliance; using the government's authority to command behaviour; using public funds to (disc)incentivise behaviours; and leveraging physical and human capital of the government to deliver programmes and services that affect behaviour (Adger et al. 2003; Henstra, 2016; Steg and Vlek 2007). Climate policy will be more effective when important antecedents of climate change actions are targeted, including contextual factors, abilities, perceptions and motivations. These may differ across contexts and individuals (Stern 2011). When people perceive serious barriers or constraints to act upon climate change, the context in which decisions are made needs to be changed, as to make climate mitigation and adaptation actions more feasible and attractive. Besides, various strategies can be employed to target individuals' perceptions and motivations to act on climate change.

Current policy approaches largely derived from rational choice models emphasize infrastructural and technology development, regulation, financial incentives and information provision. These approaches target only some of the many (motivational) factors and processes influencing actions on climate change. They also fall short of their true potential if their social and psychological implications are overlooked and when behavioural anomalies are not considered (Stern et al. 2016). For example, promising energy-saving devices or low carbon technology may not be adopted, or not be used as intended (Pritoni et al 2015). People may lack cognitive resources to make well-informed decisions or not know where to find trustworthy advice or competent technical help (Balcombe et al. 2013; Stern 2011).

Financial incentives, financial appeals and feedback on financial savings are not always effective (Bolderdijk et al, 2013; Delmas et al. 2013), and can be less effective than emphasizing benefits for other humans and the environment (Asensio and Delmas 2015; Bolderdijk et al. 2013; Handgraaf et al. 2013; Schwartz et al. 2015). This can happen when financial incentives, appeals and feedback reduce a focus on environmental concerns and crowd out intrinsic motivation to engage in climate change actions (Agrawal et al. 2015; Evans et al. 2013; Schwartz et al. 2015). Besides, pursuing small financial gains is perceived to be less worth the effort than pursuing similar reductions in CO_2 emissions (Bolderijk et al. 2013; Dogan et al. 2014). Also, people may not respond to financial incentives e.g. to improve home energy efficiency because they do not trust the organisation sponsoring incentive programmes or because it takes too much effort to receive the incentive (Stern et al .2016).

While providing information on the causes and consequences of climate change or on effective action to mitigate or adapt increases knowledge - it often does not result in behaviour change (Abrahamse et al. 2005). To promote climate mitigation and adaptation actions, it is particularly important to provide credible and targeted information at the point of decision (Stern et al. 2016). For example, communicating the impacts of climate change is more effective when provided right before adaption decisions are taken (e.g. before the agricultural season) rather than just making climate change visible by providing information on change itself (e.g., weather forecasts, seasonal forecasts, decadal climate trends, Dorward et al. 2015; Singh et al. 2017). Information provision is more effective when it is tailored to the personal situation of consumers, demonstrates clear impacts, and when it resonates with their core values (Abrahamse et al., 2007; Bolderdijk et al. 2013; Lokhorst et al 2013; Singh et al., 2017; Jones et al., 2016); tailored information prevents information overload, and people are more motivated to consider and act upon information that aligns with their core values and beliefs (Hornsey et al. 2016; Campbell and Kay 2014). Tailored information can, for example, be provided *via* energy audits that are effective to promote energy savings (Abrahamse et al. 2005), and *via* participatory deciphering of climate information and planning based on forecasts that have been shown to promote climate change adaptation actions (Dorward et al. 2015; Singh et al. 2017). Tailored information is key to target the most vulnerable individuals, such as elderly during heat waves. To maximise impact; care should be taken to remove barriers faced by vulnerable groups to receive and interpret such information (Keim 2008; Vandentorren et al. 2006).

Provision of simple, salient and relevant 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 motivate climate change mitigation action by providing information and feedback in a format that immediately makes sense and mostly not requires users' conscious attention. For example, feedback through a lamp that changes colour depending on one's actual energy consumption is more effective than numeric feedback (Maan et al. 2011). Such lighting feedback is particularly effective when colours are used that are associated with energy savings (Lu et al. 2016). Prompts can be effective as they serve as reminders to perform a certain action (Osbaldiston and Schott 2012). Furthermore, feedback is generally effective in promoting sustainable energy behaviour (Abrahamse et al, 2005; Delmas et al., 2013; Karlin et al. 2015), particularly when provided in real-time or immediately after the behaviour has been performed (Darby 2006; Tiefenbeck et al. 2017) as this makes the implications of one's behaviour more salient.

Social influence approaches that emphasise what other people do or think are effective to promote actions on climate change (Clayton et al. 2015), particularly when they involve face-to-face interaction with consumers (Abrahamse and Steg 2013). For example, block leader approaches, where local volunteers initiate or help deliver an intervention are effective in promoting actions on climate change (Abrahamse and Steg 2013), particularly when community ties are strong (Weenig and Midden 1991). Similarly, community approaches where change is initiated from the bottom-up and community members are actively engaged are effective to promote action on climate change (Middlemis 2011; Seyfang and Haxeltine 2012). Furthermore, goal setting and commitment strategies where people make a pledge to engage in climate change actions promote behaviour change (Lokhorst et al. 2013; Abrahamse et al. 2005; Abrahamse and Steg 2013), even more so when individuals additionally indicate how and when they will engage in the relevant actions and anticipate how to cope with possible barriers when they occur (i.e., implementation intentions, Bamberg 2000, 2002).

Goal setting and commitment strategies take advantage of individuals' desire to be consistent (Steg 2016). Similarly, hypocrisy strategies, in which case people are made aware of inconsistencies between their attitudes and behaviour proved to be effective in encouraging actions on climate change (Osbaldiston and Schott 2012; Steg 2016). Moreover, providing social models of desired actions can encourage behaviour change (Abrahamse & Steg 2013; Osbaldiston & Schott 2012). Social influence approaches that do not involve face-to-face interaction, such as social norm information, social comparison feedback and group feedback, are less effective to change behaviour, but are more easily administered on a large scale enabling targeting large groups at relatively low costs (Abrahamse & Steg 2013; Alcott 2011).

Sustainable behaviour can be rewarded and facilitated or unsustainable behaviour can be punished and inhibited (i.e. carrots versus sticks), and behaviour change can be voluntarily (e.g., via information) 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. 2006). 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. 2003). Strategies can target intrinsic versus extrinsic motivation. It may be particularly important to enhance intrinsic motivation so that people voluntarily engage in behaviour that is both sustainable and reduces sensitivity to climate impacts over and again. 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 & Barling 2015; Stern et al., 2016).

Individuals across the world need to engage in many different behaviours to meet the 1.5°C target and to adapt to climate change already occurring, and support climate change policy. Endorsement of mitigation and adaptation 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). Overall, energy efficiency rebound effects are limited, and energy efficiency improvements are not reversed by the rebound effect (Gillingham, Rapson, & Wagner, 2016). 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, general awareness of climate change caused by one's actions and feelings of responsibility to reduce climate change (Hornsey et al. 2016; van der Werff et al. 2016; Steg 2016; Van Der Werff and Steg 2015). Besides, initial climate related actions can lead to further commitment to climate mitigation and adaptation behaviour (Juhl et al 2017) when people learn that such actions are easy and effective (Lauren et al. 2016), and when initial actions make them realise they are an environmentally-sensitive person, motivating them to act on climate change and support climate change policies in subsequent situations to be consistent (Lacasse 2015, 2016; Van der Werff et al., 2014).

4.4.5.4 Acceptability of policy and system changes

Policy and system changes need public support. Public support will be higher when people expect more positive and less negative implications of policy and system changes (Demski et al. 2015; Perlaviciute & Steg 2014; Shwom et al. 2010). Because of this, people generally prefer adoption of energy-efficiency measures above behaviour changes and shift in consumption patterns to reduce their overall energy consumption (Poortinga et al. 2003). Besides, climate change policy and energy system changes are more acceptable when people strongly value other people, nature and the environment (Dietz et al. 2007; Perlaviciute & Steg 2014, 2015; Perlaviciute, Steg, & Hoekstra, 2016; Shwom et al. 2010). Also, public support for climate change policy is higher when people are concerned about climate change, when they think they can engage in effective actions to reduce its negative impacts, and when they feel responsible to act on climate change (Eriksson et al. 2006; Jakovcevic & Steg 2013; Steg et al. 2005).

Besides, perceived distributive and procedural fairness affect climate change policy support (Gross 2007): acceptability is higher when costs and benefits are distributed equally and when nature and future generations are protected (Schuitema et al. 2011; Sjöberg & Drottz-Sjöberg, 2001), and when fair decision-making procedures have been followed, including active public participation (Bidwell 2016; Bernauer et al. 2016; Dietz 2013; Wolsink 2007). Public support for global climate policy is higher when public society organisations have been involved in the process (Bernauer & Gampfer 2013; Bernauer et al. 2016). Providing community benefits to compensate affected communities for losses to ensure distributional fairness enhanced public acceptability of energy projects in some cases (Perlaviciute & Steg, 2014). Yet, people may disagree on what would constitute a worthwhile compensation (Aitken 2010; Cass et al. 2010). For example, offering compensation does not enhance acceptability of the siting of wind farms when procedural fairness is challenged (Cowell et al. 2011) or when people suspect they are being bribed (Cass et al. 2010; Perlaviciute & Steg, 2014).

Public support will be higher when individuals trust responsible parties (Perlaviciute & Steg 2014). Public support is not higher for multilateral climate policy than for unilateral policy (Bernauer & Gamfer 2015); in fact, public support for unilateral, non-reciprocal climate policy is rather strong and robust (Bernauer et al. 2016). Public opposition may result from a culturally valued landscape being affected by adaptation or mitigation options, such as renewable energy development (Warren et al. 2005), particularly when people have formed strong emotional bonds with the place (Devine-Wright 2009, 2013; Devine-Wright & Howes 2010; Perlaviciute & Steg 2014). Also, people may not support adaptation policies that affect their attachment to their place (Adger et al. 2013). Yet, a strong global place attachment promotes climate change concerns and beliefs (Devine-Wright et al. 2015). Public support can increase when people experience positive effects after a policy has been implemented (Schuitema et al. 2010; Weber 2015; Wolsink 2007). It is often believed that climate change adaptation and mitigation actions reduce quality of life, as these actions involve some costs, effort or discomfort (Venhoeven et al. 2013). Yet, this is a limited view of what constitutes quality of life, as it focuses on hedonic and neglects eudemonic aspects. Action on climate change can enhance quality of life as doing so is meaningful. Pursuing meaning and purpose (i.e. euadimonia) by acting on climate change makes people feel good about themselves (Venhoeven et al. 2013, 2016; Taufik et al. 2015), which enhances long-term wellbeing (Aristotle, 2000; Steger, Kashdan, & Olshi, 2008), more so than merely pursuing pleasure. Indeed, pro-environmental actions are related to higher quality of life (Kasser & Sheldon, 2002; Schmitt et al. 2017; Xiao & Li, 2011), and both are higher when people care about the community (Brown & Kasser 2005), suggesting that improvements in wellbeing can be attainable without adverse effects on the environment (Dietz et al. 2009).

Box 4.9: How transport behaviour in Singapore, Stockholm and London has changed

Policy can promote behaviour change. In Singapore, Stockholm and London, significant shares of the city population have changed their travel behaviour, with a noticeable effect on car ownership, pollution and GHG emissions, as a consequence of pricing and regulatory policies combined with flanking policies that support and facilitate behavioural changes. Notably, support for such policies increases when people experience positive effects of policies.

For example, Singapore implemented a combination of policies including electronic road pricing (ERP), a vehicle quota and registration fee system, and investments in mass transit. As a result, per capita transport emissions are approximately 1.25 tonnes of CO_2, which is much lower than cities with comparable income levels. Modal share of public transport was 63% during peak hours in 2013 (LTA 2013), and car ownership of 107 vehicles per 1000 capita (LTA 2017) is substantially lower than in comparable cities. The ERP scheme covers the central business district and major expressways. The vehicle quota system implies that registration of new vehicles is conditional upon a successful bid for a Certificate of Entitlement (Chu 2015), the costs of which were about 50,000 US$ in 2014 (LTA 2015). In addition, a registration tax aims to incentivize purchase of low-emission vehicles through a feebate system.

The Stockholm congestion charge implemented in 2007 (after a trial period in 2006) resulted in a 16% reduction of kilometres driven in the inner city, and a 5% reduction outside the city; traffic volumes reduced by 20% and remained constant across time despite economic and population growth (Eliasson 2014). This resulted in a 2-3% reduction of CO_2 emissions from traffic in the county of Stockholm. The charge implied that vehicles entering or leaving the Stockholm city centre were charged during the day (except for weekends and holidays). Charges varied between 1 and 2 € (with a maximum of 6 € per day) and were higher during peak hours; some vehicles like taxis, emergency vehicles and busses were not charged. Before the introduction of the charge, public transport was extended, and new parking places were created near mass transit stations. The aim and effects of the charge were extensively communicated to the public *via* different channels. Acceptability of the pricing scheme was initially low, but increased substantially after the implementation of the scheme gaining support of about two thirds of the population and all political parties (Eliasson 2014); the initially hostile media became more positive during the trial period and eventually declared the scheme to be a success story. After the trial period, people believed that the congestion charge had more positive effects on environmental, congestion and parking problems and cost increases were lower than they anticipated beforehand (Schuitema et al. 2010).

In 2003, the London congestion charge was implemented in the Greater London area, together with an enforcement and compliance scheme and public information campaigns. All vehicles entering, leaving, driving or parking on a public road in the zone at daytime and weekdays pay a congestion charge of initially £ 8 (till 2005 it was £ 5); some exemptions and discounts are at place. The total number entering the zone decreased by 18% in 2003 and 2004. Vehicle kilometres driven inside the charging zone decreased by 15% in the first year and a further 6% a year later (Santos 2008), and a 20% CO_2 emission reduction from road traffic was observed in the charging zone (Santos 2008).

4.4.6 Enabling technological change and enhancing innovation

4.4.6.1 Recent innovations and their impact on 1.5°C

Several innovations affect the feasibility of a 1.5°C pathway, and the ability to adapt to 1.5°C or higher temperature scenarios. A few telling examples are explained for illustrative reasons and include the costs of solar PV and batteries, as well as advances in artificial intelligence and in computing power.

The cost of the solar PV sharply declined, and the bid price dropped to as low as three cents per kilowatt-hour (kWh) in the United Arab Emirates (UAE) where solar energy conditions are most favourable (IEA/IRENA 2017). The rapid cost decline – more rapid than projections by mainstream models including those assessed in Chapter 2 of this volume – happened due to a combination of policy instruments (primarily feed-in tariffs and feed-in subsidies), mostly in Europe, fast innovation in China, which is now the world's largest manufacturer of solar PV, and spill-over from general technological progress notably from semiconductor industries (Nemet 2014). In addition, the cost of battery sharply declined, thanks to research and development and mass production for portable equipment applications. This resulted in cheaper electric vehicles (Nykvist and Nilsson 2015).

Advances in Artificial Intelligence (AI), by the invention of 'deep learning' technology, in combination with other Information and Communication Technologies (ICT), if deployed for the benefit of mitigation and adaptation, may result in emission cuts that could help reaching 1.5°C. For example, energy management systems have been drastically improved and put in use in factories, offices, and homes (IEA 2017). In addition, the rapid and steady improvement of computing power enabled detailed simulation of material science, and development of highly functional yet inexpensive materials. This, for example, has had impacts on the cost of hydrogen fuel cell vehicles, which have declined (IEA 2017, Iguma and Kidori 2016).

The common thread of the above innovations.is that general progress of technology, such as in computers, ICT, semiconductors, AI, the Internet of Things (IOT), and robotics, has contributed to innovation relevant to mitigation and adaptation. The performance of mitigation technologies has improved, and the costs of mitigation technologies dropped thanks to a combination of specific and more general technological progress (Laitner et al. 2010, IEA 2017).

4.4.6.2 Emerging trends and 1.5°C-compatible technologies and innovation policy

Technology systems evolve over time by combination of existing technologies like biological ecosystems (complex systems theory: see Arthur 2009; Kauffman 2000 for more). The enabling condition for a new technology is sufficient accumulation of prior technologies (called adjacent possibilities). As such, advances in mitigation technologies are often not directly related to dedicated mitigation technology policy. Instead, they have been greatly benefited from the advance of technology in general. For example, utilizing deep learning, a wide range of climate mitigation and adaptation technologies such as intelligent energy saving and precision agriculture are becoming possible. As such, some expect that, in the future, the development of AI and IOT will expand the range of adjacent possibilities. For example, deep learning is used for refining estimates and control of the load of air-conditioning equipment by image analysis of a room and save energy in the office (IEA 2017). Furthermore, by combination of self-driving, car-sharing and electric vehicle technologies, to all of which ICT contributes, it is estimated that significant emission cuts are possible (ITF 2017). For a wider range of ICT-enabled mitigation technologies, see (IEA 2014).

However, to reap the benefits of such innovations, three issues have to be addressed. First, care should be taken that the rebound effects may be as large as the potential emission cuts. Policy intervention may be necessary to reduce such rebound effects (IEA 2017; ITF 2017). Second, climate policy and economic growth or other economic priorities must be compatible, as innovation occurs in virtuous cycle with economic growth (Bresnahan et al 1995) or prosperity. This consideration is important when nations aim at deep emissions cuts such as 1.5°C, as ambitious mitigation policy might undermine economic progress if inadequately implemented. On the other hand, the general notion of economic growth as a necessary condition of addressing climate change and of innovation is contested (e.g., Klein 2014). Third, regulatory systems must be supportive of innovation. It was argued that ICT innovation in Europe had been greatly delayed compared to the United States due to heavy security regulations that impeded free corporate activities (Thierer 2016). However, 'permissionless innovation', as argued by Thierer (2014) is not generally favoured though; other authors argue for a greater directional role in governmental support and regulation around innovation (e.g., Mazzucato 2013).

Although ICT, including AI, may enable emission cuts through various channels mentioned above, it is very difficult to predict the pace and potential in quantitative manner, since we do not know how fast ICT and how wise AI will be at all beyond 2020, let alone 2050. AI may outperform human-beings to the extent it replaces labour at most workspace known today (Brynjolfsson and McAfee 2011; Ford 2009). Furthermore, it may improve the manufacturing process of the solar cell, and the installation work of photovoltaic systems (PV) may be carried out by robots, cutting so-called Balance of Systems costs. As such the cost of the PV may further be reduced (IEA/IRENA 2017).

4.4.6.3 1.5°C-relevant insights from innovation policy

Although mitigation and adaptation technology depends on broader technological advances and developments in the broader innovation system, innovation policy directed at mitigation or adaptation can make a difference. Dedicated policies for mitigation technologies remain important. In this light, there have been many calls for increasing R&D funding for climate mitigation and adaptation (examples). In 2015, twenty countries responded by an initiative called 'Mission Innovation', and committed to doubling their energy R&D funding, although 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'.

The climate-resilient pathways in Chapters 2 and 5 require new technology and more widely-applicable, lower-cost, existing technology. This will not sufficiently come about autonomously (IPCC WGII 2014 Chapter 15, GEA 2012). Governments have employed various different innovation policies. Revenues for R&D could come from the general budget, but could also be generated by carbon pricing schemes (see also section 4.4.7) or, for instance, energy or resource taxation. Investing in climate-related R&D has as an additional benefit in building up of capabilities to implement climate mitigation and adaptation technology (Coninck and Sagar, 2015), see also Section 4.4.4.

4.4.6.4 Technology and the implementation of the Paris Agreement

Technology transfer and innovation are recognized as enablers of both mitigation and adaptation in the Paris Agreement, and well before that in the UNFCCC (UNFCCC 1992:Article 4.5). It is obvious that technology transfer and innovation can help adapting technologies to local circumstances, reduce costs, develop indigenous technology, and build capabilities globally (Ockwell et al. 2014). A 1.5°C world is hard to imagine without a significant increase in global R&D expenditures, and development of innovation systems and associated capabilities around technologies for mitigation and adaptation in all countries (Coninck and Sagar, 2017, forthcoming).

The international institutional landscape around technology transfer and innovation includes the UNFCCC (*via* its technology framework and technology mechanism), the UN (a technology facilitation mechanism for the SDGs) and a huge variety of non-UN multilateral and bilateral cooperation initiatives, such as Mission Innovation (founded in 2015), 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. By far most technology transfer is happening driven by human needs and markets, in particular in areas with growing institutional and innovation capabilities (Glachant and Dechezleprêtre 2016), and the current landscape does leave gaps, in particular in least-developed countries, adaptation and innovation capabilities (de Coninck and Puig 2015). Literature suggests that the management or even monitoring of all these initiatives will fail to lead to better results; it is more cost-effective to 'let a thousand flowers bloom', while at the same time challenge and entice researchers in the public and the private sector to direct innovation towards low-carbon options (Haselip et al. 2015).

For adaptation specifically, Olhoff (2015) argues that networks can build capabilities globally on adaptation technologies (and options and policies), 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 an 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), which, among other things, should facilitate the undertaking 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.

4.4.7 Strengthening policy instruments

The immediate policy challenge raised by the transition to a 1.5°C world is to trigger drastic and almost immediate changes in technical choices, land-use patterns, urbanisation, lifestyles, consumption and behaviour. This will need to be enabled without negative socio-cultural and political responses that could block the transformation process, from the outset.

This builds on an old debate in public economics about the relative weight and effectiveness of 'command and control' measures and price signals to coordinate individual and collective behaviour. The first entails the risk of political arbitrariness and of raising the costs of climate policies to politically infeasible levels. The second can lower arbitrariness and policy costs but are limited by potential market and governance failures that are not easy to mitigate against. The core challenge of the Paris Agreement of realizing a 1.5°C world, may require the effective use and design of 'price signals', various forms of 'market-based instruments', along with appropriate regulation and financial incentives, depending on the region and country in question.

The nature of the challenge: questions of costs and equity

Whatever the content of the policy-mix, the low-carbon transition will imply higher short-run energy costs, owing to off-setting existing infrastructure lock-ins and making a transition out of climate incompatible path dependencies. Negative cost measures exist (Section 4.3.6) and some lifestyle changes can take place without price signals (Section 4.4.5) but their pace of deployment will be constrained by the inertia of existing capital stocks, market structures and lack of enabling conditions, cultural habits and behaviour. Therefore, a range of policy and market incentives will be needed to accelerate the deployment of carbon neutral technologies, before they are more cost-effective than conventional fossil energy.

The order of magnitude envelope for the worldwide marginal abatement costs for a 2°C target in AR5 was: 35-60 \$ t^{-1} in 2020, 62-140 \$ t^{-1} in 2030 and 140-260 \$ t^{-1} in 2050. While, these estimates can be challenged, their lower bound relies on optimistic technical assumptions, coming from models assuming least-cost planning with neither market imperfections, including missing or informal markets, nor uncertainty for decision-makers and in some cases.

Technical change can be accelerated by learning-by-doing processes and R&D, to accelerate the cost-effectiveness of low carbon technologies. However, in all these processes, the deployment of the new techniques implies higher costs at its early phase. This is why the German energy transition, resulted in the highest consumer prices for electricity in Europe, and needed to be supported by strong non-price policy measures. At the global level high energy costs tend to propagate from one sector to another amplifying overall production costs, depending on the structure of the economy under consideration. 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 purchasing power of wages and lower final demand for non-energy goods.

Higher energy prices may thus have adverse effects on the distribution of welfare, potentially exacerbated by slower economic growth in the absence of accompanying policies. The negative welfare impact is typically, inversely correlated with the level of income (Harberger 1984; Fleurbaey and Hammond 2004) and with the share of energy in the households budget for low - and middle - income households in temperate and cold countries (Hourcade et al. 2012; Guivarch and Hallegatte 2011; Chiroleu-Assouline et al. 2011; CORNWELL and CREEDY 1996; Cremer et al. 2003; West and Williams 2004) (Proost, et al. 1995, Barker et al. 1998). Here, vulnerability to high energy prices depends upon heating and mobility needs 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 will also be impacted by an overall price increase of non-energy goods.

A unique global carbon price is hard to implement because of the huge discrepancies in *per capita* income and the difficulty of large international compensatory transfers, exacerbated by purchasing power parity (PPP) exchange rates in poorer countries (e.g. 1.8 in China and Brazil, 2.3 in South Africa and 3.8 in India). Hence, a second matter of concern, in a minority of regions, is the distortion of international competition by heterogeneity of carbon constraints (Demailly et al. 2009) 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 (Demailly and Quirion 2008; Sartor 2013) while others could suffer a sufficiently severe shock to generate 'carbon leakage' that is cheaper imports of goods from countries with lower carbon constraint (Branger et al. 2016). This can weaken the surrounding industrial fabric with serious economy wide and employment implications.

A third challenge during the carbon transition, weakly reflected in scientific literature, is the depreciation of assets whose value is based on carbon-intensive capital stocks, like coal-fired power 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 resources not yet transformed into economic production as in the case of coal, gas and oil production, where future revenues may decline precipitously with higher carbon prices (Waisman et al. 2013; Jakob and, Hilaire 2015; McGlade,and Ekins 2015).

4.4.7.1 Mastering the cost-efficiency-equity challenge

After a quarter century of policy experimentation and economic literature on carbon pricing (IPCC TAR, AR4 and AR5) 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 \$ 10 ton^{-1} of CO_2 (World Bank 2016).

A dominant share of climate and energy policies mobilize non-price instruments (technical regulations and standards, financial instruments, infrastructure projects, information and training) but these policies also entail mobilization of economic resources at higher energy costs, at least in a first phase, when there may be a major difference between the explicit price and implicit cost of carbon.

A transition to a 1.5°C world requires, even more than for less stringent targets, the prioritization of policies that enable a minimisation of social costs. In principle, this implies that: (1) that marginal costs of abatement are equated across all sources of emissions; (2) investors *a priori*, make the right financial and technical choices, without any information asymmetry; and (3) the general equilibrium effects of higher energy prices are managed to minimize their negative impact and potentially to even transform it a positive gain. Many low carbon transition assessments are primarily based on partial equilibrium frameworks with very attention to economy wide implications.

In a frictionless world, explicit carbon prices equal to marginal abatement costs could secure the cost efficiency of climate policies sending a clear signal in favour of decarbonisation to all economic actors provided the adverse distributive impacts of higher energy costs are offset through compensating transfers. Off-setting mechanisms will be a critical challenge for which a transparent institutional and governance architecture will be required to be set up. Balancing distributional implications are usually inter-temporal affairs with large cost-benefit uncertainties in space and time.

In practice, explicit carbon pricing can offset the propagation effect of high energy costs because they raise significant revenue, that can be recycled using a 'revenue neutrality' condition into reducing more distortionary taxes (Stiglitz et al. 2017). They could help lower technical abatement costs by reducing social charges imposed on production, a challenge if a major part of the market transaction happens informally. Even setting up such frameworks will be challenging, particularly in developing countries, from the perspective of informational access cost and reliance on voluntary disclosures.

Substitution of direct income taxes with carbon taxes is a positive measure, both in countries with a high level of social security as well as those that are building their social welfare system, like China (Li and Wang 2012). This substitution, *via* an effective fiscal transfer from energy intensive sectors, could lead to lower energy intensity and hence lower production costs in decarbonising economic sectors.

Explicit carbon taxes can also help in offsetting the adverse redistributive effects of higher energy costs. They can do this by redistributing part of their revenues through direct rebates or cash transfers to households. If rebates are divided equally, adjusted for household size, then most people, especially poor households, would be even better off after the imposition of a carbon tax. These positive distributional effects are typically due to the larger share of wages in the total income of poor households compared to high-income households who have other sources of income from capital, such as interest and rents. Even though their carbon fee burden may be a relatively smaller share of their overall income, higher income people pay more in absolute terms and the revenue would be redistributed across all households (Arze del Granado, Coady, and Gillingham 2012). The balance between the share of the revenues of carbon taxes that can be used to offset redistributive, reduce the inflationary effect of higher energy prices, is country specific, depending on its income and production structure (Combet et al. 2010); Combet et al. 2015). The efficiency of this recycling depends on a country specific market and potential local institutional distortions.

Explicit carbon pricing offers a good tax base, as it is difficult to evade, thereby decreasing the gap between the tax burden across the formal and the informal labour market (Bovenberg 1999; Goulder 2013). This could lead to lower labour cost, potentially reducing unemployment, helping to increase real wages, thus counteracting the recessive effect of higher energy prices. Therefore, recycling carbon tax revenues maay lead to a double dividend of fostering the decarbonization transition while simultaneously promoting economic growth and social development (Combet et al., 2015; Grottera, William, and La Rovere 2016; La Rovere et al. 2017; Goulder 1995). This is why numerous studies highlight the potential benefits from such reforms to turn technical costs into economic gains (IPCC 2007, 2001) under certain conditions (Goulder 2013; R. A. de Mooij 2000) offering a 'double dividend' by providing both environmental benefits and an aggregate economic gain.

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

Explicit cross-sectoral and global carbon prices could be the 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 (Greening et al. 2000; Sorrell et al. 2009).

An 'implementation gap' is likely to persist between medium-run carbon prices calculated in models that align them with levelled costs of technologies and the 'switching carbon prices' needed to trigger abrupt changes in behaviour or innovation (180). First, their level should be higher than in climate models because they need to outweigh the 'noise' from: the volatility of oil markets (in the range of \$ 100 tCO_2^{-1} over the past decade), other price dynamics (interest rates, currency exchange rates and real estate returns) and regulatory uncertainties in the energy, transportation and industrial sectors. As an example, the dynamics of mobility depends to a great extent upon 'commuting costs', the trade-off between housing prices and transportation costs (Lampin et al. 2013) and 'spatial planning'.

Second, they have to be embedded in a consistent set of fiscal and social policies, so that a carbon price can be perceived as a desirable signal instead of an arbitrary burden. When systemic changes are at play on many dimensions of development, switching carbon prices are contingent upon other policy means. This is the old lesson that prices levels 'depend on the path and the path depends on political decisions' (Drèze and Stern1990).

These considerations have been reflected in attempts to secure a minimum carbon price in existing emissions trading systems (Fell et al 2012; Wood et al 2011; Fuss et al 2017) and *via* pricing mechanisms like fee-bates or 'bonus-malus' that foster the penetration of low carbon options (Butler and Neuhoff 2008). It also applies to the reduction of fossil fuel subsidies, which are estimated at \$ 548 billion in 2013, or 5% of the GDP and 25-30 percent of government revenues in forty mostly developing countries (IEA 2014). The OECD estimates that its member countries spent \$ 55-90 billion a year subsidizing fuels over 2005-2011 (OECD 2013) and \$ 650 billion in 2015 (Coady et al. 2016). Banning these subsidies is urgent from a below 2°C perspective, but raises the same issues as carbon pricing with long-term benefits and short-term social costs

(Jakob et al. 2015; Zeng et al 2016).

Any transition to a 1.5°C world may therefore, require coordinating a complex set of 'signals' to shape long term expectations, and align a low carbon transition with equitable access to development opportunities, entitlements and benefits.

The potential of implementing policy packages, rather than discrete policies, was indicated in AR5. For example, to enable a 1.5°C transition, carbon pricing may need to be combined with non-price policies including efficiency standards, due to high consumer discount rates and price inelasticity (Parry et al. 2014). Over the past two decades, regulatory instruments have been effective, cost-effective and primary tool of achieving energy efficiency improvements, enhancing renewable energy penetration and enabling increased energy savings in OECD countries (e.g., US, Japan, Korea, Australia, the EU) and more recently in other countries (e.g., China) (Scott et al. 2015; Brown et al. 2017). Many developing countries are adopting these policy instruments to avoid import of products banned in other countries, but there is still a large technological efficiency potential (Knoop and Lechtenböhmer 2017) in equipment and buildings to be captured.

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 to 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 successful 'Top Runner' programme for domestic appliances in Japan.

Regulation and standards have been effectively used in the transport sector, for light and heavy-duty vehicles by imposing efficiency requirements (e.g. miles/gallon or level of CO_2 emission per km). In the EU, regulatory instruments are imposed on manufacturers (Ajanovic and Haas 2017), which require them to meet a certain target of annual fleet CO_2 emissions for new vehicles. A similar instrument exists in the US - the CAFE standard (Sen et al. 2017). A fleet target allows manufacturers to continue selling high emission vehicles to be compensated by the entry of low emission vehicles, into the fleet, with a gradual reduction of fleet emissions over time. This regulatory instrument assures more efficient vehicles, but does not limit the driven distance. Nevertheless, 'rebound' effects, of increased emissions, driven by efficiency gains can take place in the absence of high carbon prices, which can offset the expected savings (Freire-González 2017; Chitnis and Sorrell 2015).

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). Building codes are regularly revised prescribing an increased level of efficiency, either through the prescriptive use of efficient technologies and insulation levels or through energy or CO_2 limits per unit floor space. This instrument is very relevant for countries with rapid urbanisation and a large share of new construction, to avoid the lock-in effect of new poorly performing buildings remaining in use for the next 50-100 years. As the rate of new building construction is low in many OECD countries, it is important to incentivize the retrofit of existing buildings, to adopt energy efficiency and renewable energy measures. As indicated in Section 4.3.4 on Net Zero Energy Buildings is where Building codes for both new and existing buildings should converge (D'Agostino 2015). Expanding consumption and emission levels need to be addressed for equipment, vehicles and buildings. (Bertoldi). In the context of a 1.5°C world these policy instruments will require public and private co-ordination including with urban policies.

Another set of policies to foster investment in low carbon-technologies, are grants, subsidies, loans and feed-in tariffs. Grants are mainly used to support R&D, where risk and long-term perspectives reduce the private sector's willingness to invest (e.g. nuclear fusion research). Subsidies are used to fostering market penetration of low-carbon technologies and can take the form of tax rebates (e.g. lower VAT or a rebate on income tax), subsidies for investments (e.g. renewable energy or refurbishment of existing buildings), rebates for consumers and manufacturers, and feed-in tariffs (Mir-Artigues and del Río 2014). Subsidies may be provided from the public budget or via consumption levies (e.g. on kWh); carbon taxes or via a cap-and-trade systems. To have a neutral impact of national budgets the feebates 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).

An alternative form of subsidy is the feed-in tariff that is based on the quantity of renewable energy produced or by energy saving resulting from efficiency improvements and/or energy conservation 'nega-watts' (Ritzenhofen and Spinler 2016; Pablo-Romero et al. 2017; García-Álvarez et al. 2017; Bertoldi et al. 2013).

Information campaigns are a common instrument used by national and local governments 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 *[ref]*, 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, as a way of motivating citizens and altering behaviour (Allcott 2011; Alló and Loureiro 2014)(Also see Section 4.4.5 for more details).

Efficiency standards are not disconnected from the use of market based instruments (Haoqi et al. 2017). Such a combination has 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 the utilities energy sales and others scholars have investigated emission caps at a personal level (Sioshansi et al. 2010). A key to the success of these policies is stringent obligations (i.e. the cap), as well different options to set the cap according to the interaction between energy markets and other policy instruments (García-Álvarez et al. 2017; Bhattacharya et al. 2017).

Voluntary actions by non-governmental actors are gaining importance and could make a, important contribution to achieving a 1.5°C world. Commitments by local authorities and cities, as in the Covenant of Mayors in the EU and the US, where many cities have committed to long-term targets of 60% to 80% emissions reductions, some becoming carbon-neutral by 2050 (Kona et al. 2017).

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 policies can undermine their efficiency (Lecuyer and Quirion 2013). See also Box 4.4 for evidence from case studies.

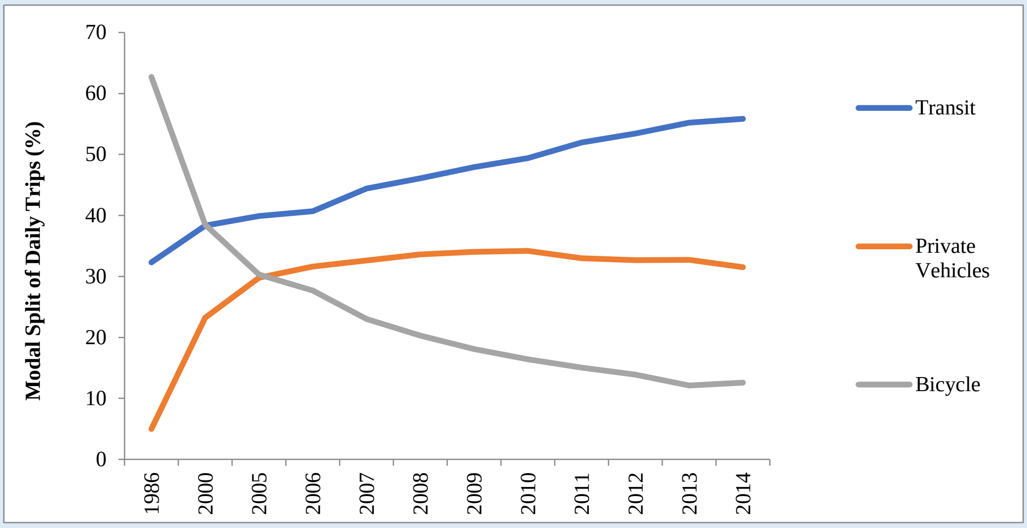
The simultaneous launch of multiple policies in many domains in a regional context where carbon prices are too low to hedge against their arbitrariness is challenging. A well-established tradition in public economics is to resort to implicit (notional) prices representing the social values of public goods, to hedge against such a risk. Such notional carbon prices have been adopted in countries like the US, the UK and France, but do have the volume, price level nor the 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 article 108 of the Paris Agreement) represent the Social Value of Mitigation 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, non-price policies and financial incentives to catalyse savings towards low carbon investments. One sign of success of these policy packages will be to 'make finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development' (Paris Agreement, Art. 2). This will depend upon their capacity to resist regulatory uncertainty (Laffont and Tirole,1993), which cannot be completely overcome. Even well-designed policies will have to be adapted in response to implementation experience, as empirical evidence from case studies in Box 4.10 underline.

Box 4.10: Emerging Cities and Peak Car Use: Evidence from Shanghai and Beijing

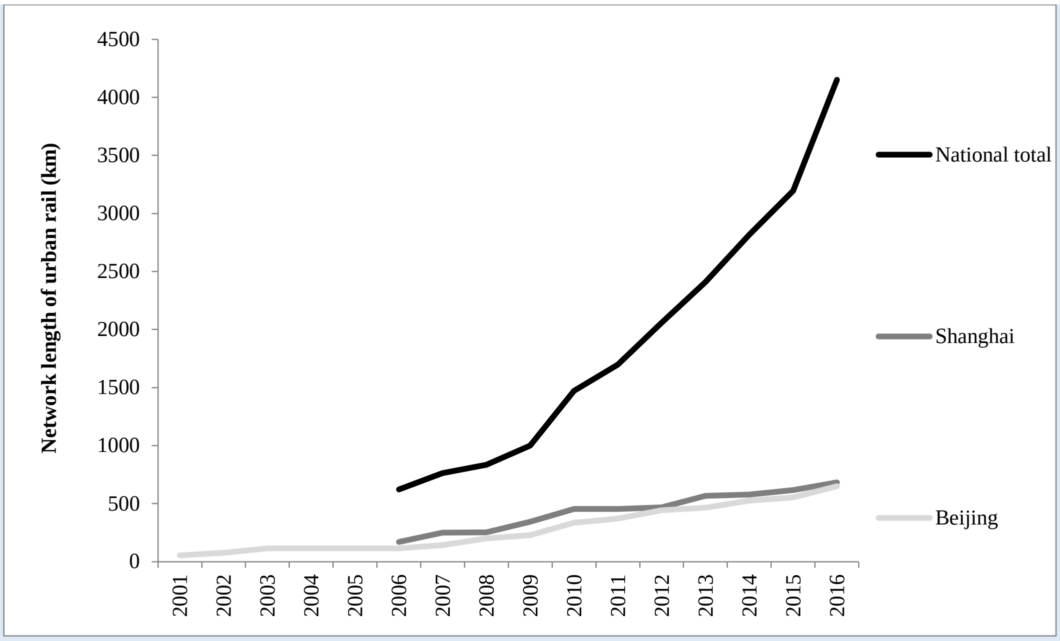
The phenomenon of 'peak car', reductions in per capita car use, provide hope for continuing reductions in greenhouse gas from oil consumption (Millard- Ball and Schipper 2011; Goodwin and Van Dender 2013; Newman and Kenworthy 2011). The phenomenon has been mostly associated with developed cities, though 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 *[ref]*.

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 *[ref]* 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 4.10, Figure 1).



Box 4.10, Figure 1: The modal split data in Beijing indicating the peaking in car use as mass transit growth takes over. Source: (Gao et al. 2017)

Similar trends are observable in Shanghai (Gao et al. 2017). This is explained by Gao et al (2017) by understanding how Chinese urban fabrics, featuring traditional dense linear forms and mixed land use, favour such mass transit systems over automobiles. However, it does require investment and as shown by Box 4.10, 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 (Gao et al. 2017).



Box 4.10, 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 (Gao et al. 2017)

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 and 194 million EV cars in 2017 (Gao et al. 2017). The transition to an all-electric transport system is well underway in China, suggesting there is a model for emerging cities and nations that can enable this important dimension of the 1.5°C agenda *[ref]*.

Box 4.11: 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, other 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 optimizing 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 have been conducted on a number of national case studies.

The Deep Decarbonisation Pathways Project (DDPP) provides a common frame for designing country-driven low-emission scenarios (Bataille et al. 2016). This analysis, conducted for 16 countries covering 70% of world emissions helped identifying country-specific policy packages and obstacles to a transformation consistent with domestic socio-economic priorities (DDPP Network 2016).

The CD-LINKS project has developed guidelines for 17 national-level case studies of past and ongoing policies at the interface of climate and development with a balanced regional coverage across the G-20. Pahle et al. (under review) present the synthesis with findings based on three criteria: (1) policy effectiveness; (2) policy robustness; and (3) ability to monitor and evaluate performance.

A common finding of these two projects is that the effectiveness of policy-packages depend 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 for example 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) on the potential of current policies to contribute to a rapid exit from coal, necessary to enable the 1.5°C transition (Spencer *under review*), 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. *under review*).

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. 2016). Both scenarios achieve ambitious decarbonisation, of an 80% decrease of the ratio of carbon emissions to GDP between 2010 and 2050. But this is achieved with lower ranges of absolute carbon prices compared to those reached in other developed 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 (Oshiro et al. 2016).

Durability 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. *under review*).

Other lessons concerns the performance of market mechanisms. In a case study on China's wind power program, a gradual shift to market mechanisms is considered necessary to sustain the promotion of wind power. Yet, commitment problems and lack of credibility and transparency of regulation have consistently led to low carbon prices, for example in the case of the European Emissions Trading Scheme (Koch et al. 2014, 2016). (Hoch 2017) examine the cases of 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, and conclude that auctioned price floors for emission reductions could provide an alternative to existing public climate finance strategies.

Finally, a common lesson identified (Pahle et al. *under review*) is that the lack of data on policy performance and cost observed in almost all case studies, along with frequent changes of policies in many assessed cases, undermine the ability to monitor and evaluate policies. A 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 - a serious knowledge gap in climate policy.

4.4.8 Enabling climate finance

Finance plays a critical role in governing long-term market responses. There are however, some concerns about the short-term bias of climate finance (Black and Fraser 2002; Bushee 2001; Miles 1993). This has been previously explained by 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 the risks of debt accumulated via leverage-by-outs.

This bias typically leads to chronic under-investment in long-term projects and unrealistic expectations on financial returns from low-carbon investments. It therefore, needs more than direct carbon pricing to deliver this transition. At a minimum, it will require the building of appropriate financial intermediation to make low-carbon assets attractive for savers and tempering the current market preference for liquidity.

4.4.8.1 The quantitative challenge

Many assessments have been made by expert groups of the investment needs for a 2°C target. The World Economic Forum (WEF 2013) estimates that $ 85 trillion in investment in low-carbon infrastructure is required by 2030 to meet a 2°C target. The Global Commission on the Economy and Climate (GCEC 2014) has a higher estimate, of $ 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, that is an additional $ 10 trillion per year in the ‘two to three years after 2018’ (Wolf et al. 2017).

One difficulty is that, while investments in the energy sector and energy efficiency are well identified, investments needs to decarbonize transportation and other infrastructure are poorly defined. The Cities Climate Finance Leadership Alliance e.g. notes that ‘global demand for low-emission, climate-resilient urban infrastructure will be in the order of $ 4.5 trillion to $ 5.4 trillion annually from 2015 to 2030’ (CCFLA 2016). There is also large uncertainty about upstream investments in the material transformation and manufacturing sectors. One first attempt to assess them suggests a multiplier effect of 1.2 (Aglietta et al. 2015b).

[A consolidated table to clarify the orders of magnitude at stake will be presented in the SOD]

Whatever their uncertainty, these figures amount to about 0.5% to 0.8% of world GDP for the 2°C target and an increase of between 2-3% of the total Gross Capital Formation in comparison with a non-climate policy scenario. This increase is higher in most developing countries (IEA 2014) because they typically are in a catch-up development phase, with heavy dependence on energy and energy-intensive sectors.

A critical issue is whether the low-carbon transition will imply a drain on consumption (Bowen et al. 2017). The consumption response can be influenced by the use of appropriate policies, for example drawing upon savings allocated to the real-estate sector and liquid financial products, or enabling the redirection of savings to productive carbon-sensitive investments (Summers 2016; Teulings and Baldwin 2014; King 2010).

The financial flows for 1.5°C transitions seem to more significant that estimated by most climate models. First, the up-front investment costs are 1.9-3.2-fold higher than estimates relying on levelized costs (World Bank 2016). Second, the amount of redirected investments in mitigation is far higher than incremental investments because most of low-carbon technologies are not end-of-pipe equipment, and may involve significant incremental capital investments over conventional carbon-based options. Aglietta et al. (2015b) estimate the redirected investment to be around three times higher than the incremental investments. Third, the notion of incremental costs is not relevant in a below 2°C world because the first priority is to reduce the funding gap for low-carbon, climate resilient infrastructures in many developing countries (Arezki et al. 2016). Once that gap has disappeared, so have incremental costs. Fourth, funding needs depend upon the magnitude of the risk-weighted capital costs, which are higher than the typical capital costs.

Ultimately, whether the transition to a 1.5°C world will be confronted by insurmountable macroeconomic challenges or will help regional and global economic recovery will depend on the evolution of a financial system that bridges the regional and temporal gap between short-term cash balances and long-term low-carbon assets.

4.4.8.2 Redirecting savings and de-risking low-carbon investment

The financial community's attention for climate change grew after COP 15 in Copenhagen in 2009 (Gros et al. 2016). The three-risk alert by the Governor of the Bank of England on the Tragedy of the Horizons (Carney 2016) is confirmed by literature: the physical risk of the impact of climate events on the value of financial assets (Battiston et al. 2017), the liability risk (Heede 2014) and the transition risk due to devaluation of entire classes of assets (Platinga and Scholtens 2016). These factors represent a potential threat to the stability of the global financial system (Arezki et al. 2016; Christophers 2017). The transition risk will be exacerbated by the 1.5°C imperative, while physical risk would be mitigated.

The UNEP-Inquiry (2015), the G20 Green Finance Study Group and the Financial Stability Board (2015) also focus on the importance of transparency and of the disclosure of climate-related risks in financial portfolios. For instance, France adopted a mandatory disclosure (see Article 173 in its 2015 Energy Transition Law). Such disclosure obligations might lead to the creation of low-carbon financial indices that investors could consider as a 'free option on carbon' and as a hedge against a cap on emissions (Andersson et al. 2016).

With the possible exception of REDD+ for forest protection, which tried to leverage private finance (Laing et al. 2015), the movement to accelerate the emergence of climate friendly financial products is too recent to have been analysed by scientific literature. Estimates of green bonds issuance, largely due to the momentum of private capital, are about $ 200 billion in 2017 according to Moody (BNEF 2017). However, there is an accounting challenge due to the lack of standardization of what is a 'green bond' and of the control of their 'greenness'. Another is that relying on climate-related information alone assumes that the 'efficient market hypothesis' applies, that is integrating all climate uncertainties into an ex-ante probability distribution to enable the financial system to allocate capital in an optimal way (Christophers 2017). It is argued that climate change is unhedgeable by individual strategies (Kelly and Reynolds 2016) and is a systemic risk (Schoenmaker and Tilburg 2016). The debate on this theme is only just starting.

The voluntary disclosure approach may be a first step to encourage financial actors to stop investing in fossil fuels (Ayling and Gunningham 2017; Platinga and Scholtens 2016). In the absence of structural incentives, asset managers might not resist the attractiveness of carbon-intensive investments in many regions. Decarbonizing an investment portfolio is not synonymous with investing in a low-carbon development path.

The crux of the challenge is to: (1) link the emergence of climate-friendly financial products with the reduction of the risk-weighted capital costs of low-carbon projects; and (2) increase the quantity of bankable projects at a given carbon price. The specific barrier problem of low-carbon investment is a low 2 to 4 leverage compared with a degree of leverage of 3-15 range for other public funding mechanisms (Maclean et al. 2008; Ward et al. 2009). This weak financial performance is due to the interplay between the intrinsic uncertainty of low-carbon technologies in the mid-term of their learning-by-doing cycle, of future revenues because of the volatility of oil and gas prices (Gross et al. 2010; Roques et al. 2008), and of the very regulatory risks about carbon pricing policies. This is not only an inhibiting factor for corporations functioning under a 'shareholder value business regime' (Berle and Means 1932; Roe 2001; Aglietta 2015; Froud et al. 2000), but also for cities and local authorities, SMEs with restricted access to capital, and households with high discount rate preferences (when they invest in energy efficiency). For these economic actors the expected 'reward' of carbon taxes or carbon prices on the current carbon market come too late to compensate for uncertainty about the technical performance of low-carbon projects and about the 'reward' itself.

Recent literature therefore places a focus on policy instruments aimed at de-risking, ranging from interest rate subsidies, feebates, tax breaks on low-carbon investments, concessional loans from development banks, and public investment funds. These instruments will need to incorporate an agreed Social Value of Mitigation Activity to reduce the risk of arbitrariness and ensure the overall economic efficiency of climate policies (Hourcade et al. 2015; La Rovere et al. 2017).

Many proposals have been made around the use of public guarantees to secure high leverage public financial support to reduce regulatory uncertainty for example Green Infrastructure Funds managed by a multilateral development fund (Studart & Gallagher, 2015; De Gouvello and Zelenko 2010; Emin et al.)[1]. An advantage of public guarantees is that they imply a direct burden on taxpayers only in case of default of the project; a risk that can be mitigated by strong Monitoring Reporting and Verifying systems (MRV) (Bellassen 2015). Another advantage is a lower risk-weighted capital cost of low-carbon investment supported by public guarantees compared to the present value of project SVMA (Hourcade et al. 2012). Hirth and Steckel (2016) show the substitution curve between carbon price and decreasing capital costs that could trigger a given amount of investments, which is important for developing and emerging economies, where capital costs tend to be higher than in high-income countries (Steckel 2016; De Gouvello and Zelenko 2010).

Combining public guarantees and a predetermined value of avoided emissions would improve the consistency of non-price measures by using a common notional price in projects' selection and support the emergence of financial products backed by a new class of certified assets to attract savers in search of safe and ethical investments (Aglietta et al. 2015b). It could dispel suspicions about the 'green-washing' of financial flows and hedge against the fragmentation of climate finance initiatives. However, these market-based mechanisms may not be appropriate to respond to non-market priorities like the provision of infrastructure for basic needs and the enhancement of adaptive capacities, which may need overseas development assistance, innovative removal of fossil fuel subsidies (Jakob 2016) and introduction of carbon taxes (Jakob 2016).

4.4.8.3 Public commitments and evolution of the financial systems

Public guarantees have been a privileged national tool to enable systemic transformations like the deployment of the railway systems at the end of the 19th century. Such guarantees in the climate case amount to quantitative easing of monetary policy with money issuance backed by the low carbon projects as collateral. Amongst suggested international mechanisms are the use of Special Drawing Rights of the IMF to fund the paid-in capital of the Green Climate Fund (Bredenkamp and Pattillo 2010), and public guarantees at a pre-determined face value per tonne to refinance low-carbon loans (Aglietta et al. 2015a,b). All these proposals are tentative and demand further scrutiny. Yet, they might be needed to accelerate on three aspects, which are outlined below.

First, the access of developing countries to affordable loans *via* bond markets and lower exchange rate risk, which constitutes a barrier for large classes of long-term investments. Given lowering support for ODA in developed countries, such loans might be the only way of establishing a burden sharing mechanism between rich and poor countries that enhances reciprocity and enables countries to deploy ambitious NDCs, including the increase of their domestic carbon prices (Edenhofer et al. 2015; Stern-Stiglitz 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; and 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' syndrome (Venables

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

2016; Ross 2015)

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

Public guarantees and the involvement of non-state actors are also important for investments enhancing the adaptive capacity of societies to climate change. However, the economic rationale of these investments differs from mitigation investments because (1) their social value cannot be expressed in a ‘per tonne’ metric; (2) climate models are not very good in predicting the consequences of global warming at regional scales; (3) the challenge to reduce investment deficits on basic infrastructure; and (4) they concern non market-based services. This implies that adaptation investments could remain in the domain of domestic or overseas development assistance, also given the recent decline of the CER prices.

One issue under debate is the premise that money should remain neutral (Annicchiarico and Di Dio, 2015; Annicchiarico and Di Dio, 2016 Nikiforos and Zezza, 2017). This implies that central banks could act as a facilitator of low-carbon financing instruments, while ensuring better the stability of the financial system. This might lead to the use of carbon-based monetary instruments to diversify reserve currencies (Jaeger et al. 2013)and to differentiate reserve requirements (Rozenberg et al., 2013) in a prospective Climate Friendly Bretton Woods (Sirkis 2015; Stua 2017).

An unresolved macro-economic debate is whether investing in low-carbon programmes or adaptation projects would ultimately be cost-saving (NCE 2016) and could unlock new economic opportunities (GCEC) 2014), without crowding out private or public investments (Pollitt and Mercure, 2017). This could be done injecting liquidity into the low-carbon transition *via* underinvested infrastructure sectors (IMF, 2014) that have a potential ripple effect large enough to trigger a new growth cycle (Stern 2015, 2013). This could, if managed appropriately, assist managing the dangerous waters between stranded assets and green financial bubbles (Safarzynska and Van den Bergh, 2017).

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. A key strategy to successfully enable this is to 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 2016).

4.5 Integration and enabling transformation

4.5.1 Knowledge gaps and key uncertainties

Concerning the pathways keeping global warming to 1.5°C by 2100, new scenarios show how mitigation would need to respond – both in terms of an increased scale and a more rapid pace. 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. Furthermore, while there are rates of change in energy and land transitions available, they do not reflect short-term changes and tipping points that are emerging for some renewable energy options. Finally, 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.

However, when looking at impacts and adaptation, to date 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 when overshooting the target during the century. In particular, there is a lack of knowledge on how much climate damage at the global level is reduced as a result of being more ambitious and an absence of information on avoided adaptation investments associated with keeping warming to 1.5°C compared to business-as-usual or keeping warming to 2°C. The available evidence outlined in Section 4.2 is mostly on specific impacts in specific regions that will not allow any sort meaningful comparisons or generalization aiding implementation. Furthermore, relatively literature has been published on individual adaptation options since AR5 – as evident from the assessment in Section 4.3 - and neither are there any 1.5°C-specific case studies In addition, the literature on effectiveness of current adaptation is very 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 for which mitigation and adaptation options have been assessed in this chapter, 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 climate change in cities in different parts of the world is needed for this. Similarly, including the criteria of justice in climate responses is a key omission in the current literature. Furthermore, the possibility of a new city/urban science that bridges disciplinary boundaries and practices a mix of approaches to create an evidence base for action should be explored. In this context, it is also important to better understand processes and mechanisms linked to co-design and co-production of climate knowledge (across practice and research, across multiple actors), particularly at the science-policy interface. On the economic side, regional and sectoral adaptation cost assessments are missing, particularly in the context of welfare losses at household level, across time and space. Related to this, 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 then needed on hot-spots, for example the growth of peri-urban areas, populated by large informal settlements. Finally, major uncertainties emanate from the lack of knowledge on integration of climate adaptation and mitigation, disaster risk reduction, and urban poverty alleviation.

For the land system, land-based mitigation will play a major role in 1.5°C stabilization pathways and more knowledge is needed with respect to how this can be reconciled with land demands for adaptation and development. However, while there is now more literature on the underlying mechanisms at work here, data are often more than 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, which can help to fill this gap. This lack of data counts especially also for social and institutional information, which is therefore also not integrated in large-scale land use modelling.

For the energy system, it is important to note the special challenges that a 1.5°C target brings with it: 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 at least. 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. Furthermore, the shift to intermittent renewables that many countries have implemented are just reaching levels where large scale storage systems are required to enable resilient grid systems, thus new knowledge on the opportunities and issues associated with scaling up zero carbon grids is now needed. Knowledge about how zero carbon electric grids can also integrate with the full scale electrification of transport systems is also needed. 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, with ocean fertilization, for example, needing much more robust results rather than a reliance on few experiments and theoretical modelling, and land-used-based options like BECCS and afforestation and reforestation having environmental implications that have hitherto not been systematically assessed and quantified. In order to thus obtain more information on realistically available and sustainable potentials, more bottom-up, regional studies are needed. These can then inform the larger models again with their insights. Other knowledge gaps pertain to issues of governance and public acceptance, the impacts of large-scale removals on the carbon cycle and potential hysteresis, the potential to accelerate deployment and upscaling, and means of incentivisation in the absence of carbon pricing and public support. Finally, the use of captured $CO_2$is not per se generating negative emissions and needs further scrutiny as a mitigation option. Reducing Short-Lived Climate Pollutants (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 (for 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. Further challenges arise on the international level, where frameworks are needed that help integrate SLCPs into emissions accounting and reporting mechanisms and a better understanding of the links between Black Carbon, air pollution, climate change and agricultural productivity must be achieved.

Another strategy assessed in Section 4.3 that is increasingly discussed in the face of our dwindling emissions budgets is Solar Radiation Management (SRM). Yet, on 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 appear, how to construct a compensation system of SRM and what precautions to take against objectionable mitigation obstruction.

Finally, turning to the implementation of the options to mitigate and adapt, Section 4.4 has generally identified a lack of 1.5°C-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 seems to address behavioural anomalies and behavioural change strategies in relation to mitigation and adaptation actions in the 1.5°C context. From a modelling point of view, a paramount challenge is to what extent a representation of (empirically estimated) behavioural determinants of technology choice or adoption is actually feasible in detailed process IAMs (Chapter 2). These aspects continue to limit our understanding and treatment of behavioural change and the potential effects of related policies in ambitious mitigation pathways. Furthermore, behaviour and lifestyle change are hardly addressed in modelling, and mitigation behaviour tends to be studied more extensively than adaptation behaviour, even though Section 4.4.5 points to a growing body of recent literature on adaptation 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, access to information etc.) as barriers or enablers of adaptation, but tends to underplay the role of cognition (through perceived self-efficacy, risk perception etc.). Finally, 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 groups (e.g. communities), organizations and political systems.

For implementation of adaptation options, there is a lack of monitoring & evaluation of adaptation measures, with most studies enumerating the M&E challenges and emphasizing the importance of context and social learning. Very few studies seek out to 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 and data for models; this is especially seen for IWRM.

Concerning policies, there is also very little literature that is 1.5°C -specific in the area of mitigation, yet building on knowledge from the 2°C -specific literature and taking into account the shorter time window for policies to take effect, many lessons could be drawn in Section 4.4.7. In addition, some case studies are emerging that allowed Section 4.4.7 to study the effectiveness of policies and policy packages for accelerated change and across multiple objectives. Yet, much more empirical research is needed to derive robust conclusions on what works and what does not in order to provide aid to decision-makers seeking to ratchet up their national commitments in 2018. Adaptation policy meanwhile has focused more on engineering and the built environment and institutions, however, 'social' adaptation, such as social protection initiatives have been critiqued because they don't address climatic risk specifically. So there is a need for adaptation initiatives that address social vulnerability (social protection, cohesion, capacity) while addressing climatic risk at the same time.

For climate finance assessed in Section 4.4.8, there is now a better understanding of the flows of finance and where they can come from. Also here, knowledge gaps persist with respect to the vehicles to match this finance to its most effective use in mitigation and adaptation.

Generally speaking, an upscaled and more rapid transition introduces new challenges for efforts to assess the feasibility of projects and programmes 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 the 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 therefore required to develop assessment methodologies that prioritize the types of 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 to options that produce unforeseen negative consequences.

4.5.2 Implementing mitigation

[Synthesis of 4.2, 4.3 and 4.4 relevant to mitigation to be included in the SOD]

4.5.3 Implementing adaptation

[Synthesis of 4.2, 4.3 and 4.4 relevant to adaptation to be included in the SOD]

4.5.4 Convergence with sustainable development

[Synthesis of 4.2, 4.3 and 4.4 relevant to sustainable development to be included in the SOD]

Box 4.12: Consistency between NDCs and 1.5°C scenarios

Mitigation

The COP21 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 2015).

The Paris Agreement departs from the top-down approach of the Kyoto Protocol, which assigns mandatory reduction limits to Annex I 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 stocktaking 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 ‘common but differentiated responsibilities and respective capabilities, in the light of different national circumstances’.

There is high agreement in the literature that NDCs provide an important part of the global response to climate change and represent an innovative instrument, which has all countries committed to contributing to mitigation (Rogelj et al. 2016; Robiou du Pont et al. 2016; Vandyck et al. 2016; Hof et al. 2017; Iyer et al.

2015; Fujimori et al. 2016; Sanderson et al. 2016; Pan et al. 2017; Jiang et al. 2017; den Elzen et al. 2016). NDCs represent in any case an improvement compared to the Business as Usual pathway to 2030 (Rogelj et al. 2016; Hof et al. 2017; den Elzen et al. 2016). According to the UNFCCC by the end of 2016, a total number of 190 Parties, or 96% of all Parties to the UNFCC, have submitted 162 NDCs. In May 2016, the UNFCCC completed a full analysis on the NDCs, reporting that the temperature would continue to rise to reach 2.2°C to 3.4°C above preindustrial levels in 2100, even with a full implementation of NDCs policies and measures (UNFCCC 2016). This range has been broadly confirmed by other analyses from UNEP (UNEP 2016), or the peer-reviewed literature (Fawcett et al. 2015; Rogelj et al. 2016).

Several studies estimate global emission levels that would be achieved under the NDCs, for example, (Fujimori et al. 2016; Vandyck et al. 2016; Sanderson et al. 2016; Iyer et al. 2015; Hof et al. 2017; Rose et al. 2017; Rogelj et al. 2017; Luderer et al. 2016; Rogelj et al. 2016; Fawcett et al. 2015).

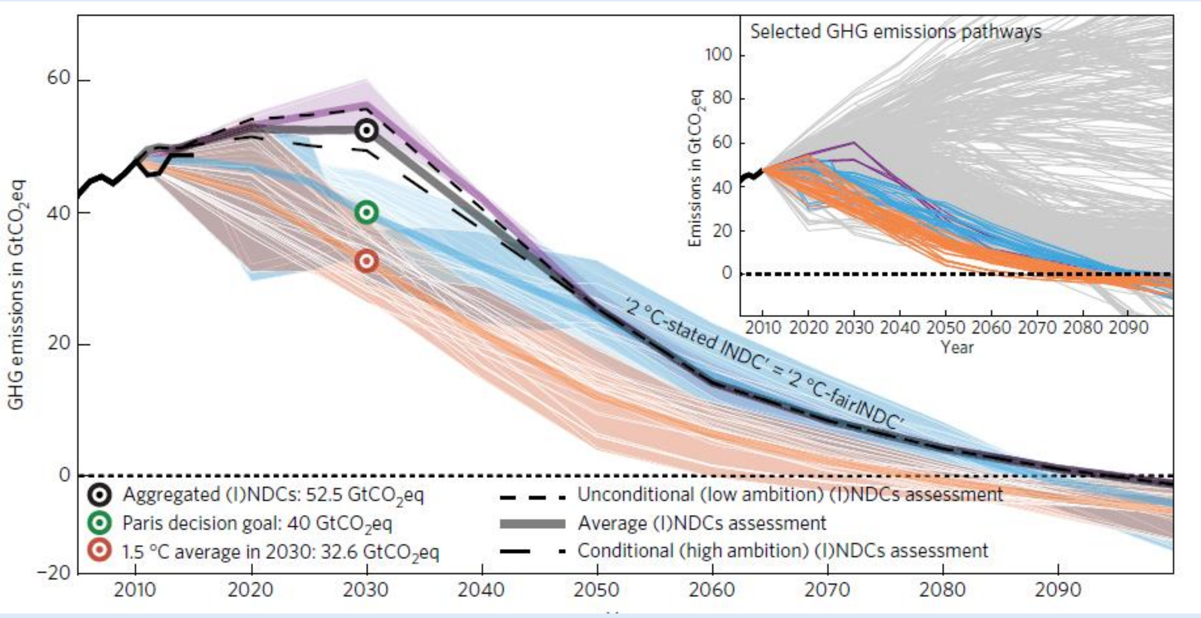
The key question related to current NDCs and 1.5°C pathways is whether the implied emissions reductions are in line with a 1.5°C consistent pathway. As the time horizon of NDCs is maximally until 2030, most of the NDCs do not include long-term targets (Fujimori et al. 2016), with only a few countries such (e.g. US and the EU) have included indicative targets or ranges for 2050 (Rose et al. 2017) and 1.5°C pathways require a deep decarbonisation over multiple decades to reach carbon neutrality by around mid-century, the NDCs by themselves cannot be sufficient. However, an analysis of their implied measures and emissions reductions can provide insights into whether a transition towards the required transition for a 1.5°C pathway is already envisaged. Several authors (Rogelj et al. 2016; Robiou du Pont et al. 2016; Vandyck et al. 2016; Hof et al. 2017; Iyer et al. 2015; Fujimori et al. 2016) have run integrated assessment models to assess the contribution of NDCs to achieve the 1.5°C targets in the Paris agreement. Different assumption for the period post 2030 have been made. The multiple assessments that have looked into this question find that current NDCs are not in line with pathways that limit warming to 1.5°C by the end of the century (Fujimori et al. 2016; Vandyck et al. 2016; Sanderson et al. 2016; Rogelj et al. 2016; Iyer et al. 2015; Hof et al. 2017; Rose et al. 2017; Fawcett et al. 2015; Rogelj et al. 2017; Luderer et al. 2016). The latter 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. However, as the measures proposed in NDCs are not legally binding under the Paris Agreement, on the one hand, there is no strong guarantee that they will be implemented or that will achieve the proposed national 2030 targets (Nemet et al. 2017), and, on the other hand, there are also indications that in some regions there could be over-delivery on emissions reductions compared to what is indicated in their NDCs. This would further impact estimates of anticipated 2030 emission levels.

Estimates of 2030 emissions levels in line with the current NDCs fall outside the range of 2030 emissions found in 1.5°C pathways (see Section 2.3.3 in this report, Figure 2.10). 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 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). However, no such flexibility has been found for 1.5°C pathways (Rogelj et al. 2017; Luderer et al. 2016) 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. 2015b). Some studies show that if the current decarbonisation trends of the NCDs is continued after 2030, this most probably will results is a very late achievement of carbon neutrality (Sanderson et al. 2016), thus resulting in a higher effort of negative emissions and higher costs (Iyer et al. 2015).

Implementing deeper emissions reductions by 2030 towards the levels identified in Section 2.3.3, either as part of NDCs or by over-delivering on NDCs, would significantly reduce this risks of failure. The mechanisms for stock-taking and ratcheting-up of the targets can help in reinforcing the national pledges (Wakiyama and Kuramochi 2017).

Assessment frameworks have been proposed to analyse, benchmark and compare NDCs between countries. The variation in compliance with particular equity principles across NDCs and countries is large, an aspect which will be further elaborated in the Second Order Draft. Various assessment frameworks have been proposed to analyse, benchmark and compare NDCs (Jiang et al. 2017; Wakiyama and Kuramochi 2017; Postic et al. 2017; Fridahl and Johansson 2016; den Elzen et al. 2016). Most of the authors agree on a multi-criteria assessment framework (Höhne et al. 2017; Jiang et al. 2017; Pan et al. 2017) based in six equity principles of effort sharing to allocate emission targets most of the NDCs are ambitious apart India (Pan et al. 2017), while Robiou du Pont (2016) in a similar analysis based on equity allocation of cost-optimal scenarios, shows that all NDCs analysed fail on some equity principles used in the authors' assessment framework. Alternatively authors (Vandyck et al. 2016; Robiou du Pont et al. 2016) have allocated emission allowance to countries for the different pathways (e.g. at 2030 year) and have assessed the country gap between the pathways and the emissions in the NDCs.

In any case, the NDCs are also recognised by authors as increasing the transparency and credibility of the process (Nemet et al. 2017), even if in the present very open format and by using different types targets (Rodríguez and Pena-Boquete 2017), the aggregation of targets results in very high uncertainty (Rogelj et al. 2017). This uncertainty could be reduced with more focused energy accounting and clearer guidelines for compiling the future NDCs (Rogelj et al. 2017).



Box 4.12, Figure 1, (Robiou du Pont et al. 2016)

Adaptation

The National Adaptation Plans (NAPs) and Nationally Determined Contributions (NDCs) of each country already indicate the main areas of risk and vulnerability, and the flexibility allowed by the adaptation pathways allows for different options to be considered and changed as monitoring is carried out at each phase.

The Paris Agreement stipulates that adaptation communications shall be submitted as a component of or in conjunction with other communications, such as a Nationally Determined Contribution (NDC), National Adaptation Plans, or National Communication. Of the 190 Parties, there are a total of 160 NDCs submitted, out of with 140 have an adaptation component. 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 ensure accountability. At national the level they provide momentum for the NAP process and raise the profile of adaptation (Sanchez-Ibrahim et al. 2017).

NDC adaptation goals have been presented quantitatively and qualitatively. A percentage of countries use the NDCs to communicate their adaptation goals in quantitative terms. Adaptation cost estimates in the NDCs aggregated to the global level are at $ 653.2 billion (reporting from 35% of NDCs with adaptation component). Estimated costs for activities that are already planned, in USD, are at $ 146.2 billion (reporting from 221% of NDCs with adaptation component). Quantified requested support for general adaptation implementation in USD: $ 38,024,480,000 ($38 billion – reporting from 4% of NDCs with adaptation component). Quantified committed for support for specific adaptation measures and/or sectors is, in USD, $ 19 billion (only 5% of NDCs with adaptation component).

Adaptation measures presented in qualitative terms, include sectors, risks, and vulnerabilities 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%) (Sanchez-Ibrahim et al. 2017). The table below shows a complete breakdown of sectors targeted in the NDCs:

Box 4.12, Table 1: NDC Targeted sectors.

Sectors specified	% of NDCs mentioning sector
Water	71%
Agriculture	63%
Health	54%
Biodiversity/Ecosystems	50%
Infrastructure/Transport	42%
Forestry	41%
Energy	27%
DRR	50%
Coastal protection	42%
Fishery	33%
Food Security	33%
Finance and Insurance sector	18%
Human settlement/Landuse	39%
Waste	9%
Education	13%
Tourism	22%

In order to strengthen the NDCs framework to deliver on adaptation goals, improving the structure, content, and planning processes is essential (Magnan, A., Ribera, T., Treyer et al. 2015). This will involve better adaptation communication (Kato and Ellis 2016), which will need a strong national and sub-national infrastructure that identifies, collates and reports adaptation-related progress.

The NAPs are country-owned and country-driven, they seek to enhance coherence between adaptation and development planning, and they are designed so countries can monitor and review them on regular bases. Out of 54 countries mentioning the NAP process in their NDC, 22 indicate that they have started the process and 32 say they plan to do so prior to 2020.Around 45% of developing countries and more than 80% of LDCs have started process of formulation and implementation of NAPs.

Linking the NDC and NAP process will be key to strengthening adaptation response (Magnan, A., Ribera, T., Treyer et al. 2015). The NDCs should inform and mirror the processes on the ground as countries operationalize national adaptation policy through the NAP. From a reporting perspective, then, it is important that progress on the NAP is fully reported in the NDCs.

Other benefits of linking the reporting on the NAP through the NDC process are (Smithers, R., Holdaway, E., Rass, N., and Sanchez Ibrahim 2017):

- Coordination between NDC and NAP development establishes coherent governance structures at national level to avoid duplication of adaptation efforts and make efficient use of limited resources.
- Linking the NAP process with the NDCs can support adaptation/mitigation co-benefits and synergies. The NAP process can inform development of the NDC's adaptation goals and how these goals are implemented.
- Linkages between the NDCs and NAP process can emphasize countries' transparency frameworks regarding adaptation policy.

Box 4.13: Solar Radiation Management: Methods, effectiveness and technical feasibility

Solar Radiation Management methods

Solar radiation management (SRM) refers to the modification of the Earth's albedo to increase the reflection of incoming solar radiation. Several SRM technologies have been proposed to reduce global mean temperature:

- Stratospheric aerosol injection (SAI) (Crutzen 2006; Keith and Irvine 2016; Irvine et al. 2016) which would involve injecting of sulphates or other reflecting particles into the stratosphere continuously using airplanes, tethered balloons, or other delivery technologies
- Marine cloud brightening (MCB) (Latham et al. 2014; Wang et al. 2011) (Alterskjær et al. 2013) which would involve spraying sea salt or other particles into marine clouds, making them more reflective. Spraying sea salt may also increase effective radiative forcing in clear-sky conditions (Ahlm et al. 2017)
- Cirrus cloud thinning (Jackson and Webster 2016; Muri et al. 2014) through seeding to promote nucleation, reducing optical thickness and cloud lifetime, to allow more outgoing infrared radiation to escape into space
- Sunshade geoengineering or 'space mirrors' which can be set in orbit in order to reflect sunlight back into space (Angel 2006); Gaidos 2016)

Ground-based albedo modifications have also been suggested but are generally of smaller spatial footprint and do thus not strongly affect the global temperature (Irvine et al. 2011, Seneviratne et al *submitted*). These include *white roofs* (Akbari et al. 2012; Jacobson and Ten Hoeve 2012), planting *more reflective crops* (Irvine et al. 2011), *changes in land use management (e.g. no-till farming)*, which increase the reflectivity of crop areas (Davin et al. 2014). *Change of albedo at a larger scale* (Irvine et al. 2011)(Seidel et al., 2014) could involve covering glaciers or deserts with reflective sheeting with significant impacts on circulation patterns and global temperature.

Impacts on global temperature

SRM approaches are generally discussed in the context of counteracting global climate change and reducing warming. However, a world with 1.5°C mean global warming achieved with SRM is unlikely to have the same characteristics, especially at the regional level, as a world where 1.5°C is reached through a fast decrease of greenhouse gas emissions and a net zero CO2 budget (Chapter 3). Among the SRM methods listed above the ones that could most strongly affect global mean temperature are stratospheric aerosol injection (SAI) and marine cloud brightening (MCB). Sunshade geoengineering could be effective in temperature reduction also but is not feasible.

The idea of stratospheric aerosol injection (SAI) in the tropical lower stratosphere (a layer of the atmosphere that begins between 10 and 18 km above the surface), was originally proposed by Budyko (1974, 2013) and further developed by Crutzen (2006). The direct effect of aerosols injection is an increase in the local concentration of optically active aerosol particles in the lower stratosphere. These particles increase the amount of back-scattered solar radiation, resulting in less radiation arriving at the Earth's surface and cooling the troposphere. Reviews of the current knowledge on SAI are found in Visioni et.al. (2017), MacMartin (2016) Keith and Irvin (2016) and Irvin et al. (2016).

The most often used SAI approach is sulphate geoengineering which mimics a volcanic eruption by injecting sulphate aerosol precursors. Following the Mount Pinatubo eruption of June 1991, when 7–10 Tg S were injected into the stratosphere, a sharp reduction in the net radiative flux at the top of atmosphere was observed (2.5 Wm^{-2}), as well as a significant drop in global surface temperatures of about 0.5°C (Visioni et.al. 2017).

Marine cloud brightening (MCB) would inject sea salt aerosols into the marine boundary layer to directly scatter light, and increase the albedo of low-lying clouds. While the radiative forcing from stratospheric aerosols is potentially relatively uniform in space and time, marine cloud brightening would create spatially heterogeneous forcing and potentially more spatially heterogeneous climate effects (Latham et al. 2012).

Numerous recent simulation experiments assess the effectiveness of different SRM techniques. Comparison of SAI and MCB effectiveness based on G3 GeoMIP experiment (Kravitz et al. 2011; Niemeier et al. 2013) made by Aswathy et al. (2015) shows that both schemes reduce temperature increases by about 60% globally compared with the baseline RCP4.5 scenario, but are more effective in the low latitudes and exhibit some residual warming in the Arctic. The change in shortwave radiative forcing at the top-of-the-atmosphere for the MCB experiment is smaller than the one for SAI over both ocean and land, but, for the MCB top-of-the-atmosphere short wave fluxes are slightly larger over ocean relative to land. This reflects the more local nature of MCB, since it is applied only over tropical oceans. The long-wave fluxes of both SRM schemes are similar, with less difference between SRM techniques.

In case of MCB, the injection strategy is critical in determining the spatial distribution of injected particles and the effectiveness of radiative forcing. The radiative effects from different simulated MCB experiments summarized by Kravitz et al. (2013) vary depending on geoengineering technique and level and aerosols injection area. The influence of ocean albedo increase on stabilization of global air temperature varies spatially with most effective decrease is observed for ocean temperatures in the tropics and mid latitudes, with less success in reducing temperature over land areas and the Arctic. The sea salt injection technique under RCP4.5 forcing, starting in 2021, needs a uniform distribution of about 212 Tg a^{-1} dry sea-salt aerosol emissions in the marine boundary layer between 30°S and 30°N by, to produce a global-mean effective radiative forcing (ERF) of -2.0Wm^{-2} (Kravitz et al. 2013). The largest ERF values are generally confined within the 30°S to 30°N injection area.

Cirrus cloud thinning is well studied. Generally the effects of cirrus cloud thinning depends on the degree of cloud optical depth modification (Schmidt et al. 2014). The estimated global cooling effect varies from 1°C (Crook et al. 2015; Muri et al. 2014) to 1.4˚C (Storelvmo et al. 2014).

The effectiveness, advantages and disadvantages comparison of SRM techniques are summarized in the Box 4.13 Table 1 (MacMartin et.al., 2017).

Box 4.13, Table 1: Effectiveness, advantages and disadvantages of SRM techniques.

SRM method	Ability to achieve global temperature stabilization	Advantages	Disadvantages	Application burden	Climatic response	Reference
Stratospheric aerosol injection	Very high Current technologies can likely be adapted to loft materials and disperse SO_2 at relevant scales. Other aerosols injection: lofting similar to sulphate but aerosol dispersal much more uncertain	Similarity to volcanic sulphate gives empirical basis for estimating efficacy and risks. Some other solid aerosols may have less stratospheric heating and minimal ozone loss	Limited ability to adjust zonal distribution; ozone loss; stratospheric heating	Baseline – RCP8.5; start in 2040; max. injection 8.5 Tg S yr^{-1} (in form of SO_2) in 2100	RF = -2.5 W m^{-2} Temperature stabilization +2 ˚C above pre-industrial	Tilmes et al, 2016
				Baseline – RCP8.5; start in 2049; max. injection 4.5 Tg S yr^{-1} (in form of H_2S) in 2100	Temperature stabilization +2˚C above pre-industrial	Izrael et al., 2013
				Baseline – RCP4.5; start in 2020; equal annual injection 2.5 Tg S yr^{-1} (in form of SO_2) till 2069	RF = from -1.6 to -3.6 W m^{-2}	Kravitz et al. 2011; Kashimura et al., 2017
				Baseline – RCP8.5; start in 2020; max. injection 45 Tg S yr^{-1} (in form of SO_2)	RF = -5.5 W m^{-2}	Niemeier, Timmreck, 2015
Marine cloud brightening	Uncertain: observations support wide range of CCN impact on albedo; no system-level analysis of cost of deployment	Ability to make local alterations of albedo; and modulate on short timescales. Can also be used in clear-sky conditions	Mostly applicable on marine stratus covering -10% of Earth means RF inherently patchy.	Baseline – RCP4.5; start in 2020; 212 Tg a^{-1} dry sea-salt aerosol emissions in the marine boundary layer 30°S - 30°N	RF = -2 W m^{-2}	Kravitz et al., 2013
				11000 Tg a^{-1} dry sea-salt aerosol emissions over all open ocean	RF = -4.8 W m^{-2}	
Cirrus thinning	Uncertain: deep uncertainty about fraction of cirrus strongly dependent on homogeneous nucleation; no studies examining diffusion of CCN	Works on longwave radiation so could provide better compensation	Maximum potential cooling limited; zonal distribution of RF constrained by distribution of cirrus			
Sunshade geoengineering or “space mirrors”	Low physical uncertainty, but deep technological uncertainties	Possibility of near “perfect” alteration of solar constant	Likely prohibitively expensive			
Based on MacMartin et al., 2017 (forthcoming)						

Technical implementation and feasibility of the deployment

Most studies of technical implementation are focused on SR through stratospheric aerosol injection. Sulphur dioxide (SO_2) is most often used as a precursor of sulphate aerosol (Crutzen, 2006; Kravitz et al. 2011; Izrael et.al. 2014; Visioni et.al. 2017; Keith and Irvin 2016), however, other sulphate precursors (such as hydrogen sulphide (H_2S) can also be effective and may be preferable technologically and economically (Ryaboshapko et. al 2015). Different scattering aerosols (silicon carbide (SiC), synthetic diamond, aluminium oxide (Al_2O_3), titanium dioxide (TiO_2), zirconium dioxide (ZrO_2), calcium carbonate) could also be chosen that have less stratospheric heating potential relative to sulphate (Dykema et. al. 2016) or that might reduce other side effects of SAI (Keith et.al. 2016).

The highest burden to injection ratio is modelled for stratospheric injections between 30° N and 30 ° S (English et al. 2012). The altitude also plays a significant role in determining the aerosol lifetime, due to a faster sedimentation removal in the upper troposphere when the sulphur injection is closer to the tropical tropopause layer (Aquila et al. 2014). The SO_4 stratospheric lifetime in the simulations of Aquila et al. (2014) was approximately 1.2 and 1.8 years for sulphur injection in the altitude layers 16–25 and 22–25 km, respectively. The lifetime of sulphur aerosols erupted by Pinatubo was about four years.

The Geoengineering Model Intercomparison Project (GeoMIP) G4 experiment (Kravitz et al. 2011) used the RCP4.5 scenario as a baseline and injected SO_2 every year from 2020 to 2069 with a fixed SO_2 injection rate 5 Tg yr^{-1}. The mean values of radiation forcing (RF) reduction vary widely from approximately -3.6 to -1.6Wm^{-2}. Significant feedback mechanisms exist among the magnitude and location of SO_2 injection, aerosol microphysics, background stratospheric dynamics, aerosol induced surface cooling and stratospheric heating rates, and induced changes in the stratospheric circulation and stratosphere–troposphere exchange (Visioni et.al. 2017; Kashimura et.al 2017). The sum of all direct and indirect radiative forcing (RF) with an injection of 5 Tg SO_2 yr^{-1} accounts for -1.4±0.5Wm^{-2}, which means a compensation of the projected positive RF in 2100 relative to 2011 by 64, 38, and 23% for the IPCC scenarios RCP4.5, RCP6.0 and RCP8.5, respectively (Visioni et.al. 2017).

SRM for global temperature stabilization at the level of 1.5°C above pre-industrial level has been proposed as a possible emergency switch if mitigation efforts do not produce global climate stabilization or if there is a temporary temperature overshoot (Keith and Irvin 2016; MacMartin et.al 2017; Chen and Xin 2017). The level of stratospheric sulphur burden required to meet the stabilization target may significantly depend on radiative response of different simulation models, injection height and technology (Izrael 2013; Tilmes et al. 2016; Niemeier and Timmreck, 2015).

SRM implementation requires lifting millions of tons of material to the stratosphere each year (Robock et al. 2009; Davidson et al. 2011; McClellan et al. 2012; Ryaboshapko et al. 2015; Irvine et al. 2016.). The literature suggests the most feasible are (Irvine et al. 2016): high-altitude aircraft or tethered balloons (Davidson et al. 2011; McClellan et al. 2012). All assessments agree that aircraft have the potential to deliver millions of tons of material to the lower stratosphere (~20 km or 60 hPa) at a cost on the order of 1–10 billion US dollars per mega-ton of material per year (Robock et al. 2009; Davidson et al. 2011; McClellan et al. 2012). Tethered balloons offer a potentially cheaper alternative especially for large injection amounts, with estimated costs ranging from an order of magnitude less to an order of magnitude more than delivery by aircraft; (Davidson et al. 2011). Balloon borne injections would rely on less certain technologies, and as such, assessments disagree on its potential feasibility. (Davidson et al. 2011; McClellan et al. 2012).

Implications for regional climate and impacts of generally considered SRM techniques

The regional climate impacts of Global-scale Solar Radiation Management (SRM) are mostly assessed for Sunshade Geoengineering (SG) (which is mostly hypothetical but easier to implement in climate model simulations), and Stratospheric Aerosol Injections (SAI). (Rasch et al. 2008; see also previous subsections). These global SRM approaches are designed to offset the global mean warming induced by a certain level of increase in GHG. SG can be considered as a highly idealized model experiment, which represents some of the first-order climatic effects of SAI, but with significant differences in climate response (e.g., Robock 2014; Irvine et al. 2016). Both SG and SAI are set up to balance a particular radiative forcing (e.g., 4xCO_2 or RCP4.5), but SAI may produce a non-uniform forcing depending on where and in what form aerosols are inserted in stratosphere (e.g. Muri et al. 2014; Laakso et al. 2012). For the same global mean temperature reduction, SAI produces a greater change in the hydrological cycle than SG and would lead to greater regional change in climate, particularly in the tropics (e.g., Irvine et al. 2016). For both SG and SAI an abrupt termination of employment would lead to a 'termination-shock' with rapid global warming and unknown consequences for the Earth system (Jones et al. 2013; for more information see Section 3 of this Box).

In general, global model experiments suggest, that in case of a global SRM implementation, surface temperatures would be reduced most in regions and lead to more moderate temperature and precipitation extremes (Curry et al. 2014). However, this would be accompanied with an overcooling of tropical ocean (Curry et al. 2014), a shift in the diurnal cycle (i.e. shift in night-time vs. day-time warming) (Lunt et al. 2008) and a residual temperature increase over high-latitude land regions and in Polar Regions (Curry et al. 2014). SRM model experiments indicate a reduction in the intensity of the hydrological cycle compared to a 4xCO_2 warming, with substantial regional differences in the hydrological cycle patterns, for instance, a reduction of precipitation on land, particularly in monsoon regions, and more low-intensity rainfall events (e.g., Bala et al. 2008; Tilmes et al. 2013). SRM methods may further induce shifts in ITCZ, Walker, and Hadley cell circulations, with implications for precipitation changes in affected regions and towards prevailing La Niña like conditions. (Niemeier et al. 2013). The weakening of tropical circulation as projected under increased GHG would not be reduced by SAI (Ferraro et al. 2014). Atlantic hurricane storm surges may be reduced by half (but only marginally statistically significant) with further implications for coastal flood levels due to reduced sea level rise (Moore et al. 2015).

Ricke et al. (2010) point out that it would not be physically feasible for SRM to simultaneously stabilize global precipitation and temperature if GHG continue to rise. While SRM, deployed along with emissions cuts, could make it possible to reach a 2.0°C or even 1.5°C global-mean temperature warming, the associated climate would be very different from a 2.0°C or 1.5°C climate associated only with greenhouse gas mitigation (see Box 3.12). Tilmes et al. (2016) emphasize that the climate impacts by stringent emissions cuts would be different from those of moderate emissions cuts supplemented by SRM cooling. This means that global mean temperature would not be a good proxy for aggregate climate risks if solar geoengineering were to be deployed (Irvine et al. 2017). The changes in spatial and temporal distributions of temperature, precipitation and wind conditions induced by SRM would affect regions in different ways with recognizable economic consequences. Specifically, under RCP4.5, SRM economic benefits are small, and may become negative. While global GDP may increase with lower warming, regions with negative benefits (i.e. losses) from SRM cannot be avoided (Aaheim et al. 2015), and thus SRM would inevitably create winners and losers (e.g., Kravitz et al. 2014; Hegerl and Solomon 2009).

Because of these recognized shortcomings and risks associated with SRM, more recent publications have also discussed more moderate deployments of SRM as potentially more realistic options (Keith and MacMartin 2015). Nonetheless, a main issue remains that traditionally considered SRM implementations such as SAI do not have scope for regional adjustment of the applied radiative forcing (MacMartin et al. 2012).

Beside SAI, modifications of the land surface reflectivity, for example *via* changes in the albedo of agricultural land or urban areas (Irvine et al. 2011; Davin et al. 2014; Seneviratne et al. *submitted*) may be considered. These land-surface radiation management methods have a smaller spatial footprint than SAI or SG, because the forcing is more restricted in space. The land-surface radiation management approaches are potentially better suited than SAI to affect local and regional temperature but would have at most only a negligible effect on global temperature (e.g. Seneviratne et al. *submitted*). They should therefore be considered as a different strategy than traditional SRM approaches, and may have more direct relevance in the context of regional-scale adaptation (Boucher et al. 2013), although such regional effects may be relevant in the development of realistic global socio-economic pathways (Chapter 2, and Box 3.12).

It is important to note that independently of any regional footprint of application, changes in temperature that result from changes in radiative forcing (such as with SAI-based SRM, but also land-based changes in surface albedo) do not address non-temperature impacts of greenhouse-gas concentrations, and in particular ocean acidification (see Chapter 3, Section 3.3.1.1, IPCC 2014).

Other risks of SAI include: 1) the lack of testing of the proposed schemes (e.g. Schäfer et al. 2013); 2) potential associated depletion of stratospheric ozone (Tilmes et al. 2008) which remain very uncertain (Irvine et al. 2016); 3) possible tropospheric impacts (Irvine et al. 2016); and 4) effects on vegetation and crop production (for more information see Section 4 of this Box). This last point is uncertain and has important implications for sustainable development (see the Sustainable Development and SRM section of this Box and Chapter 5).

The overall impacts on food production and ecosystems would result from the combined effects of 1) changes in regional climate (with potential benefits, Pongratz et al. 2012, but also negative modifications on regional scale in particular with respect to the water cycle); 2) changes in the ratio of incoming direct and diffuse radiation (Pongratz et al. 2012); and 3) the extent of CO_2 effects on plant photosynthesis (Wenzel et al. 2016; Mystakidis et al. 2017) and their possible reduction through nutrient or water limitation (Ciais et al. 2013, Reichstein et al. 2013).

Given the level of uncertainty in the various underlying processes, and the lack of comprehensive assessments in the literature, it is not possible at the present time to confidently assess the effects of SAI deployment on food production and ecosystem health. The precautionary principle and the potential regional inequalities leads to the assessment, with *medium confidence* (expert judgment), that the risks of SAI deployment for global food security and ecosystem health would outweigh the benefits, even for low levels of application, at the present state of knowledge.

Implications of terminating SRM

A ‘Termination shock’ or ‘termination effect’ has been discussed in (Robock 2016; Izrael et al. 2014; Jones et al. 2013a) (McCusker et al. 2014) and also highlighted in AR5 (Boucher et al. 2013). All model results concur that a sudden stop of SRM SAI deployment will lead to rapid temperature rise, accompanied by increases in global-mean precipitation rate toward the levels they would have reached without SRM. This happens because SRM would not reduce atmospheric GHG concentrations, it would only mask their warming effect by blocking sunlight (Jones et al. 2013) examine changes in sea-ice cover and global-mean plant net primary productivity due to abrupt suspension of SRM SAI. Results show considerable agreement regarding the distribution of reductions in Arctic sea-ice, but no agreement on the impact to the global-mean plant net primary productivity. (McCusker et al. 2014) show that increased net primary productivity on land is one of potential positive impact of SRM cessation, however there is disagreement among global climate models on the sign of the response (Jones et al. 2013). According to (McCusker et al. 2014) food production could be severely reduced in many regions concurrently under a scenario of high GHG emissions and SRM termination and many species suddenly reach their survival limits due to SRM cessation.

Some recent studies indicate that the risks and benefits of SRM including “termination effect” depend on assumptions about SRM implementation (Keith and MacMartin 2015; Reynolds et al. 2016). They showed that the termination shock could be avoided or reduced under well-orchestrated deployment and cessation of SRM (for example, scenario in which SRM cooling is ramped up and then slowly ramped back down again) although this would require strong governance and institutional arrangements. (Kosugi 2013) demonstrates that if the SRM cooling remained below a certain threshold, it would be hard to detect the effects of termination against the natural variations in temperature. When SRM starts, it exerts a high degree of cooling, and it cannot be stopped suddenly, but could be phased out over a long period (Reynolds et al. 2016). SRM should be used only in combination with emission reduction and CDR (Irvine et al. 2016).

Implications for other geophysical quantities

Stratospheric water vapour

Upper-tropospheric ice and cirrus clouds

Stratospheric and tropospheric ozone and other stratospheric chemistry (ch5 address only in context of health)

Glacier evolution under SRM

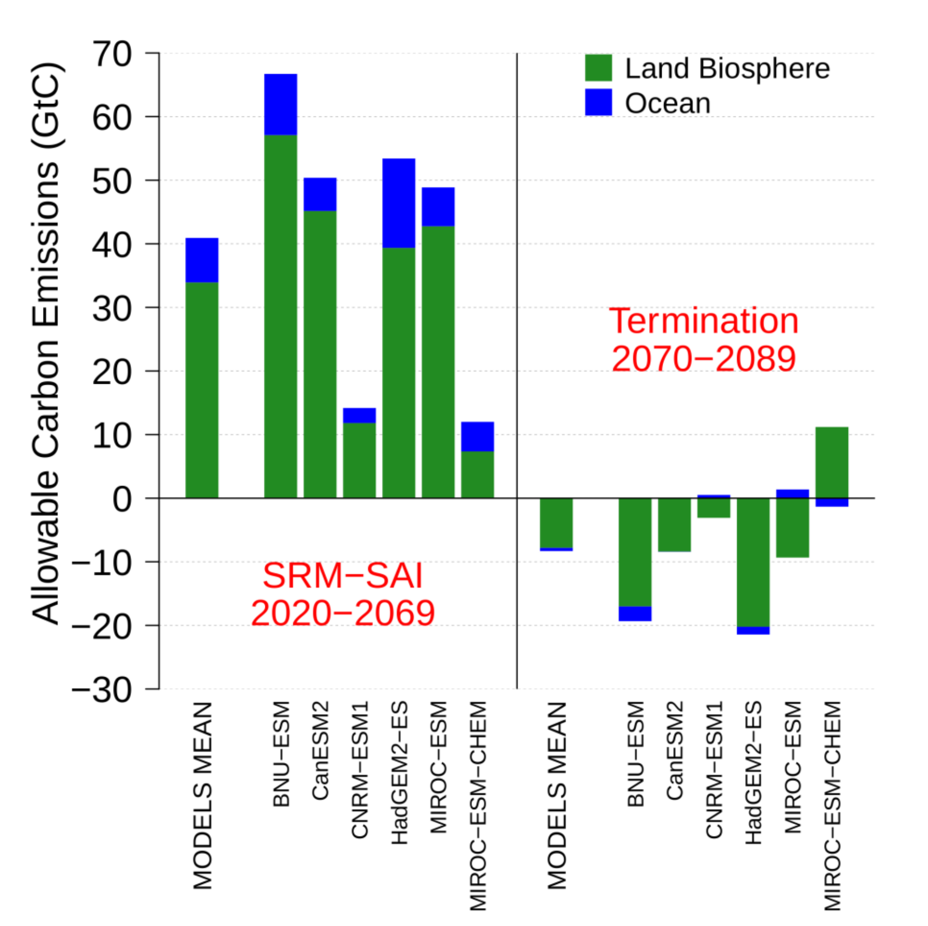
Impact of SRM on carbon budget

The global carbon cycle can be affected by the deployment of SRM because of effects on ecosystems and take up of carbon (Matthews and Caldeira 2007; Govindasamy et al. 2002; Eliseev 2012; Keller et al. 2014; Muri et al. 2015; Lauvset et al. 2017) and may affect carbon budget estimates compatible with 1.5°C or 2°C (see Section 2.2.2 for further details). SRM may enhance the natural carbon uptake by land, biosphere and the ocean based on analysis of model results (Box 4.13 Figure 1) and natural analogues such as major volcanic eruptions (Macmartin et al. 2016; Rothenberg et al. 2012; Brovkin et al. 2010; Tjiputra and Otterå 2011; Wang et al. 2013). In both cases the same mechanism is at play: the global carbon cycle responds to the thermal adjustment of the climate system following a decrease in incoming solar energy. Over the land surface, SRM would cause a decrease in soil respiration driven by a reduction in surface temperature. The difference between photosynthesis and respiration then results in a potential increase of the net carbon uptake by land and biosphere under SRM. The ocean carbon sink could also be enhanced (but less so) because decreasing sea surface temperatures increase CO_2 solubility in sea water.

A quantitative assessment of the potential efficiency of SRM to draw down atmospheric CO_2 is hampered by many large uncertainties. First, uncertainties in our understanding arise from the differences between modelled SRM experiments (intensity, time-scales etc.), modelling set-up, and emissions pathways (Edenhofer et al. 2011; Govindasamy and Caldeira 2000; Matthews and Caldeira 2007; Glienke et al. 2015; Tjiputra et al. 2015; Lauvset et al. 2017; Muri et al. 2015). These differences result in a wide range of estimated CO_2 reductions in response to SRM, from 15 ppm (Tjiputra et al. 2015) to 110 ppm (Matthews and Caldeira 2007). However, studies agree that SRM reduces more CO_2 when the duration of SRM is increased or the background level of CO_2 concentrations is increased, or both.

Second, important uncertainties remain in understanding the driving processes governing the global carbon cycle response to SRM. SRM is expected to modify the ratio between diffuse and direct radiation, leading to an enhancement of photosynthesis and hence greater gross uptake of carbon by vegetation (Xia et al. 2016b; Mercado et al. 2009b; Eliseev 2012). But SRM is also expected with a high confidence to reduce total incoming solar radiation, decreasing the amount of photosynthetically available radiation for photosynthesis, leading to a decrease in gross carbon uptake by vegetation (Ramachandran et al. 2000). These two competing effects of SRM on vegetation photosynthesis could ultimately balance each other out so that the land-biosphere response to SRM remains uncertain. Furthermore, the availability of water and nutrients to the biosphere can be modified under SRM. For example, AR5 indicated that rising atmospheric CO_2 leads to enhanced water-use efficiency of the land biosphere and reducing the water requirement to fix a given amount of atmospheric CO_2 in vegetation biomass. However, a number of studies have shown that SRM might lead to modified precipitation patterns and ultimately alter the water available for land biosphere and for specific biomes (Muri et al. 2015; Glienke et al. 2015).

There are also large uncertainties about how the carbon cycle will respond to termination effects of SRM. Although models agree in terms of temperature change following termination (in both geographical structure and amplitude), the associated change in net primary productivity remains unclear (Jones et al. 2013b). Yet, due to the response of soil respiration and ocean solubility to temperature change (Friedlingstein et al. 2006; Friedlingstein and Prentice 2010), the termination effect might release carbon previously stored in the soil and in the upper ocean layers to the atmosphere, undoing the earlier enhanced CO_2 uptake. Uncertainties in climate-carbon cycle feedbacks (as documented in Friedlingstein et al. 2013) currently hamper a quantitative determination of the amount of carbon which could be released to the atmosphere in response to the abrupt warming induced by the stoppage of SRM.



Box 4.13, Figure 1: Change in cumulated allowable carbon emissions (in GtC) due to the use of solar radiation management by stratospheric aerosol injection (SRM-SAI) as simulated in the experiment G4 of GeoMIP for each of six Earth system models and the models mean. Allowable carbon emissions are estimated from cumulated carbon fluxes over the geoengineered period (2020-2069, left) and over the twenty years after the cessation of geoengineering (2070-2089, right) using the approach of Jones et al. (2013). Land biosphere and ocean carbon uptake are represented respectively in green and blue.

Changes in solar energy resources

SRM through SAI is expected to have adverse effects for solar power on the Earth's surface (Robock et al.2009) and thus on solar energy which is a key mitigation technology. The only detailed study assesse the impacts on solar photovoltaics (PV) and concentrating solar power (CSP) (Smith et al. 2017). According to this study, SAI at a rate of 10 Tg yr^{-1} SO2 is likely to result in negative changes in CSP output in most regions of the world. The global land mean decrease in annual energy output is 4.5% and 5.9% compared to the RCP4.5 and to the historical simulation. Marine cloud brightening will reduce solar transmission through clouds, but also reduce solar transmission in clear-sky areas where sea-salt aerosol is generated. Cirrus cloud thinning will increase the incoming solar radiation slightly. The implementation of space mirrors is likely to be more homogeneous in its negative impacts for solar energy. Increasing the surface albedo is unlikely to have a direct negative impact on solar energy technologies and may be slightly positive due to additional solar radiation being reflected upwards from the ground (Smith et al. 2017).

Sustainable Development and SRM

In terms of sustainable development, some see SRM as a relatively cheap way to bring down global temperatures, with resulting benefits for SD and equity from reduced climate impacts in terms of food, water, health and ecosystems and could be a controversial response to humanitarian emergencies associated with rapid climate change (Morrow 2014; Al-sabah and Brien 2015; Anshelm and Hansson 2014; Harding and Moreno-Cruz 2016; Heutel et al. 2016; Nicholson 2013)(Buck 2012). But because SRM/SAI has uncertain effects on precipitation, may damage the ozone layer, and does not address ocean acidification there are also negative risks to SD (Heyen et al. 2015; Irvine et al. 2017; Robock 2012; Nicholson 2013). For example, some models, and analogues with historic volcanic eruptions, produce results that reduce temperatures but include a weakening of tropical circulation, 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 emphasize regional uncertainties (Ito 2017; Parkes et al. 2015; Russell et al. 2012; Xia et al. 2014; Irvine et al. 2017). SAI does not solve the problems of ecosystem and fishery decline associated with acidification, may increase health effects of ozone depletion, and, if it reduces mitigation and adaptation efforts will modify the SD side benefits of these actions. For more information about SAI impacts on ecosystems, regional patterns of precipitation, circulation regime, ozone, cloudiness and stratospheric chemistry see Chapter 3, the Impacts on global temperature section, and the Implications for regional climate and impacts of generally considered SRM techniques section of this Box.

Governance, public perception and ethics of SRM

SRM research and implementation faces considerable challenges when it comes to governance and potential impacts on sustainable development. The literature mostly suggests that SRM 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 organization will produce negative side effects for others, especially in terms of precipitation, extreme events, and photosynthesis (Horton 2011; Bodansky 2013; Virgoe 2009; Bracmort et al. 2010; Low et al. 2013; Dilling and Hauser 2013; Lempert and Prosnitz 2011; US National Academy of Sciences 2015; Al-sabah and Brien 2015). Even in the case of modest implementation or impacts, public perceptions may begin to attribute a wide range of negative environmental changes to SRM, whether or not a link can be made, creating fear, political tensions and social unrest (Boyd 2009). There is evidence that the public is confused and concerned about geoengineering, with those in developing countries unaware of the issue (Bellamy et al. 2017; Burns et al. 2016; Carr et al. 2013; Parkhill et al. 2013; Visschers et al. 2017). Key ethical questions discussed in the research literature include those of international responsibilities for implementation, financing, and compensation for negative effects, privatization and patenting, informed consent by affected publics, intergenerational ethics (because SRM requires sustained action in order to avoid termination hazards), the rights of indigenous people and women, and the moral hazard that SRM could reduce mitigation and adaptation efforts (Buck et al. 2014; Burns 2011; Whyte 2012; Morrow 2014). For more detailed information about governance, economics and ethics of SRM (including “moral hazard”) see Chapter 4 (Section 4.3.7).

Box 4.14: Cities

Box 4.15: Adaptation

This Box presents five case studies from different climate regions to provide a holistic example of definitions and key adaptation typologies from physical and human impacts (Chapter 3); implementation challenges including governance issues (Chapter 4); and poverty, livelihoods consequences and sustainability (Chapter 5). The case studies were selected to highlight specific issues, for example, the Arctic due to its rapid changing climate, the Caribbean for its potential sea level rise and numerous extreme hydro-meteorological events, the Mekong Delta for impacts on a ‘food-basket’ region, urban adaptation, and the Amazon for its adaptation efforts at scale.

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

Each case study first presents climate impacts, then explores adaptation strategies and their implementation, and concludes with poverty alleviation and sustainable development implications.

Adaptation in the Arctic

Climate change vulnerability in the Arctic reflects the elevated rate of environmental change occurring in polar regions in combination with social and economic stresses (IPCC 2014a). Current high health burdens in the region, such as food insecurity, unintentional injury and mental health issues, are linked in part to environmental systems and have the potential to worsen with climate change (Ford et al. 2014b; Arctic Council 2017). Ice-free Septembers by 2100 are very unlikely if global warming is limited to 1.5ºC, although permafrost melt, increased instances of storm surge, and extreme weather events are still anticipated (Ford et al. 2016; Melvin et al. 2016; Screen and Williamson 2017). Environmental changes are projected to have negative short- term impacts on health, housing availability, transportation, and economy across the Arctic (Larsen et al. 2008; Ford et al. 2015, 2016; Melvin et al. 2016; Arctic Council 2017). Human systems in the Arctic are also recognized for their resilience, a function of traditional knowledge systems, diversified livelihoods, and governance systems that include institutions for collective action (Arctic Council 2013b; Ford et al. 2015; Arctic Council 2017). Indeed, community and regional capacities are driving adaptation initiatives across the Arctic, with potential to reduce vulnerability (Arctic Council 2013b).

Communities across the Arctic, many with indigenous roots, have a history of adapting to environmental change, developing or shifting harvesting activities and patterns of travel and, more recently, transitioning economic systems (Wenzel 2009; Einarsson 2014b). Present economic and social conditions can limit a family or community's capacity to undertake necessary adaptations to environmental change without resources and cooperation from public and private sector actors (Ford et al. 2014b, 2015; Clark 2016; Arctic Council 2017). Further, for many Arctic communities, climate change is only one of the many dynamics that may constrain social and economic wellbeing. Adaptation initiatives, including managing future risks, reducing and responding to damages, and capitalizing on new opportunities, have been increasingly observed at community, regional, and national scales in the Arctic (Arctic Council 2013b; Labbe et al. 2016; Ford et al. 2014a; Arctic Council 2017). Across the region, investments aimed at reducing vulnerability may doubly serve to address current social and economic needs, such as improving an airport's runways, enhancing telecommunications, or reducing food insecurity (Arctic Council 2013b). These 'no-regrets' adaptations are seen as having fewer political or institutional hurdles and are socially or economically beneficial external to climatic change (Heltberg et al. 2009). Transformative adaptations, such as restructuring the education system to improve opportunities and sustain indigenous knowledge, have also been identified as having significant opportunity to reduce vulnerability by addressing root causes, but generally take more resources and political will (Kates et al. 2012; Ribot 2011).

Adaptation actions are being noted in all Arctic nations, with the highest number occurring in the Canadian Arctic (Ford et al. 2015). Further, most documented adaptation initiatives are occurring at local levels and are in response to both observed and projected environmental changes as well as social and economic stresses. In a recent study of adaptations in Nunavut, Canada, most adaptations were found to be in the planning stages, lacking coordinated effort within and between the territorial governments, and largely driven by a select few institutions and individuals (Labbe et al. 2016).

It has been argued that sufficient information on vulnerability exists for adaptation implementation in some sectors and countries, but research gaps remain (Arctic Council 2013b; Ford et al. 2016). Moving beyond community case studies to fine resolution system modelling, larger scale climate models that include projections for variables such as permafrost melt, surface winds, and sea level rise are demanded in conjunction with linked economic and demographic projections (Ford et al. 2016; Arctic Council 2017). Continued assessments of potential regional economic and social benefits are important and will need to be built into regional projections and adaptation plans (Arctic Council 2013). Addressing knowledge gaps, and incorporating Indigenous knowledge and stakeholder views is essential to the development of much-needed adaptations policies and initiatives across the Arctic (Boyle and Dowlatabadi 2011; Hansen and Larsen 2014). Studies have suggested that a number of the adaptation actions in the region are not sustainable, lack evaluation frameworks, and hold potential for maladaptation (Loboda 2014; Ford et al. 2015; Larsson et al. 2016). More proactive, empirically driven, and regionally coherent adaptation plans and actions have been identified as important in Arctic nations to address the impacts from 1.5°C level climate change scenario (Larsson et al. 2016; Melvin et al. 2016; Arctic Council 2017).

Adaptation in the Caribbean

Key climatic risks and vulnerabilities
Damage from hurricanes and their increased frequency and severity is the largest risk facing Caribbean island nations. It is estimated that average damage from each hurricane since the mid-20th century has been 4.8% of GDP for Caribbean island nations (Acevedo Mejia 2016). By 2100, average hurricane damage in the Caribbean is expected to increase between 22% and 77%, with large variations in damage across islands (Acevedo Mejia 2016; Bertinelli et al. 2016). The damage from hurricanes is manifested through a range of socioeconomic and ecological impacts: 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 such as localised extinction of sea turtles (Laloë et al. 2016).

Vulnerability to the impacts of hurricanes and sea level rise is driven by multi-scalar social and economic factors. High levels of poverty (Rhiney 2015; Beckford and Rhiney 2016), limited institutional capacity (Pittman et al. 2015), lack of reliable data (Muis et al. 2016), land use change (Cashman and Nagdee 2017), and food security instability (Pemberton and Patterson-Andrews 2016) have negative impacts on Caribbean nations' ability to cope and recover from the impacts of hurricanes and sea level rise.

An assessment of adaptation readiness done by Deklu (Deklu 2015), identified 3 countries as having high adaptation readiness scores (Cuba, Grenada, and St. Lucia), 8 countries with moderate adaptation readiness (Antigua and Barbuda, Bahamas, Barbados, Dominican Republic, Jamaica, St. Kitts and Nevis, St. Vincent and the Grenadines, and Trinidad and Tobago), and 2 countries with low adaptation readiness (Dominica and Haiti) (Deklu 2015).

Adaptation mechanisms
Institutional: Studies have found that governance to address climate change in the Caribbean relies on holistic, integrated management systems, improving flexibility in existing collaborative decision-making processes, increasing capacity of local authorities with support from higher-level government, private-social partnerships, and adequate social-environmental monitoring programs (Pittman et al. 2015). Social work programs to promote human and community well-being have also been proposed to reduce social vulnerability to climate change impact in the Caribbean (Joseph 2017). Robust institutions with proper technology, such as information and communication technologies (ICT's) can help in the use of early warning systems, as well as help in the exchange of information required for decision-making and emergency situations (Eakin et al. 2015; Ley 2017).

Social: Settlement relocation or migration have been documented as social responses to climate change risks in the Caribbean islands (Rivera-Collazo et al. 2015; Betzold 2015). However, retreating from coastal areas at risks has also been argued to be problematic, as islanders have close ties to home and strong place-based identities, so islands becoming uninhabitable poses important consequences for global justice, human rights, and cultural heritage (Betzold 2015). Micro-landscape modification is also viewed as a strategy which, together with relocation, can strengthen community bonds that lead to social resilience or vulnerability (Rivera-Collazo et al. 2015).

Engineering and built environment: Studies of resilient housing design for low income households with limited resources, for example, proposes several design modifications to make homes more resistant to high winds and flying debris during hurricanes (Prevatt et al. 2010). Moreover, building codes and standards haven't been updated in many cases to account for the extreme weather events that are now occurring (Garsaball and Markov 2017). Urbanization in low-lying areas has also increases potential run-off and flash-flood events, such as in the case of St. John's in Grenada (Pratomo et al. 2016). Therefore, engineering applies not only to buildings but also to other infrastructure such as coastal defences, ports, docks, marinas, bridges, and water supply (Sammy et al. 2016; Boyce 2016). The Blue Urban Agenda has emerged as a solution, especially for urban coastal adaptation (Donovan 2017).

Implementation gaps and challenges
Awareness and perceptions: Local residents and decision makers often have limited knowledge and

understanding of climate change, and in more remote communities, climate change is even more unfamiliar. Other seemingly more pressing problems like poverty and food security compete for attention of locals and decision makers (Betzold 2015). Perceptions are important to consider when designing adaptation measures, and need to be included in vulnerability assessment. Stakeholder perceptions of climate change can have implications on local adaptation plans and strategies and can help to a more unified implementation of adaptation measures (Altschuler and Brownlee 2016). Until there is better awareness and understanding of climate change and its risks, it will be difficult for risk management needs to be institutionalised as part of the planning process, which is increasingly required (Boyce 2016).

Lack of resources: After Hurricane Ivan struck in 2004 with estimated losses of as much as twice the GDP in the case of Grenada (Joyette et al. 2015), a regional catastrophe insurance scheme was created. The lack of financial resources after a disaster has been a major constraint for most of the islands, but the hazard models used in different schemes have low levels of acceptability, which impede financial schemes from being truly beneficial (Joyette et al. 2015).

So far, donors have funded adaptation measures to a substantial extent, with the national government also contributing significant amounts. However, donors fund what they see as a priority, not necessarily reflecting community priorities. Short funding cycles on donor projects also leave the local community paying for maintenance or repair of adaptation interventions, e.g. seawalls (Betzold 2015). It has also been reported that development programs have focused attention on climate change adaptation (Donovan 2017), however, there is still more integration needed between the development and climate change sectors, especially when understanding trade-offs and synergies. Vergara (Vergara et al. 2015) estimate that damages to climate impacts in LAC will be about US$100 billion by 2050 (Vergara et al. 2015), indicating that rapid adaptation needs to happen now to reduce the magnitude of future events and to avoid the permanent loss of natural and cultural capital, some of which is already being lost.

Adaptation in the Mekong food-basket region

Status and transitions

The Mekong Basin is a climate change hotspot (de Sherbinin 2014; Lebel et al. 2014) and home to a population of nearly 20 million (Chapman et al. 2016). The largest riverine wetland complex in South-east Asia, it plays a critical role in regional economy and food security (Smajgl et al. 2015) contributing to 90% of Vietnam's rice production (Kontgis et al. 2015). It is witnessing several transitions which have implications for climate adaptation.

Land use transitions are rapidly shifting from forest to agriculture (especially rice which is a regional staple food) and increasing development of highlands through increasing hydropower and road networks (Kura et al. 2017; ICEM 2013). Agriculture has also seen a shift towards greater commercialization with a concurrent degradation of ecosystems and associated services (Sebesvari et al. 2017) which have raised sustainability concerns (Anthony et al. 2015). While this agricultural transition has alleviated poverty and improved food security (Schipper et al. 2010), long-term distributive effects and implications for adaptation remain poorly examined (Ling et al. 2015). Some studies note that such transitions exacerbate risks of vulnerable populations to climate change and extreme event (ICEM 2013) and may even be maladaptive (Chapman and Darby 2016).

Economic expansion and demographic shifts are transforming the economies and environment but rural populations remain significantly dependent on natural resources and ecosystem services for livelihoods: 75% of peoples' livelihoods in the Lower Mekong basin are dependent on agriculture, fishery, livestock, and forestry (Sebesvari et al. 2017).There is also significant urbanisation in pockets within the Mekong Deltaic region: for example, SocTrang province in Vietnam has seen a 50% increase in urban dwellers between 1992 and 2011 (Smith et al. 2013).

Analyses of past climate data have shown a fluctuating upward trend for temperature and annual mean precipitation in the Lancang-Mekong River basin from 1980 to 2009 (Wu et al. 2011). However, this increase in precipitation is primarily in the wet season. Drought incidence and severity has increased significantly in the Lancang River Basin during 1991-2010 (Yu et al. 2015).

In the Lower Mekong Basin, under the A1B scenario (moderate emissions), temperature increases are expected to reach an average 3-5°C by 2100 while in some pockets such as eastern Cambodia and regions in the Mekong Delta of Vietnam and Cambodia, increases of 2-3°C may be reached before 2050 and up to 5°C by 2010 (ICEM 2013). Under the same scenario, a basin wide temperature increase of 0.79˚C, with greater increases for colder catchments in the north are projected (Eastham et al. 2008). Importantly, under all RCPs, the Mekong River Basin is projected to see an increase in annual average temperature with the largest increases in upstream areas. Annual precipitation is also projected to increase except for a weak decreasing trend during early-21st century under RCP4.5 and RCP8.5 scenarios (Zhang et al. 2016a). The persistent rising of summer temperature might accelerate melting of glaciers, and impact the local freshwater availability. Summer precipitation will most certainly increase in the short, medium and long terms, which would increase the risk of flood-related disasters (Zhang et al. 2016a). While higher flows (due to warming-induced intensification of the hydrological cycle) can reduce dry season water shortages and control downstream salinization, higher and more frequent peak discharges will exacerbate flood risk in the basin (Hoang et al. 2016).

The region is also highly susceptible to flooding (Ling et al. 2015), with 75% of Vietnam's areas at risk located in the Mekong Delta (Smith et al. 2013). Finally, sea level rise and saline intrusion are ongoing risks agricultural systems are facing and adapting to (Renaud et al. 2015).

Adaptation Interventions

The main implications of these transitions will be on ecosystem health through salinity intrusion, biomass reduction and biodiversity losses (Le Dang et al. 2013; 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. 2015; Wu et al. 2013) with implications for human mortality and economic and infrastructure losses.

Main adaptation strategies in the Mekong include technical, behavioural, financial and institutional shifts in agriculture, coastal management and ecosystem services (Schipper et al. 2010). The region also sees several landscape-based initiatives (Zanzanaini et al. 2017) that have potential adaptation implications through livelihood strengthening, agriculture development and ecosystem conservation.

Adaptation related to agriculture including improving water use technology (e.g. pond capacity improvement, rainwater harvesting), shifting farming systems or crops, soil management and diversification, and strengthening allied sectors such as livestock rearing and aquaculture (ICEM 2013).
Several ecosystem-based approaches have been suggested and implemented in the Mekong River Basin. For example, integrated water resources management (IWRM) has demonstrated successes in mainstreaming climate adaptation into existing basin strategies and water management (Sebesvari et al. 2017).

Coastal adaptation strategies include dyke construction and mangrove restoration to reduce the impacts of sea level rise and storm surge (Smith et al. 2013) and ecological engineering such as densification of coastal vegetation (Renaud et al. 2014). However, some of these adaptation measures have been identified to have negative impacts as well: a study in the Vietnamese Mekong Delta suggests that dyke construction and resultant sedimentation has increased agricultural productivity but sharpened the divide between land-rich and land-poor farmers and reshaped the socioeconomic system (Chapman et al. 2016). The entry of high dykes ushered triple-cropping which benefits land-wealthy farmers but forces debt on poorer farmers (Chapman and Darby 2016). Thus, when seen holistically and over a longer time frame, certain seemingly adaptive strategies (dyke construction) can be maladaptive and cause new risks. Studies have repeatedly called for an ensemble of hard and soft policies where focus on hard options such as building water infrastructure are balanced by investment in soft adaptation measures such as land-use change to deal with impacts of rising sea levels and salinity intrusion in the Mekong (Smajgl et al. 2015).

The Mekong River Commission (MRC) is an intergovernmental body established in 1995 by agreement of the governments of Cambodia, Lao PDR, Thailand and Viet Nam. In the face of growing impacts of climate variability and change, the MRC responded to a call for regional cooperation to share knowledge and build capacities, and implemented the Climate Change and Adaptation Initiative (CCAI) in 2009. This politically backed institution has facilitated impact assessment studies, regional capacity building and local project implementation (Schipper et al. 2010), demonstrating a workable template.

The region also sees significant civil society presence and communities of practice such as the Asia-Pacific Adaptation Network, Adaptation Knowledge Platform and Asian Cities Climate Change Resilience Network (Schipper et al. 2010).

National governments have also undertaken action to deal with climate change but their progress varies substantially (Gass et al. 2011). Laos PDR and Cambodia have NAPAs, Thailand has a Climate Change Master Plan (2015-2050) and Viet Nam launched a 'National Target Program to Respond to Climate Change' in 2008 with full implementation in 2015. However, overall, the region has been critiqued for inadequate mainstreaming of adaptation into development policies and low adaptation action (Gass et al. 2011). However, these are explained by significant capacity barriers and other national priorities that limit adaptation progress (Gass et al. 2011).

Adaptation funding in the Mekong region is typically project-based and channelled through national projects financed by the Asian Development Bank (ADB), Global Environment Facility (GEF), LDCF, Special Climate Change Fund (SCCF), United Nations Development Programme (UNDP), World Bank and World Health Organization (WHO). The Adaptation Fund (managed by the GEF) is currently funding two projects in the region focusing on climate resilience of communities in protected areas (Cambodia) for $3 million and enhancing climate and disaster resilience rural and emerging urban settlements (Lao PDR) for $45 million. Some bilateral assistance from developed countries is also directed towards adaptation though this varies by country.

To strengthen current adaptation action in the Mekong, there needs to be more investment in developing drought and saline-tolerant rice varieties and shifts towards crop diversification and integrated agriculture-aquaculture practices (Renaud et al. 2014). 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 directly and instantly accessed by the local authority or farmers are also recommended (Renaud et al. 2014). Finally, it is critical to identify and invest in synergistic strategies from an ensemble of hard options (building dykes) and soft adaptation measures (land-use change) (Smajgl et al., 2015), to combinations of top-down government-led strategies such as the Living With the Flood (LWF) program to relocate residents from flood areas and bottom-up household strategies such as increasing house height (Ling et al. 2015).

Urban Adaptation

Status

Studies tracking progress on urban adaptation report that between 18% (from total n=401 of cities >1m population) (Araos et al. 2016b)and 25% of city governments (from total of n=468 surveyed ICLEI member cities) (Aylett 2014) are developing a climate change adaptation plan. An additional 18% report already having implemented a plan (Aylett 2014). In Europe, a 2014 study of 200 cities found that 28% (from total n=200 cities >500k population) have an adaptation plan (Reckien et al. 2014, 2015).

High-income regions such as Europe, North America, and Australia report higher levels of engagement with adaptation than developing regions, yet within these regions less than half of the cities have a plan (Reckien et al. 2014). Several cities in low-income countries are currently reporting extensive adaptation activity such as Quito, Ecuador, Durban, South Africa, and Semarang, Indonesia. These cities represent focal points for learning from their success. In these cities, the emergence of policy entrepreneurs and champions has enabled an emphasis on urban adaptation. While urban adaptation is in the early stages, there are substantive examples of governments taking leadership regardless of wealth levels and institutional barriers (Roberts 2008).

Adaptation measures

Across studies, the most frequently addressed urban adaptation measures are protection of the built environment, coastal protection, and green infrastructure (Araos et al. 2016b; Austin et al. 2015). Only a small portion of initiatives have targeted health and social services, while the rest focus on protecting physical infrastructure (Araos et al. 2016b).

A study of 10 megacities' spending on adaptation found that protection of the built environment is the sector where cities spend the most on adaptation (~35% of global expenditure), followed by transport infrastructure (~13% of total spend on average) (Georgeson et al. 2016).

Implementation gaps and challenges

Lack of funding is reported as the most significant challenge for implementing urban adaptation projects and programs by 78% of 350 surveyed ICLEI member cities (Aylett 2014). Competing priorities such as health, housing, sanitation, and economic growth are also cited as a significant challenge by cities planning adaptation. Finally, cities report difficulties incorporating climate change, a relatively new issue, into existing departmental functions and procedures (Aylett 2014).

Adaptation mechanisms

Mainstreaming adaptation into spatial planning: Spatial planning in cities offers the potential to support cross-sectoral urban adaptation, where climate change concerns can be integrated into urban policy and planning. This means mainstreaming climate change projections and considerations into city plans, including land use planning, public health, transportation, and social services (Archer et al. 2014; Chu 2016; Chu et al. 2016; Friend et al. 2014; Lehmann et al. 2015; Rivera and Wamsler 2014).

Community-based adaptation (CBA): As adaptation tends to be a more localised approach in dealing with climate change effects, there is increasing focus of placing local communities at the heart of forming policy and adaptation plans. CBA presents opportunities for local participation in the design and implementation of adaptation activities and yields greater transformative potential for urban governance (Archer et al. 2014). It can also offer a cost-effective, sound way to tackle climate change by capturing the wealth of knowledge, skills and experience that communities have on dealing with climate variability and change (Fenton et al. 2014; Brink et al. 2016; Mitchell and Borchard 2014; Reid and Huq 2014; Tran 2014).

In Dhaka, for example, the city's largest informal settlement Korail, has created a community savings group which provides loans to residents to rebuild their housing structures with more durable material in the event of flood destruction (Jabeen 2014). Of the informal households in the community, 50% save regularly with the CBA project and in 2009, 30% of households withdrew loans for repairs.

Ecosystem based adaptation (EbA): In recent years, policy makers and planners are increasingly promoting integrated 'EbA' and CBA approaches. EbA is defined as the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change (Wamsler et al. 2014; Wamsler 2015; Reid 2016).

With the increasing uptake of green infrastructure such as green roofs and street trees, ecosystems and their services can increase local resilience and adaptive capacity, most notably as a substitute to built infrastructure. Examples of EbA in urban spaces include coastal mangroves providing protection against cyclone damage and storms, wetlands acting as floodwater reservoirs and well-vegetated hillsides reducing risks from erosion, landslides and downstream flooding during heavy downpours of rain (Brink et al. 2016; Reid et al. 2009; Wamsler 2015; Wamsler et al. 2014).

City networks and learning partnerships: Transnational networks of cities such as C40, Resilient Cities, and ICLEI have also played a key role supporting accelerated learning and action local adaptation. The growth in membership of transnational networks signals an interest in learning and experimentation with more flexibility than through mandated government policy (Spaans and Waterhout 2017; Heidrich et al. 2016; Fünfgeld 2015).

Adaptation in the Amazon

The highest terrestrial carbon dioxide uptake on Earth is due to tropical forests (Beer et al. 2010). The Amazon photosynthetic system is responsible for a significant amount of the CO_2 uptake of the planet and stores an enormous amount of carbon, mainly in trees. At the same time, the Amazon is quite sensitive to changes in the climate, especially to drought (Laurance and Williamson 2001). According to Nobre et al. (2016), there are two "tipping points" that should not be transgressed: 4C warming or 40% or total deforested area. Thus, the danger of crossing these tipping points come from two directions: human activities, mainly related to land use change for food production, and global warming. Depending on the choices taken during the first quarter of this century, the Amazon may or may not survive to the warming effects.

Because climate change is closely associated with GHG emissions, and mitigation is vital to maintaining Earth temperature well below 2°C (Rogelj et al. 2015), the Amazon is thought to play a critical role in future strategies to avoid global warming. Crossing the tipping points mentioned above (Nobre et al. 2016) would lead to significant changes in the climate of the region, possibly leading to a backfiring effect that could affect the whole agricultural and settlement systems established at the expense of the forest. The devastation of the Amazon, even advancing slowly as it is today, would increase CO_2 emissions and contribute to warming, preventing most of the actions that could be taken towards a 1.5°C.

Deforestation of the Amazon has been discussed since the 1980s. Authors have pointed out to several adverse consequences such as loss of habitats and biodiversity, loss of indigenous people and culture, and climate change (Fearnside 1985; Shukla et al. 1990; Malhi et al. 2008; Nobre et al. 2016). The consequences of human activity in the region through burning with the purpose of freeing land for agriculture has been quite drastic, leading to loss of biodiversity and increasing CO_2 emissions (Tasker and Arima 2016; Numata et al. 2017).

Because the Amazon forest has a key role in the climate equilibrium at regional and global levels, whatever happens to that forest will potentially affect not only the local biodiversity and people, but also produce teleconnections that may influence the world in many ways (Bonan 2008). Burning has been decreased dramatically over the last two decades (Magrin et al. 2014), but has not been eliminated (Tasker and Arima 2016). Even though it was a significant governance intervention in a large forest and quite successful, the threat continues as the forest is slowly disappearing. Human activity that leads to deforestation is complex and depends on national government policies as well as on possible coalitions of countries that could work together towards preservation, sustainable use and the possible recovery of lost areas. Although the biodiversity loss is irreversible (Oliver and Morecroft 2014), the complete arrest in burning and clearing of the forest along with the restoration of part of the biodiversity would be an important action to help to stay in a 1.5°C scenario. 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 US$ 1 billion in projects (REDD+) for reforestation of the Amazon. According to a study of the Centre for Global Development, the investment is generating successful results, but there are challenges and lessons learned that can be used as guides for other agreements of the type in the Amazon region. This will probably be one of the main challenges to cope with the Amazon forest during this century.

Conclusion

The case studies presented here are representative of multiple climate impacts that are being felt in key regions and hot-spots worldwide, along with the array of adaptation options and strategies as well as the multiple challenges that remain to be met. Each case study presents the importance of local circumstances and contexts, which are important to consider when implementing an adaptation option. While describing planned or implemented adaptation strategies, there is a lack of empirical studies and monitoring and evaluation of current efforts to generalise across regions and themes. It is s not yet possible to determine how effective these efforts have been. 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.

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