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Executive Summary

Current Greenhouse Gas (GHG) emission trends at the global level, extrapolated, are incompatible with the goals agreed in the Paris Agreement, which highlights the need for urgent and accelerated mitigation actions at all scales (*robust evidence, high agreement*). Since IPCC's Fifth Assessment Report (AR5), important changes include the greater global ambition established in the Paris Agreement of 2015, alongside rising climate impacts and levels of societal awareness. However, while the Nationally Determined Contributions (NDCs) offer important steps towards limiting GHG emissions, the gap between current NDCs, current implementation, and the rate of emission reductions consistent with meeting Paris goals remains large. Continuing investments in carbon-intensive activities would heighten the multiple threats to human development and well-being associated with climate change, risk assets being stranded, and impede societal and industrial transformation towards low carbon development. Meeting Paris Agreement goals requires global CO_2 emissions to peak before 2025, and decline to net zero generally within the third quarter of the century. This implies urgent and ambitious action combining national initiatives with regional and global cooperation. The unprecedented COVID-19 pandemic has also had far-reaching impacts on global economic and social system, and recovery will present both challenges and opportunities for climate mitigation. {1.2, 1.2.2, 1.3, 1.7, Chapter 3}

Globally effective climate mitigation needs to be implemented to achieve global sustainable development and to eradicate poverty as enshrined in 17 SDGs, recognising there are synergies and/or trade-offs. Climate mitigation is one of many goals that societies pursue in the context of sustainable development, as underlined by the wide range of UN Sustainable Development Goals. There has been a strong relationship between development and GHG emissions, as historically both per capita and absolute emissions have risen with industrialisation. Countries have different priorities in achieving the SDGs as dictated by their respective national conditions and capabilities. Given the differences in historical and current responsibilities, impacts, as well as capacities within and between nations, equity and justice are important issues to address to get national and international support for deep decarbonisation. Failures to address such inequities over time can undermine social cohesion and stability. International co-operation can enhance efforts to achieve ambitious global climate mitigation in the context of sustainable development. {1.4, Chapters 2, 3, 4, 5, 13 and 17}.

Advances in technologies and policies, including transformative changes in some regions and sectors, has opened up new and large-scale opportunities for deep decarbonisation, and for alternative development pathways, which could deliver multiple social and developmental goals (*robust evidence, medium agreement*). The development and deployment of innovative technologies and systems at scale are important for achieving deep decarbonisation. In recent years, several clean energy technologies have expanded rapidly and declined in costs, and significant numbers of countries have sustained emission reductions. The understanding and scope of technology and policy options to respond has increased. This enhances opportunities for mitigation. However, competing priorities combined with institutional and political inertia could pose challenges. The transition to low carbon development depends on a wide range of additional drivers and enabling conditions. These include: the means by which services are being provided and for whom, the emissions intensity of traded products, finance and investment, political economy forces, equity and fairness, social innovation and behaviour change, legal framework and institutions, and the quality of international cooperation. These factors matter in different measures with each exacting more or less force depending on prevailing social, economic, cultural and political context. They often exert both push and pull forces at the same time, in the same and across different scales. {1.3, 1.5, Chapter 4}

Accelerating mitigation to avoid or limit dangerous anthropogenic interference with the climate system will require integration of broadened assessment frameworks and tools that combine multiple perspectives, applied in a context of multi-level governance *(robust evidence, medium agreement)*. Analysing a challenge on the scale of fully decarbonising our economies requires integration of multiple analytic frameworks including approaches to risk assessment established across IPCC Working Groups. *Economic frameworks* indicate increasing convergence of cost-benefit assessment with cost-effective delivery of the Paris goals. *Ethical frameworks* are essential to choose policies to avoid negative distributional impacts across income groups, countries and generations. *Transition and transformation frameworks* explain the dynamics of transitions to low-carbon systems arising from interactions amongst levels, with inevitable resistance from established socio-technical structures. *Psychological, behavioural and political frameworks* underline the constraints (and opportunities) arising from human psychology and the power of incumbent interests. A comprehensive understanding must combine these multiple frameworks. Together they explain potential synergies and trade-offs, imply a need for a wide portfolio of policies attuned to different actors and levels of decision-making, and underpin 'just transition' strategies in diverse contexts. {1.6}

The speed, direction and depth of transition will be determined by choices in geophysical, environmental, technological, economic, socio-cultural and institutional realms *(robust evidence, high agreement)* Transitions typically are not smooth and gradual. They can be sudden and disruptive. The pace of transition can be impeded by 'lock-in' from existing physical capital, institutions, and social norms. The interaction between power, politics and economy is central in explaining why broad commitment does not always translate to urgent action. At the same time, attention to and support for climate policies and low carbon societal transition has generally increased. Supporting policies in the realms of finance, regulation, institutions and societal norms are essential to accelerate low carbon transitions in multiple sectors, whilst addressing distributional concerns endemic to any major transformation. {1.5, 1.6, Chapters 2-4}

Achieving global transition to a low-carbon, climate-resilient and sustainable world requires purposeful and largely coordinated planning and decisions at many scales of governance including municipal, subnational, national and global levels (*robust evidence, high agreement*). Multi-level governance of climate change is necessitated by the imperative for strong action across multiple jurisdictions and decision-making levels. Choices that cause climate change as well as the decisions and processes involved in making and implementing decisions on climate change involve a range of non-nation state actors such as cities, businesses, and civil society organisations. At global, national and subnational levels, climate change policies and actions are interwoven with and embedded in the context of much broader social, economic and political goals. Therefore, the governance required to address climate change has to navigate power, political, economic, and social dynamics at all levels of decision making. Institutions, ideas, and experimentation are key factors in shifting perceptions, engaging stakeholders, and building momentum for effective climate action at all scales of governance. {1.2, 1.5, 1.7, Chapters 13-14}

1.1 Introduction

The accumulating impacts of climate change will get much worse without stronger emissions mitigation (IPCC Sixth Assessment (AR6), WGI and WGII reports). The UN Framework Convention on Climate Change (UNFCCC 1992) agreed the global Objective to "avoid dangerous anthropogenic interference" with the climate system.[1] Reflecting this, the Paris Agreement (UNFCCC 2015) established the mitigation aim of "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C."

Despite growing climate mitigation policies around the world, previous IPCC Assessments highlighted the continued rise of GHG emissions. Since the Fifth Assessment Report (IPCC 2015), global emissions continued to increase to 2018/9 though more slowly (CO_2 increase averaged 0.7% per year 2014-19, cf 2.2% per year 2008-13) , thus continuing the trend of global CO_2 concentrations rising at over 2ppm per year (see Figure 1.2). Because CO_2 cumulates in the atmosphere, halting global warming requires the concentration of CO_2, to be stabilised, with net zero emissions. Any given temperature target is closely tied to cumulative emissions up to that point, underlining the urgency of the mitigation challenge, as demonstrated in this report (chapter 3).

The IPCC has also published three Special Reports in the Sixth Assessment Cycle all of which emphasise the rising threat of climate change and the need for more ambitious mitigation efforts at all scales. These are the 'Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty' (hereafter SR1.5, 2018) (IPCC 2018a); the 'Special Report on Climate Change and Land' (SRCCL); and the 'Special Report on the Ocean and Cryosphere in a Changing Climate' (SROCC) (IPCC 2019a).

AR6 aims to assess new literature on climate mitigation and draw out their implications for global sustainable development. Along with a better understanding of the physical science basis of climate change (AR6 WGI), and vulnerabilities, impacts, and adaptation (AR6 WGII), the landscape of climate mitigation has evolved substantially since AR5 and subsequent Special Reports. At the same time, the Paris Climate Agreement and the SDGs, both of which were adopted in 2015, set out a globally agreed broader agenda within which climate mitigation efforts must be located. The Special Report on 1.5°C underlined that humanity is now living with the "unifying lens of the Anthropocene" (SR1.5 IPCC 2018a; p.52 & 53), as an over-arching context, that requires a sharpened focus on the impact of human activity on the planet and the need for urgent steps to address climate change in the context of equity, nationally determined action, global sustainability, international cooperation, and multi-level governance.

Despite the global trend of emissions rising until 2018/9 (and only then reducing under the impact of COVID-19 pandemic), national emission trends have been diverse. The majority of developed countries have cut absolute emissions in the past decade – both on their territory, and including their 'consumption-based' emissions (i.e. taking account of trade) - alongside sustained economic growth (Chapter 2) – but generally much slower than the pace required for the Paris goals.[2] Per-capita GHG

FOOTNOTE [1] UNFCCC Article 2 (Objective): "to achieve … stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

FOOTNOTE [2] By 2018, CO_2 emissions were below 2010 levels in 32 developed countries, but only in 24 when including other GHGs. Reductions were by less than 10% in half these countries. Data from Chapter 2: see (2.2.3) emissions between countries even at similar stages of economic development (GDP per capita) vary by a factor of three (Figure 1.6), and by more than two on consumption basis (Chapter 2).

Strong differences remain in responsibilities for, and capabilities to take, climate action, within and between countries. These differences, as well as differences in the impact of climate change, point to the need for collective action to address the challenge of achieving urgent and ambitious global climate mitigation in the context of sustainable development with attention to issues of equity and fairness (Chapter 14).

Innovation and industrial development of key technologies in several relevant sectors have transformed prospects for mitigation at much lower cost than previously assessed (Chapters 2 and 6–12). Large reductions in the cost of widely-available renewable energy technologies, along with other behavioural changes (Chapters 5 and 9–11) can enable societies to provide services with lower energy demand. However, there are still significant differences in the ability to access and utilise low carbon technologies across the world (Chapter 4, 15, 16). New actors, including cities, businesses, and numerous non-state transnational alliances have emerged as important players (Chapters 13–16).

Analytically, along with continued development of concepts, models and technologies, there have been numerous insights from both successes and failures of mitigation action. This can inform both policy design and the political realisation of more ambition. However, policies and investments are still clearly inadequate to put the world in line with the PA's aims (Chapter 15).

Recent literature assessed by WGs I and II of this AR6 implies a renewed and heightened need for urgent climate action. The remaining 'carbon budgets' associated with 1.5°C and 2°C temperature increases equate to about 1 to 3 decades of current emissions, respectively, from before 2020 (for emission pathways implied by the Paris goals, with timing of peak and 'net zero', see section 1.2.2 and Chapters 2 and 3). The greater the inertia (including political) in emission trends and the obstacles to mitigation, the more that CO_2 will continue to accumulate, increasing the scale of costs and risks also associated with having to subsequently remove CO_2 from the atmosphere, particularly to achieve the lower ends of the Paris Agreement goals (Hilaire et al. 2019)(Chapter 3). Climate change will in turn impact net emissions by affecting resources used for energy production and terrestrial carbon sinks (IPCC 2019b) (WGI). Overall, these factors and the associated literatures point to more dynamic consideration of intertwined challenges concerning the transformation of key GHG emitting systems: to minimise the trade-offs, and maximise the synergies, of delivering deep decarbonisation whilst enhancing sustainable development.

This Report, consequently, draws upon a rapidly expanding body of literature covering theory, modelling and practical experience, to assess latest knowledge on climate mitigation and the interlinked efforts to global achieve sustainable development and societal transformation the face of climate change.

Figure 1.1 below provides a map of the broad structure of the Assessment Report including the chapters and how they link. A more detailed description of the Roadmap to the report is presented in Section 1.10 of this chapter.

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and Figure 2.11 for panel of 36 countries that have sustained territorial emission reductions longer than 10 years, as analysed in (Lamb et al., Submitted), and decomposition analysis of national trends in (Xia et al. 2020). The previously rising trend of 'outsourced/embodied emissions' associated with goods imported into developed countries peaked in 2006, but detailed data on this are only available to 2015 (Chapter 2 section 2.3). See Chapter 3 for reduction rates associated with 1.5 and 2°C.

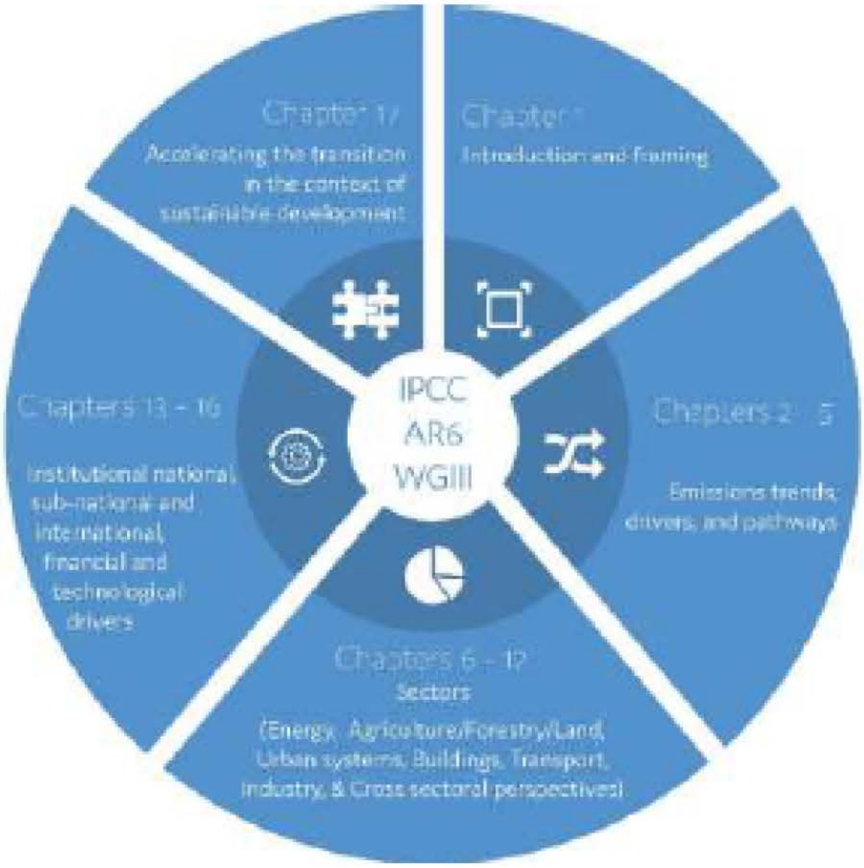

Figure 1.1 The Structure of AR6 Mitigation Report

1.2 Previous Assessments and UNFCCC Developments

1.2.1 Key findings from previous Assessment Reports and Special Reports

Successive IPCC Assessments have emphasised the importance of climate mitigation along with the need to consider broader societal goals especially sustainable development. Key insights from AR5 and the subsequent three Special Reports (IPCC 2018a, 2019b,a) are summarised below.

In AR5, the projections of business as usual (BAU) emission pathways obviously did not take into account national commitments as submitted within the Paris Agreement. AR5 projected that in baseline scenarios (scenarios based on prevailing trends without explicit additional efforts to constrain emissions), Agriculture, Forestry and Other Land Uses (AFOLU) would be the only sector where emissions could fall by 2100 but even this projection is based on some measure of CO_2 removal (p.17 SPM WGIII AR5) (IPCC 2014a). On the same baseline scenarios direct CO_2 emissions from energy sector could double or even triple by 2050 (p.20 SPM WGIII AR5) due to global population and economic growth, resulting in global mean surface temperature increases in 2100 from 3.7°C to 4.8°C compared to pre-industrial levels. AR5 noted that mitigation effort and the costs associated with such effort differ significantly across countries for all mitigation scenarios. It is also observed that in the globally cost-effective scenarios, the majority of reductions are made in the countries with the highest future emissions in the baseline scenarios (p.17 SPM WGIII AR5).

A key message from recent Special Reports is the urgency to mitigate GHG emissions in order to avoid rapid and potentially irreversible changes in natural and human systems (IPCC 2018a, 2019b,a). Successive IPCC reports have drawn upon increasing sophistication of modelling tools to project emissions in the absence of ambitious decarbonisation action, as well as the emission pathways that meet long term temperature targets. The SR1.5 found that pathways limiting warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (*high confidence*) (IPCC 2018a). Since most physical capital (e.g. power plants, buildings, transport infrastructure) involved in GHG emissions is long-lived, the timing of the shift in investments and strategies will be crucial (p.18 SPM (IPCC 2014a).

The Nationally Determined Contributions (NDCs) as declared under the Paris Agreement (PA) suggest global GHG emissions between 52 and 58 $GtCO_2eq\ yr^{-1}$ in 2030 (IPCC 2018a), similar to the 58 (±5.8) $GtCO_2eq$ GHG emissions in 2018 (Chapter 2)). The emission contributions as submitted under the Paris Agreement (PA) suggest global GHG emissions between 52 and 58 $GtCO_2eq\ yr^{-1}$ in 2030 (IPCC 2018a), which is at the same level of similar to the 58 (±5.8) $GtCO_2eq$ of global GHG emissions in 2018 (Chapter 2). This would not limit warming to 1.5°C. To stay below 2°C, ambition would have to rapidly ramp up after 2030. The NDCs are not sufficient to meet the stated aim of the Agreement, or they could only do with rapid transition to *net* negative emissions – subsequent CO_2 removal at a scale exceeding emission and/or Solar Radiation Modification (SRM). Both measures involve uncertain costs, environmental risks and governance challenges as discussed in SR1.5 (for negative emissions) and chapters 12 and 14 of this report.

AR5 and the Special Reports analysed economic costs associated with climate action. The estimates vary widely depending on the assumptions made as to how ordered the transition is, temperature target, the technology deployed, the metric or model used, among others (Chapter 6). Modelled direct mitigation costs of pathways to 1.5°C, with no/limited overshoot, span a wide range, but were typically 3-4 times higher than in pathways to 2°C (*high confidence*), before taking account of benefits, including significant reduction in loss of life and livelihoods, and avoided climate impacts (IPCC 2018b).

Successive IPCC Reports highlight a strong connection between climate mitigation and sustainable development. Climate mitigation and adaptation goals have synergies and trade-offs with efforts to achieve sustainable development, including poverty eradication. A comprehensive assessment of climate policy therefore involves going beyond a narrow focus on specific mitigation and adaptation options to incorporate climate issues into the design of comprehensive strategies for equitable sustainable development. At the same time, some climate mitigation policies can run counter to sustainable development and eradicating poverty. Examples include synergies between climate policy and improved air quality, reducing premature deaths and morbidity (AR5 WGIII Fig SPM.6), but there would be trade-offs if policy raises net energy bills, with distributional implications. The Special Report on Climate Change and Land (SRCCL) also emphasises important synergies and trade-offs, bringing new light on the link between healthy and sustainable food consumption and emissions caused by the agricultural sector. Land-related responses that contribute to climate change adaptation and mitigation can also combat desertification and land degradation and enhance food security.

Previous ARs have presented detailed understanding of the contribution of various sectors and activities to global GHG emissions. When indirect emissions (mainly from electricity, heat and other energy conversions) are included, the four main consumption (end-use) drivers are industry, AFOLU, buildings and transport (for updated estimates see SPM.4). These – together with the energy and urban systems which feed and shape these end-use sectors – define the sectoral chapters in this AR6 report.

Estimates of emissions associated with production and transport of internationally traded goods were first presented in AR5, which estimated the 'embodied emission transfers' from upper-middle-income countries to industrialised countries through trade at about 10 percent of CO_2 emissions in each of these groups (AR5 IPCC (Fig.TS.5)). The literature on this and discussion on their accounting has grown substantially since then (chapter 2).

The atmosphere is a shared global resource and an integral part of the "global commons". In the depletion/restoration of this resource, myriad actors at various scales are involved, for instance, individuals, communities, firms and states. This implies that international cooperation and collective action on climate change alongside local, national, regional and global policies will be crucial to solve the problem (Chapter 13, 14). *Inter alia*, international cooperation to tackle ozone depletion and acid rain offer useful examples.

AR5 noted that greater cooperation would ensue if policies are perceived as fair and equitable by all countries along the spectrum of economic development–implying a need for equitable sharing of the effort. A key takeaway from AR5 is that climate policy involves value judgement and ethics. (AR5 WGIII Box TS.1 "*People and countries have rights and owe duties towards each other. These are matters of justice, equity, or fairness. They fall within the subject matter of moral and political philosophy, jurisprudence, and economics.*" p. 37)

AR5 also underlined that climate policy inherently involves risk and uncertainty (in nature, economy, society and individuals). There exists a rich suite of analytical tools, for example, cost-benefit analysis, cost-effectiveness analysis, multi-criteria analysis, expected utility theory and catastrophe and risk models, all of which have pros and cons (Doukas and Nikas 2020), to help manage this risk and uncertainty. We consider these tools briefly in section 6 of this chapter.

Recent Assessments (AR5 and SR1.5) (IPCC 2015, 2018a) began to consider the role of individual behavioural choices and cultural norms in driving energy and food patterns. Notably, SR1.5 (section 4.4.3) outlined emerging evidence on the potential for changes in behaviour and culture to contribute to decarbonisation (and lower the cost); for the first time, AR6 devotes a whole chapter (Chapter 5) to consider these and other drivers of energy demand, food choices and social aspects. The most recent Assessments (AR5 and SR1.5) (IPCC 2015, 2018a) have begun began to consider the role of individual behavioural choices and cultural norms in driving energy and food patterns.

1.2.2 Recent developments in the multilateral context and the 2015 agreement

Since 2015, there have been some notable multilateral efforts relevant to climate action. These include: the Paris Agreement which aims to enhance the implementation of the 1992 United Nations Framework Convention on Climate Change (UNFCCC), the UN agreements on Disaster Risk Reduction (Sendai) and Finance for Development (Addis Ababa), and the SDGs.

The Paris Agreement. The Paris Agreement (PA) aims to "hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UNFCCC 2015). The PA aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty. It also underlines the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances as the basis for global action on climate change (PA Article 2 paragraph 2).

The Paris Agreement is predicated on encouraging progressively ambitious climate action from all countries on the basis of voluntary Nationally Determined Contributions (Rajamani 2016; Clémençon 2016), unlike the Kyoto Protocol's legally binding obligations on developed countries only. The NDC approach requires countries to set their own level of ambitions for climate change mitigation but within a collaborative and legally binding process to foster ambition towards the agreed goals (Falkner 2016a; Bodansky 2016). The PA entered into force in November 2016 and as of June 2020 it has 189 Parties (out of 197 Parties to the UNFCCC). The PA explicitly underlines the roles of countries in its Article 4, paragraph 4: developed country Parties shall continue taking the lead by undertaking economy-wide absolute emission reductions. Developing country Parties should continue enhancing their mitigation efforts, and are encouraged to move over time towards economy-wide emission reduction or limitation targets in the light of different national circumstances.

The PA acknowledges its mitigation goal implies to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century", commonly known as "net zero" (Article 3). Based on the scenarios assessed in this report, these goals entail global CO_2 emissions peaking before 2025, and declining to net zero generally within the third quarter of the century (3: Figure SPM.7; Table SPM.1 category 1-3). The net-zero CO_2 date depends on the level of ambition, the rapidity of action, and degree of 'overshoot' (with subsequent negative CO_2 emissions). Delays in CO_2 peaking imply steeper and deeper subsequent reductions to compensate for the higher interim emissions.[3] Trends for total GHG emissions are similar though the net-zero emissions year is typically 5-25 years later.

The PA provides for 5-yearly stocktakes in which Parties have to take collective stock on progress towards achieving its purposes and its long-term goal in the light of equity and available best science (PA Article 10 and 14). The first global stocktake is scheduled for 2023. The outcome of these reviews is meant to inform Parties to update and enhance the pledges in their NDCs (PA Article 14 para 3).

In keeping with the principle of differentiated responsibility and capabilities and effort to achieve global sustainable development and poverty eradication, developed country parties are to assist developing country parties with financial resources (PA Article 9). The Green Climate Fund (GCF) was given an important role in serving the Agreement and delivering the UNFCCC Objective, and supporting the goal of keeping climate change well below 2°C. The GCF rapidly gathered pledges worth USD 10.3 billion, from developed and developing countries, regions, and one city (Paris) (Antimiani et al. 2017; Bowman and Minas 2019) although still short of the goal to mobilised USD100 billion by 2020. Initiatives contributing to the PA goals include the Non-State Actor Zone for Climate Action (NAZCA) portal, launched at COP20 (Dec 2014) in Lima, Peru, to support city-based actions for mitigating climate change (Mead 2015) and Galvanizing the Groundswell of Climate Actions (GGCA) which is a UNFCCC-backed series of open dialogues intended to bring climate actions from cities, regions, companies, and other groups to a higher level of scale and ambition.

SDGs. In September 2015, the UN endorsed a universal agenda – 'Transforming our World: the 2030 Agenda for Sustainable Development'. The agenda adopted 17 non-legally-binding SDGs and 169 targets to support people, prosperity, partnerships and the planet While climate change is explicitly listed as SDG13, the pursuit of the implementation of the UNFCCC is also relevant for a number of many other goals including SDG 7 (clean energy for all), 9 (sustainable industry), and 11 (sustainable cities), as well as those relating to life on land (14) and water (15) (Biermann et al. 2017). Mitigation actions could have multiple synergies and trade-offs across the SDGs (Prajal et al. 2017b) and their net effects depend on the pace and magnitude of changes, the composition of the mitigation portfolio and the management of the transition. This suggests that mitigation must be pursued in the broader context of sustainable development. Mitigation actions could have multiple synergies and trade-offs across the SDGs (Prajal et al. 2017b) and their net effects depend on the pace and magnitude of changes, the composition of the mitigation portfolio and the management of the transition. This suggests that mitigation must be pursued in the broader context of sustainable development.

Finance. The Paris Agreement has as one of its three declared aims to make "finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development." (Article 2.1C). This reflects a broadened focus, beyond the costs of climate adaptation and mitigation, to recognising that achieving a structural shift towards low carbon climate-resilient development pathways

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FOOTNOTE [3] See Chapter 3 for detail. C1 and C2 are 1.5°C scenarios, respectively with little or no overshoot, and high overshoot compensated by subsequent 'net negative' global emissions. C3 scenarios stay below 2°C with a 66% chance, even the highest scenarios in this category show a *median* peak warming around ~1.8. All the 1.5 and 2°C 'Illustrative Pathways', summarised in section 3.5 (Box 1-2), peak emissions by 2025 and reach net zero in the period 2050-2070 (Figure SPM.7).

require large scale investments that engage the wider financial system (15.1 and 15.2.4). The IPCC 1.5C report estimated that 1.5°C pathways would require *increased investment* of 0.5-1% of global GDP between now and 2050, which is up to 2.5% of global savings / investment over the period. For low- and middle-income countries, SDG-compatible infrastructure investments in the most relevant sectors are estimated to be around 4-5% of their GDP, and 'infrastructure investment paths compatible with full decarbonisation in the second half of the century need not cost more than more-polluting alternatives' (World Bank 2019a).

The parallel 2015 UN Addis Ababa Conference on Finance for Development, and its resulting Action Agenda, aims to 'address the challenge of financing … to end poverty and hunger, and to achieve sustainable development in its three dimensions through promoting inclusive economic growth, protecting the environment, and promoting social inclusion.' The Conference recognises the significant potential of regional co-operation and provides a forum for discussing the solutions pathways to common challenges faced by developing countries (15.6.4).

Alongside this, private and blended climate finance is increasing but is still short of projected requirements consistent with Paris Agreement targets (15.3.2.1). The financing gap is particularly acute for adaptation projects, especially in vulnerable developing countries. From a macro-regulatory perspective, there is growing recognition that substantial financial value may be at risk from changing regulation and technology in a low-carbon transition with potential implications for global financial stability (15.6.3). To date, the most significant governance development is the Financial Stability Board's TCFD (Task Force on Climate Disclosure) recommendations which were welcomed by over 500 financial institutions and companies as signatories albeit with patchy implementation (15.6.3). Although this reflects concern about the risks posed by climate change to the stability of the global financial system (and *vice-versa)*, this is also accompanied by growing consensus that transparency alone cannot mitigate these risks (Ameli et al. 2019) (15.6.3).

Talanoa Dialogue and Just Transition Launched at COP23, the 'Talanoa Dialogue Synthesis Report' (UNFCCC 2018a; Mead 2018) emphasised the need to implement holistic approaches across multiple economic sectors for efficient climate change mitigation. At COP24 also, the Just Transition Silesia Declaration, focusing on the need to consider social aspects in designing policies for climate change mitigation was signed by 56 heads of state (UNFCCC 2018b; COP24 2018). This underlined the importance of aiming for a 'Just Transition' in terms of reducing emissions, at the same time preserving livelihoods and managing economic risks for countries that rely heavily on emissions-intensive technologies for domestic growth (Markkanen and Anger-Kraavi 2019).

1.3 The evolving context and our approach to Assessment

Beyond the UN and related processes, the world since 2015 has seen sharply contrasting trends in many dimensions which help determine the context for future action, and our approach to assessment. This section summarises key features of this evolving context.

1.3.1 Climate science, impacts and risk

The assessment of the Physical Science Basis (IPCC WGI AR6) documents sustained and widespread changes in the atmosphere, cryosphere, biosphere and ocean, providing unequivocal evidence of a world that has warmed, associated with rising atmospheric CO_2 concentrations reaching levels not experienced in at least the last 2 million years. Aside from temperature, other clearly discernible, human-induced changes beyond natural variations include declines in Arctic sea ice and glaciers, thawing of permafrost, and a strengthening of the global water cycle (WG1 SPM A.2, B.3 and B.4). Oceanic changes include rising sea level, acidification, deoxygenation, and changing salinity (WG1 SPM B.3). Over land, in recent decades, both frequency and severity have increased for hot extremes but decreased for cold extremes; intensification of heavy precipitation is observed in parallel with a decrease in available water in dry seasons, along with an increased occurrence of weather conditions that promote wildfires.

Against the background of 'unequivocal' (AR4) evidence of human-induced climate change, and the growing experience of direct impacts, the IPCC has sought to systematise a robust approach to risk and risk management. This plays a key role in how the IPCC assesses and communicates the potential adverse impacts of, and response options to, climate change with decision-makers and the public. This aims to provide a framework for linking scientific and technical assessments to consequences of concern to people, characterising the uncertainty in such assessments, and linking these understandings to potential solutions and decision processes. At the same time, in defining the objective of international climate negotiations as being to 'prevent dangerous anthropogenic interference' (Footnote 1), the UNFCCC underlines the centrality of risk framing in considering the threats of climate change and potential response measures.

In AR6 the IPCC employs a common risk framing across all three working groups and provides guidance for more consistent and transparent usage (AR6 WGII 1.4.1; IPCC risk guidance). AR6 defines risk as the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems (AR6 glossary)(SRA 2015). Risks can arise from potential impacts of climate change as well as human responses to climate-related risks. The risk framing includes steps for identifying, evaluating, and prioritising current and future risks; for understanding the interactions among different sources of risk; for choosing appropriate allocations of effort and resources among various approaches for reducing and equitable sharing of risks; for monitoring and adjusting actions over time while continuing to assess changing circumstances; and for communications among analysts, decision-makers, and the public.

Climate change risk assessments face challenges including a tendency to mis-characterise risks and pay insufficient attention to the potential for surprises (Weitzman 2011; Aven and Renn 2015; Stoerk et al. 2018). With deep uncertainty, risk management often aims to identify specific combinations of response actions and enabling institutions that increase the potential for favourable outcomes despite irreducible uncertainties (Marchau et al. 2019). Concepts of resilience and vulnerability also provide overlapping, alternative entry points to understanding and addressing the societal challenges caused and exacerbated by climate change (AR6, WGII, Chap 1.2.1).

Literature trying to quantify the cost of climate damages has continued to develop. Different methodologies systematically affect outcomes, with recent estimates based on empirical approaches – econometric measurements based on actual impacts – 'categorically higher than estimates from other approaches' (see Cross-Working-Group Box 1 on *Economic benefits from avoided climate impacts* in Chapter 3). This, along with other developments strengthen foundations for calculating a 'social cost of carbon', and informs a common metric for comparing different risks and estimating benefits compared to the costs of Greenhouse Gas reductions and other risk-reducing options (Sections 1.6.2, and 3.6.1).

Simultaneously however, the literature increasingly emphasises the importance of multi-objective risk assessment and management (e.g., representative key risks in WGII Chap 16). This stresses the diversity of values and objectives that different individuals use to evaluate the potential consequences of climate change on human and natural systems which may or may not correlate with any single estimate of economic value (AR6 WGII 1.4.1; IPCC risk guidance). Under such conditions, and given the deep uncertainties and risks, the international community has established goals such as those in the Paris Agreement and SDGs, informed by the scientific assessment of risks but negotiated among stakeholders, and employed methods such as cost-effective analysis (1.6.2) to evaluate options consistent with those goals.

1.3.2 Global and regional emissions

Global GHG emissions continued to rise since AR5, but the rate of emissions growth slowed (Figure 1.2). From 2010 to 2018, total GHG emissions grew on average by 1.4% yr^{-1} (compared to an average 2.5% yr^{-1} 2000 to 2010), slightly exceeding population growth (c.1.1% yr^{-1}). After a period of exceptionally rapid growth as charted in AR5, global energy-related CO_2 emissions plateaued between 2014 and 2016 while the global economy continued to expand (World Bank 2020), increased again in 2017 and 2018 (by 1.5% and 1.7% respectively). The temporary decoupling reflected interplay of strong energy efficiency improvements and low-carbon technology deployment, reducing coal demand (IEA 2019a), but these did not expand fast enough subsequently to offset the pressures for growth at global level (UNEP 2018a; IEA 2019a). After a second plateau in 2019, the COVID-19 outbreak in 2020 reduced energy-related CO_2 emissions by about 8% in 2020 (IEA 2020a); (Chapter 2).

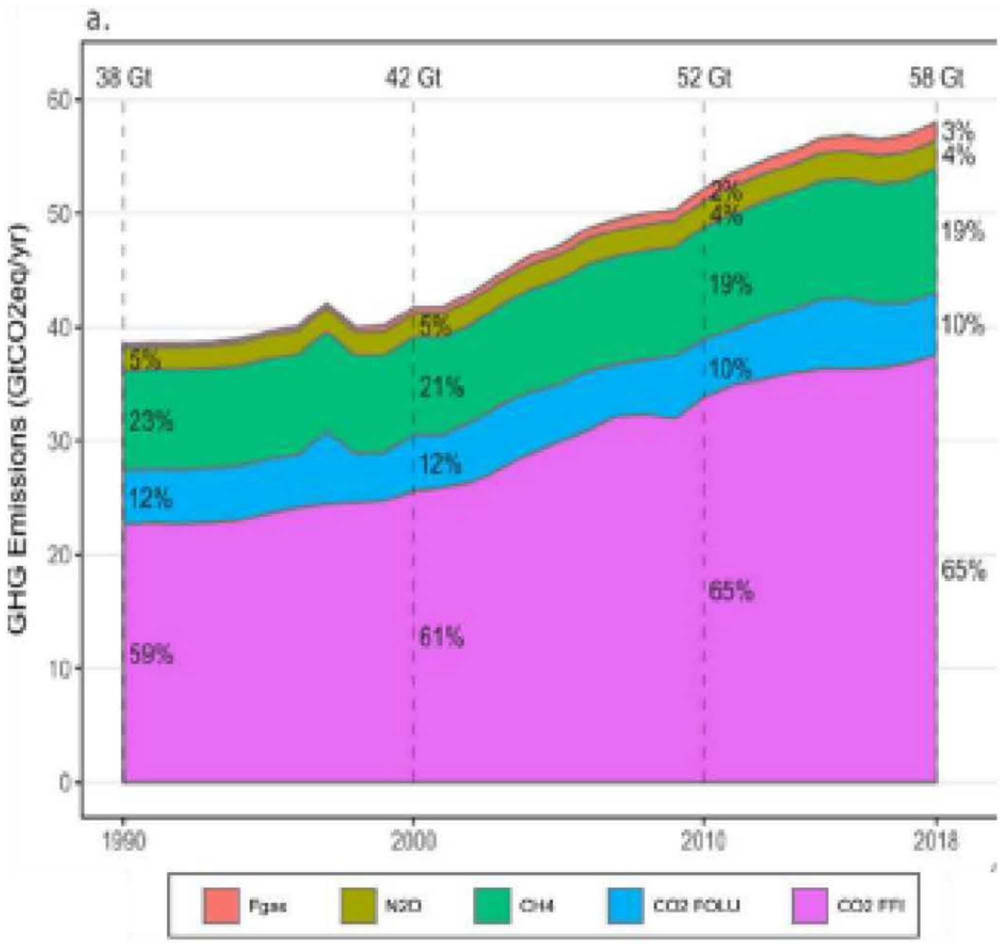
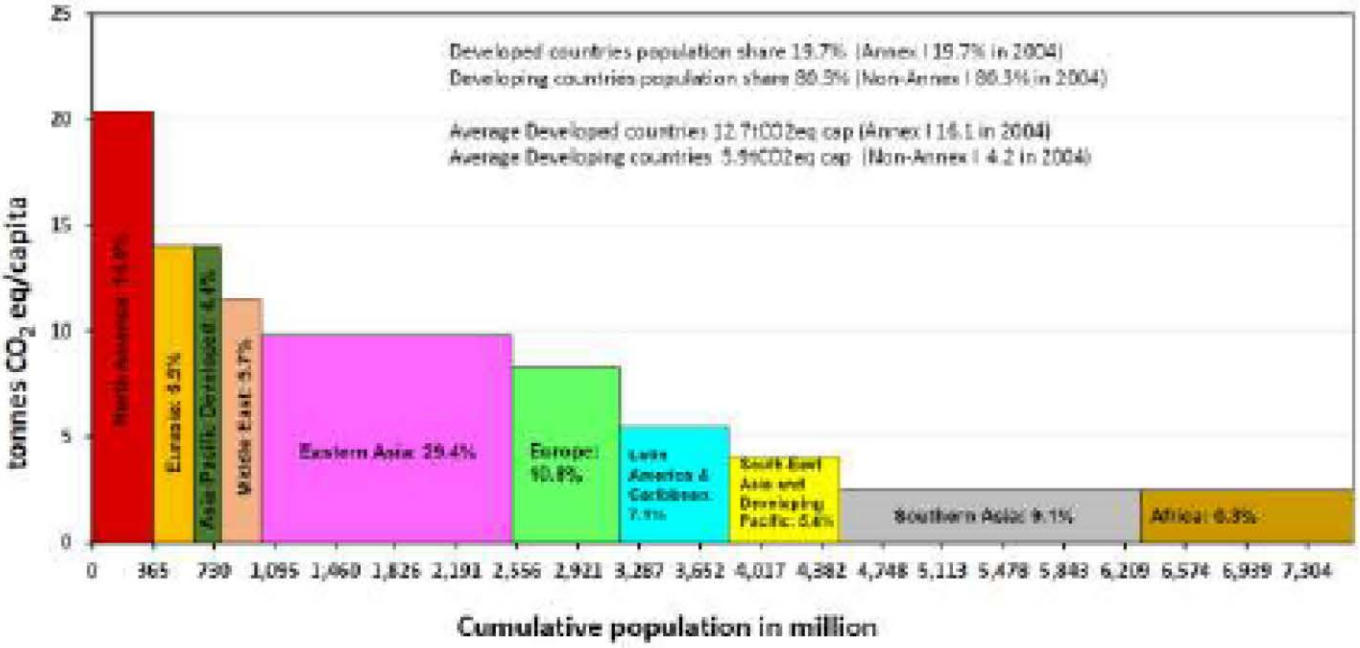


Figure 1.2 Global emission trends since 1990 by groups of gases

Note: Shows CO_2 from fossil fuel combustion and industrial processes (FFI); CO_2 from Forestry and Other Land use (FOLU); methane (CH_4); nitrous oxide (N_2O); fluorinated gases (F-gases). *Gases reported in Gt CO_2eq converted based on global warming potentials with 100-year time horizon (GWP-100). Source: Figure TS-4. Will be updated for final draft.*

Figure 1.3 show the distribution of regional GHG emissions (a) per capita and (b) per GDPppp of different country groupings in 2018. The area of each block is thereby proportional to the region's emissions. Compared to the equivalent presentations in 2004 (AR4, SPM.3) and 2010 (AR5, Figure 1.8), east Asia now forms substantially the biggest group, whilst at 10tCO_2eq per person, it remains about half of north America in per-capita terms. In contrast, a third of the world's population, in southern Asia and Africa, emit on average barely 2.5tCO_2 per person, little more than in the previous

Assessments. Particularly for these regions there also continue to be substantial differences in the GDP, life expectancy and other measures of wellbeing (see Figure 1.4, and Chapter 2).



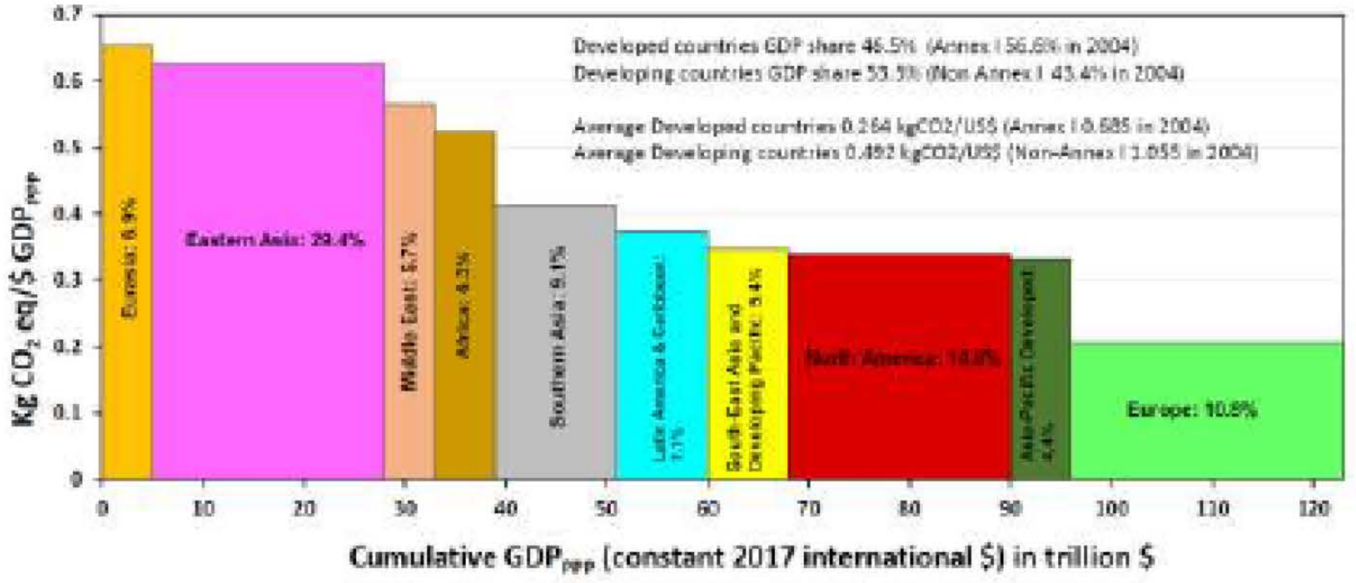


Figure 1.3 Distribution of regional GHG emissions, 2018: per-capita CO_2 vs population, and emissions intensity vs GDP_{PPP}, for different country groupings

Note: The size of each block is proportional to total emissions; the percentages indicate a region's share in global GHG emissions. Annex I and non-Annex I data has been taken from SPM 3.b of the AR4.

Emissions per unit GDP have converged significantly. Poorer countries tend to use more energy / emissions per unit GDP partly because of higher reliance on basic industries, and this remains the case, though in general their energy/GDP has declined faster. The biggest relative change in Fig.1.3b is the reduction in European emissions per unit GDP, which reflects not only efficiency improvements but accelerating decline in the carbon intensity of energy (for discussion also of trade / consumption effects see chapter 2).

Regional trends have varied. Emissions from most countries continued to grow, but in absolute terms, 32 of the developed countries reduced energy-CO_2 emissions 2010-2018, and 24 reduced overall GHG (CO_2-eq) emissions over the same period, but only half of them by more than 10% over the period in each case (chapter 2). In total, developed country emissions barely changed from 2010, whilst those from the rest of the world grew.

While extreme poverty has fallen in more than half of the world's economies in recent years, nearly one-fifth of countries faced poverty rates above 30% in 2015 (below USD 1.90 a day), reflecting high-income inequality (World Bank 2019a; Laborde Debucquet and Martin 2017). Diffenbaugh and Burke (2019) show that global warming already has increased global economic inequality. Even if between-country inequalities have decreased over recent decades, global warming has slowed the decrease (ibid), because while 1°C of global warming can be positive or uncertain for cool countries, it has more adverse impacts on growth win warm countries including most of the low-income countries (*ibid*), see also section 1.5.6 below. The pursuit of some shared socioeconomic pathways (SSPs) by regional groups could imply a growth of climate change inequalities while other combinations could reduce it (Frame et al. 2019).

Since much of the CO_2 emitted stays in the atmosphere for centuries, the atmospheric concentration and temperature will only stop rising if and when net emissions decline to zero, as acknowledged in the Paris Agreement. Consequently, an important recent development has been national commitments to reach net zero emissions. As of December 2020, six countries had legislated for net zero and another six are debating proposed legislation, all except one targeting 2050; another fourteen have declared or are considering net zero goals in official policy documents (ECIU 2020).

1.3.3 Economy, finance and innovation

However, these developments occur in an uncertain economic context, following strong growth in 2017 and early 2018. Disorderly financial market developments could disrupt activity in some economies and lead to contagion effects (Prospects Group and Bank 2019). If trade disputes, most notably between US and China, escalate or become more widespread, this would dent economic activity in these regions and elsewhere (Freund et al. 2018; Reznikova and Ivashchenko 2018). On top of this, COVID-19 is projected to contract the global economy substantially (IMF 2020), and economic troubles could affect political priorities and focus public opinion on policies that yields immediate economic benefits (Kahler and Lake 2013).

The COVID-19 pandemic profoundly impacted economy and human society, globally and within countries. Some of its impacts will be long lasting, permanent even, and there are also lessons relevant to climate change (Cross-Chapter Box 1).

Cross-Chapter Box 1: The COVID-19 crisis: lessons, risks and opportunities for mitigation

Diana Ürge-Vorsatz (Hungary), Lilia Caiado Couto (Brazil), Felix Creutzig (Germany), Dipak Dasgupta (India), Michael Grubb (United Kingdom), Kirsten Halsnaes (Denmark), Siir Kilkis (Turkey), Alexandre Koberle (Brazil), Silvia Kreibiehl (Germany), Jan Minx (Germany), Peter Newman (Australia), Chukwumerije Okereke (Nigeria/United Kingdom)

The COVID-19 pandemic has triggered the deepest global economic contraction as well as CO_2 emission reductions since the Second World War (Chapter 2; Le Quéré et al. 2020b; Liu et al. 2020a; Forster et al. 2020). While emissions and most economies are expected to rebound in 2021-2022, the impact of the pandemic on many aspects of economy and emission drivers may last far longer. These changes, as well as the pandemic response actions, bring both important risks as well as opportunities for accelerating mitigation (Chapters 1, 5, 10, 15).

Lessons. Important lessons can be drawn from the pandemic to climate change including the value of forward-looking risk management, the role of scientific assessment, preparatory action and international process and institutions (1.3, Chapter 5). There had been long-standing warnings of pandemic risks, and precursors – with both pandemic and climate risks being identified by social scientists as 'uncomfortable knowledge', or 'unknown knowns' which tend to be marginalised in practical policy (Rayner, 2012; Sarewitz, 2020). However, the warnings focused mainly on direct health dimensions; whilst previous regional pandemics had already demonstrated impacts on agricultural trade and food prices, few warnings foresaw the potential scale and interlinked extent of economic impacts of a global pandemic. This echoes long-standing climate literature on potential 'high impact' events which are at least *perceived* as low probability (Dietz, 2011; Weitzman, 2011). The costs of preparatory action, mainly in those countries that had suffered from earlier pandemics were negligible in comparison, suggesting the importance not just of knowledge but its effective communication and embodiment in society (Chapter 5). (Klenert *et al.*, 2020) offer five early lessons for climate policy, concerning: the cost of delay; the bias in human judgement; the inequality of impacts; the need for multiple forms of international cooperation; and finally, 'transparency in value judgements at the science-policy interface'.

Emissions and behavioural changes. Preliminary data suggest that CO_2 emissions from fossil fuel use and industry fell about 7% (2.7-13%) from 2019 to 2020, but consistently show that emissions picked up as lockdown eased (Forster *et al.*, 2020; Friedlingstein *et al.*, 2020; Le Quéré *et al.*, 2020; Liu *et al.*, 2020). Analysis from previous economic crises suggest significant rebound in emissions without policy-induced structural shifts (2.2.2.1; Figure 2.5). Initial projections suggest emissions may be around 4-5.5% below a 'no-pandemic' baseline by 2024 (Shan et.al 2020) . The long-term impacts on behaviour, technology and associated emissions remain to be seen, but may be particularly significant in transport. COVID-19 lockdowns have reduced all mobility-related emissions, with two major growth areas: electronic communications replacing many work and personal travel requirements; and, revitalised local active transport and e-micromobility (Earley and Newman, 2020). Temporary 'clear skies' may also have raised awareness of the potential environment and health co-benefits of reduced fossil fuel use particularly in urban areas (8.7), with evidence also indicating that the virus is carried on diesel particles and/or that air pollution itself amplified vulnerability to COVID-19 (Wu et al. 2020; Gudka et al. 2020). The impacts on aviation have been exceptionally large, and are projected to extend not just through behavioural changes, but also with fleet changes associated with retiring older planes, and reduced new orders indicating expectations of reduced demand and associated GHG emissions until 2030 (5.1.2,10.5).

Fiscal, growth and inequality impacts. Aspects of the global and regional economic crises resulting from COVID-19 may prevail much longer than the crisis itself, potentially compromising mitigation ambitions. Most countries have been forced to undertake unprecedented levels of short-term public expenditures. The IMF projects sovereign debt to GDP to have increased by 20% in advanced economies and 10% in emerging economies by the end of 2021 (IMF, 2020). This is likely to slow economic growth, and may squeeze financial resources for mitigation and relevant investments for many years to come (15.2.3, 15.6.3). At the same time, COVID-19 has further lowered interest rates which should facilitate low carbon investment. However, after decades of global progress in reducing poverty, COVID-19 has pushed hundreds of millions of people below poverty thresholds and raises the spectre of intersecting health and climate crises that are devastating for the most vulnerable (5.1.2 Box 5.1). Like those of climate change, pandemic impacts fall heavily on disadvantaged groups, exacerbate the uneven distribution of future benefits, amplify existing inequities, and introduce new ones. Increased poverty also hinders efforts towards sustainable low-carbon transitions (1.4).

Impacts on profitability and investment. COVID-19-induced demand reduction in electricity disproportionally affected coal power plants, whilst transport reduction most affected oil (IEA, 2020b).

This has sharply accelerated pre-existing decline in the profitability of most fossil fuel industries: the value of energy companies in the S&P-500, which in the decade to 2019 had shrunk from above 10% to below 5%, dropped below 2.5% during 2020 (Bloomberg/Ameli, 2020). Renewables were the only energy sector to increase output (IEA, 2020b). Within the context of a wider *overall* reduction in energy investment this has prompted a substantial *relative* shift towards low carbon investment particularly by the private sector (IEA, 2020a), (Rosembloom and Markard, 2020), within which there is growing attention to 'Net Zero' as a guide or goal for future major investment decisions (Robins, 2020);(15.2.1, 15.3.1, 15.6.1).

The post-pandemic recovery path provides an opportunity to attract finance into accelerated and transformative low-carbon public investment (15.2, 15.6.3). COVID-19 has for a period created a world of high unemployment and/or state-supported employment. There is a profound difference between short-term 'bail-outs' to stem unemployment, and the orientation of new public investment. The public debt is mirrored by large pools of private capital. There are clear reasons why a low-carbon response can create more enduring jobs, better aligned to future growth sectors: by also crowding-in and reviving private investment (e.g. from capital markets and institutional investors, including the growing profile of Environment and Social Governance (ESG) and green bond markets (15.6)), this can boost the effectiveness of public spending (IMF, 2020). A study with a global general equilibrium model (Liu et al, in revision) finds that because the COVID-19 economic aftermath combines negative impacts on employment and consumption, a shift from employment and consumption taxes to carbon or other resource- related taxes would enhance GDP by 1.7% in 2021 relative to 'no policy', in addition to reducing CO_2 and other pollutants. A multi-sector, post-Keynesian model of wider 'green recovery' policies (Pollitt et al., in review) finds a short-run benefit of around 3.5% GDP (compared to 'no policy'), and even ca. 1% above a recovery boosted by cuts in consumption taxes, the latter benefit sustained through 2030.

Orientation of recovery packages. The large public spending on supporting or stimulating economies, exceeding USD12tn by October 2020, dwarfs clean energy investment needs and hence could either help to solve the combined crises, or result in high-carbon lock-in (Andrijevic *et al.*, 2020). The short-term 'bail-outs' to date do not foster climate resilient long-term investments (15..2.3, 15.6.3): assessment up to 16th December 2020 estimated that in the G20 counties, 53% of energy-related support spending went to the fossil fuel industry compared to 35% on low-carbon energy (Energy Policy Tracker, 2020). However some countries and regions have prioritised green stimulus expenditures for example as part of 'Green New Deal' (Box 13.10; see also Oh et al. (in review) for overview of Korea, EU and US GNDs in context of COVID-19). This is motivated by assessments that investing in new growth industries can boost the macroeconomic effectiveness ('multipliers') of public spending, crowd-in and revive private investment (Hepburn et al. 2020), whilst also delivering on mitigation commitments (15.2.3).

Integrating analyses. The response to COVID-19 also reflects the relevance of combining multiple analytic frameworks spanning economic efficiency, ethics and equity, transformation dynamics, and psychological and political analyses (1.6). As with climate impacts, not only has the global burden of disease been distributed unevenly, but capabilities to prevent and treat disease were asymmetrical and those in greatest vulnerability often had the least access to human, physical, and financial resources (Ruger and Horton, 2020). However, developing country energy exporters have been hit also by the low post-COVID-19 fossil fuel prices, threatening other developmental goals; 'green' versus 'brown' recovery has corresponding distributional consequences between these and 'green' producers, suggesting need for differentiated policies with international coordination (le Billon et al., in revision). This illustrates the role of 'Just Transition' approaches to global responses including the value of integrated, multi-level governance (1.7, 4.5, 17.1).

Crises and opportunities: the wider context for mitigation and transformation. The impacts of COVID-19 have been devastating in many ways, in many countries. It may have set back development, and delivery of many SDGs, by years or even decades. It also distracts political and financial capacity away from efforts to mitigate climate change. Yet, studies of previous post-shock periods suggest that waves of innovation that are ready to emerge can be accelerated by crises, which may prompt new behaviours, weaken incumbent ('meso-level') systems, and prompt rapid reforms (1.6.5; Roberts and Geels (2019)). Lessons from the collective effort to 'flatten the curve' during the pandemic, illustrating aspects of science-society interactions for public health in many countries, may carry over to climate mitigation, and open new opportunities (5.1.2). COVID-19 appears to have accelerated the emergence of renewable power, electromobility and digitalisation (Newman 2020); (5.1.2,6.3,10.2). Institutional change is often very slow but major economic dislocation can create significant opportunities for new ways of financing and enabling 'leapfrogging' investment to happen (10.8). Given the unambiguous risks of climate change, and consequent stranded asset risks from new fossil fuel investments (Box 6.11), the most robust recoveries are likely to be those which emerge on lower carbon and resilient pathways. The Paris Agreement processes could help align recovery packages (Obergassel, Hermwille and Oberthür, 2020). Ghersi et al. (in review) identify the critical global post-COVID-19 challenge as the double-impact of heightened credit risk in developing countries, along with indebtedness in developed countries: they estimate that a 'minilateral' sovereign guarantee structure to underwrite low carbon investments could leverage 10-20 times its value in private investment, and suggest that after COVID-19, could thereby contribute to shifting development pathways consistent with the SDGs and Paris goals.

The necessity for economic recovery packages creates a central role for government-led investment, and may change the economic fundamentals involved for some years to come. As explained in (Chapter 15, Sections 15.2, 15.4), many traditional forms of economic analysis (expressed as general equilibrium) assume that available economic resources are fully employed, with limited scope for beneficial economic 'multiplier effects' of government-led investment. After COVID-19 however, no country is in this state. Very low interest rates amplify opportunities for large-scale investments which could bring enduring public benefits. Potential economic multiplier benefits of clean investment could be amplified all the more insofar as they help to build the industries and infrastructures for further clean growth (Hepburn et al. 2020). In practice however, the current orientation of COVID-19 recovery packages is very varied, pointing to a very mixed picture about whether or not countries are exploiting this opportunity (see Cross-Chapter Box 1). Moreover, whilst in theory very low interest rates should support green investment, the large public debts – including bringing some developing countries close to default - undermine both the political appetite and feasibility of large-scale clean investments. Low carbon finance remains far short of requirements (Chapter 15).

Aside from economic and COVID-19-related shocks, another big contextual change has been in technologies relevant to greenhouse gas emissions. Most striking, the cost of solar PV has fallen by a factor of 5-10 in the decade since the IPCC *Special Report on Renewable Energy* (2011a), which largely formed the basis for the AR5 assessments, The SR1.5 reported major cost reductions, the IEA (2020) *World Energy Outlook* reported PV as now 'the cheapest electricity in history', and for the next decades, costs are still projected to fall (Vartiainen et al. 2020). This AR6 report finds solar and wind energy to be increasingly competitive with fossil fuels in many conditions, and they have expanded much faster than anticipated (Hoekstra et al. 2017): globally, solar PV capacity grew at an average 40% yr^{-1} from 15GW in 2008 to 500GW in 2018, when wind reached almost 600GW (REN21 2019); wind and solar combined in 2019 generated 8% of power globally, and 15% in Europe (BP 2018). However, both costs and deployment vary widely between different countries (chapter 6, 9, 12). Rapid technological developments have occurred in many other low-carbon technologies including batteries and electric vehicles, IT and related control systems, and some sectors where electrification is not possible such as green hydrogen and CO2-based fuels. Alongside this, the shale revolution has opened up new fossil fuel resources, not yet matched by the progress in CCS (1.5.3).

1.3.4 Other Social and Political Trends

Global trends contrary to multilateral cooperation. The rise of state-centered politics and geopolitical/geo-economic tensions are emerging across many countries and issues, not only on climate cooperation (WEF 2019). In some cases, multilateral cooperation could be threatened by trends such as rising populism, nationalism, authoritarianism and growing protectionism (Abrahamsen et al. 2019). These trends could make it more difficult to tackle global challenges including protecting the environment (Schreurs 2016; Parker et al. 2017; WEF 2019).

Civil society pressures for stronger action. Rising global temperatures and extreme events elevated climate change on the political agenda in many regions. Youth movements in several countries show young people's awareness about climate change, evidenced by the school strikes for the climate that started in Sweden, but became a global phenomenon in 2018-19 (Hagedorn et al. 2019; Buettner 2020; Walker 2020; Thackeray et al. 2020). Senior figures across many religions, for instance in the papal encyclical *Laudato Si': On Care for our Common Home* (Francis 2015) have also raised strong voices about our duties to protect future generations and the natural world, and warned about the inequities of climate change. Also, the growing awareness of local environmental problems such as air pollution in Asia, also support policies that reduce GHG emissions (Karlsson et al. 2020), and the threat to indigenous people rights and existence has created climate activism (Etchart 2017) . A resurgence of grass root movements and activism, reflecting wider trends in the use of internet and social media in organising large-scale international protests (Fisher et al. 2019), may play a major role in building political pressure for accelerating climate change mitigation.

Climate policies could also encounter resistance. However, there is evidence that climate policies will not succeed unless it is a part of a larger social policy package consistent with a just transition (Urpelainen and Van de Graaf 2018). While the 'yellow vest' movement in France had broader aspect of income inequality and other social issues, it was triggered by higher fuel cost as a result of CO_2 tax hike (Lianos 2019). South African unions rejected government plans to close coal-fired power plants and award renewable energy contracts without a just transition in place. There is a mismatch between concerns on climate change and people's willingness to pay for higher costs that may result from mitigation policies. While a survey shows that 71% of Americans believe climate change is happening, 68% would be opposed if electricity bill additionally cost USD10 a month for combatting climate change. This is in stark contrast with global carbon prices compatible with 430-480 ppm CO_2eq (IPCC 2014b; EPIC et al. 2019). See also further discussion on citizen engagement in Chapter 13.

Transnational alliances. Cities, businesses, a wide range of other non-state actors also have emerged with important international networks to foster mitigation. City-based examples include the Cities Alliance in addressing climate change, Carbon Neutral Cities Alliance, the Covenant of Mayors (chapter 8), and several cities and countries have committed to 100% renewable energy in their energy sectors (Jacobson 2020) ; there are numerous other alliances and networks such as those in finance (chapter 15), technology (chapter 16), amongst many others (chapters 13, 14).

Thus, developments since AR5 have underlined the complexity of the context for climate mitigation. Economy, technology, trade, shifting geopolitics, divergent political debates over sovereignty and globalisation, inequities within and between countries, the concerns of the rising generation, multilevel and transnational actions and even religion, are all important. In section 1.5 we outline the impact of these forces on climate change mitigation.

1.3.5 Scenarios and Illustrative Pathways

The most obvious implication is that the future holds deep uncertainties, and emissions will be substantially affected both by the choices we make, and wider developments. This underlines the relevance of using scenarios to explore the possibilities. This section outlines the nature and conceptual role of scenarios, and summarises the 'illustrative pathways' developed for this Sixth Assessment.

Scenarios are a powerful tool for exploring an uncertain future world against the background of alternative choices and development. Scenarios are plausible, internally consistent representations of potential future developments used to think through potential consequences of alternative external factors such as, alternative technology availability, alternative policies, alternative resource availability, alternative socio-economic drivers or future social, political and institutional developments. Scenarios can be constructed using both narrative and quantitative methods. When combined they provide complementary information and insights. Quantitative and narrative models are frequently used to represent scenarios to explore choices and challenges. The IPCC has a long history of assessing scenarios. The AR6 scenario assessments draw from a huge body of research (Nakicenovic, & Swart 2000; van Vuuren 2011; van Vuuren et al. 2014).

This assessment draws upon a wide range of qualitative and quantitative scenarios including quantitative scenarios developed by models with heterogeneous styles including narratives, spreadsheets, and complex computational models using optimisation, simulation and recursive techniques. They span highly varied system boundaries ranging from narrow technologies and sectors, or individual places, to the long-term, global models (Chapter 3, Annex C provides further discussion and examples of computational models).

The concept of an illustrative pathway (IP) was introduced in IPCC Special Report on 1.5 (IPCC 2018a) to highlight a small number of quantitative scenarios with specific characteristics, drawn from a larger pool. IPs combine a storyline - describes in narrative form the key characteristics - with quantitative illustrations of pathways. By defining general characteristics of an IP, individual chapters can bundle scenarios from the existing literature into groups that are broadly consistent with IPs. Building upon this approach, IPs have been developed for IPCC Working Group III, AR6 (Box 1.1).

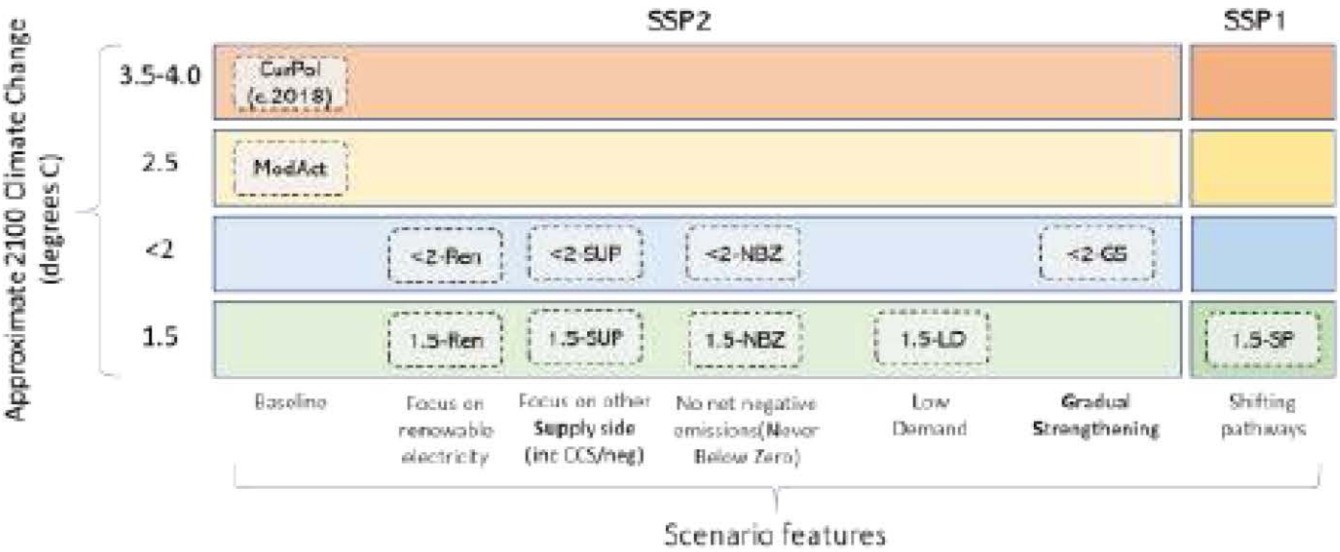
Box 1.1: Illustrative Pathways (IPs) developed for the WGIII Report

The Illustrative Pathways provide a set of scenarios which aim to show, in quantitative and narrative form, potential evolutions of human systems that illustrate themes that flow through the entire WGIII assessment. They provide illustrations of potential future developments that can be shaped by human choice including relationship between the level of ambition, climate policy and temperature outcomes. They combine a storyline with quantitative pathways. The storyline describes in narrative form the key characteristics that defines an IP. The quantitative versions, selected from the scenario database, provide numerical values that are internally consistent and can be associated directly with specific human activities (e.g. passenger transport, commercial building use, power generation, or refining).

A total of eleven IPs has been created to illustrate possible developments. All but one of these draws upon the wider socio-economic background of Shared Socioeconomic Pathway SSP2, "Middle of the Road". The eleven IPs are arrayed in the Figure below and briefly outlined in the accompanying Table. IPs are described in detail in (chapter 3).

A current-policies (circa 2018) IP, CurPol, illustrates the consequence of limiting climate mitigation policies to those in place in the base year (or policies which regress to the path so projected before COVID-19). It leads to average temperature change of 3.5-4°C (above pre-industrial) temperatures in 2100, and still rising. The Modest Action, ModAct, scenario illustrates the consequence of limited action with dynamics that lead by 2030 to aggregate delivery of the first-round NDCs, extended in ways that imply around 2.5°C in 2100.

The remaining nine IPs explore a range of ways that the Paris temperature goal could be realised. Four scenarios illustrate alternative pathways to 2°C. Four other scenarios illustrate alternative paths to 1.5°C. Two scenarios, 1.5-Ren and <2-Ren, emphasise use of renewable energy. Two scenarios, 1.5-SUP and <2-SUP, emphasise a broader range of supply technologies including CO_2 capture and storage (CCS) and other removal technologies, to achieve either 1.5°C or 2°C limits, typically after 'overshoot'. Two scenarios, 1.5-NBZ and <2-NBZ, illustrate pathways without *net negative* global emissions, that achieve 1.5°C and 2°C without overshoot, though they include some negative emissions technologies. One scenario, <2-GS, illustrates a pathway that (like ModAct) by 2030 delivers change equal to the initial NDCs, but with rapid tightening thereafter to reach 2°C. Two other IPs deliver ambition of 1.5°C: 1.5-LD, involves much lower demand based on a focus on efficiency and lifestyle change, 1.5-SP that uses SSP1, "Sustainability", as a point of departure and illustrates that both climate and other SDGs can be simultaneously achieved.



Box 1.1 Figure 1 Classification of Illustrative Pathways

Box 1.1 Table 1 General characteristics of Illustrative Pathways

Scenario		**Key characteristics**
CurPol (2018)		Continuation of current policies and trends (based mainly on emission and policy conditions c. 2017/2018)
ModAct		Modest / mixed Action, achieves by 2030 emissions equivalent to implementation of 'first round' NDCs: implies fragmentated policy landscape, post-2030 action continuing a trend of modest action until 2030.
1.5/<2	Ren	Enhanced development and rapid diffusion of renewables make a dominant contribution to decarbonisation;
	Sup	Mitigation with relatively greater reliance on other supply-side decarbonisation, includes also substantial reliance on net negative emissions after 'overshoot'
	NBZ	Still some CCS/carbon dioxide removal, but only to extent of offsetting positive emissions - net emissions Never Below Zero)
	Variants – reflecting options more directly linked to specific levels of ambition	
	<2 GS	Only a Gradual Strengthening of action in the short-term, which precludes 1.5°C but attains < 2°C with accelerated later action

	1.5 LD	Reduced demand leads to early emission reductions and expands the potential to achieve close to 1.5C
	1.5 SP	Emphasis on achieving 1.5°C and other SDGs simultaneously is demonstrated. The pathway assumes an SSP1 reference scenario.

What the IPs don't do and relationship to Working Group I Scenarios. The IPs are, as their name implies are a set of scenarios meant to illustrate some important themes that run through the entire WGIII assessment. They are not intended to be comprehensive. They are not intended to illustrate all possible themes in this report. They do not, for example attempt to illustrate the range of alternative socioeconomic pathways that could be the background against which efforts to implement Paris goals are set. They do not attempt to reflect variation in potential regional stories and variation. They are framed in terms of Paris goals rather than the goal of achieving net zero emissions—the complementary framing used in the Energy chapter. Finally, they only overlap with the scenarios employed by IPCC WG1 in one instance—SSP2-4.5.

Scenarios beyond the IPCC. Scenario development in support of a broad spectrum of issues and in support of a wide range of decision makers as was demonstrated at the 2019 scenarios workshop (O'Neill et al. 2019). Transformation-oriented scenarios have been developed to explore pathways that could achieve the SDGs by mid-century (Sachs et al. 2019). Other researchers have begun to explore the trade-offs and synergies across goals in scenarios, for example (von Stechow et al. 2016; Klausbruckner et al. 2016; Obersteiner et al. 2016; Iyer et al. 2018). Global scenarios can serve as the boundary conditions for analyses and coupled models to explore specific sectors or geographic areas (Bakken et al. 2014; Schaeffer et al. 2020). At the same time new scenario users such as the financial sector have emerged as scenario consumers (NGFS 2020; Allen et al. 2020; Hale et al. 2019).

1.3.6 Feasibility and related dimensions of assessment

The SR1.5 introduced six dimensions (listed in Figure 1.4) for assessing the feasibility of adaptation and mitigation technological contributions and pathways, motivated broadly by the question of whether 1.5ºC pathways are feasible. AR6 emphasises that all pathways involve different challenges and require choices to be made. Continuing 'business as usual' is still a choice, which in addition to the obvious geophysical risks, involves not making best use of new technologies, risks of future stranded assets, and greater local pollution.

Building on frameworks introduced by Majone (1975) and Gilabert and Lawford-Smith (2012), assessment involves consideration of both desirability and feasibility. *Desirability* accounts for the extent to which transformations required by mitigation pathways are in line with basic societal objectives and norms, as represented by other sustainable development objectives (chapter 3) explores the implications of illustrative pathways on other SDGs. *Feasibility* accounts for the plausibility of the transformation required given a particular temporal and geographical context. The transformation, measured through indicators of pace and magnitude of required change of each pathway along the six dimensions introduced above, can be evaluated against critical ranges that indicate plausibility in a given period and time.

The six dimensions as listed provide a basis for this assessment both in the sectoral chapters (6-11) and in the evaluation of global pathways (Chapter 3). The more specific indicators under each of these six dimensions offer consistency in assessing the challenges, choices, enabling requirements facing different aspects of mitigating climate change, and a common framework for cross-sectoral assessment in chapter 12. AR6 sectoral chapters (6-11) assess feasibility, enablers and barriers to implementation by attributing scores to such indicators, including negative or positive impacts, mixed evidence, limited or no evidence of impact (Box TS-6).

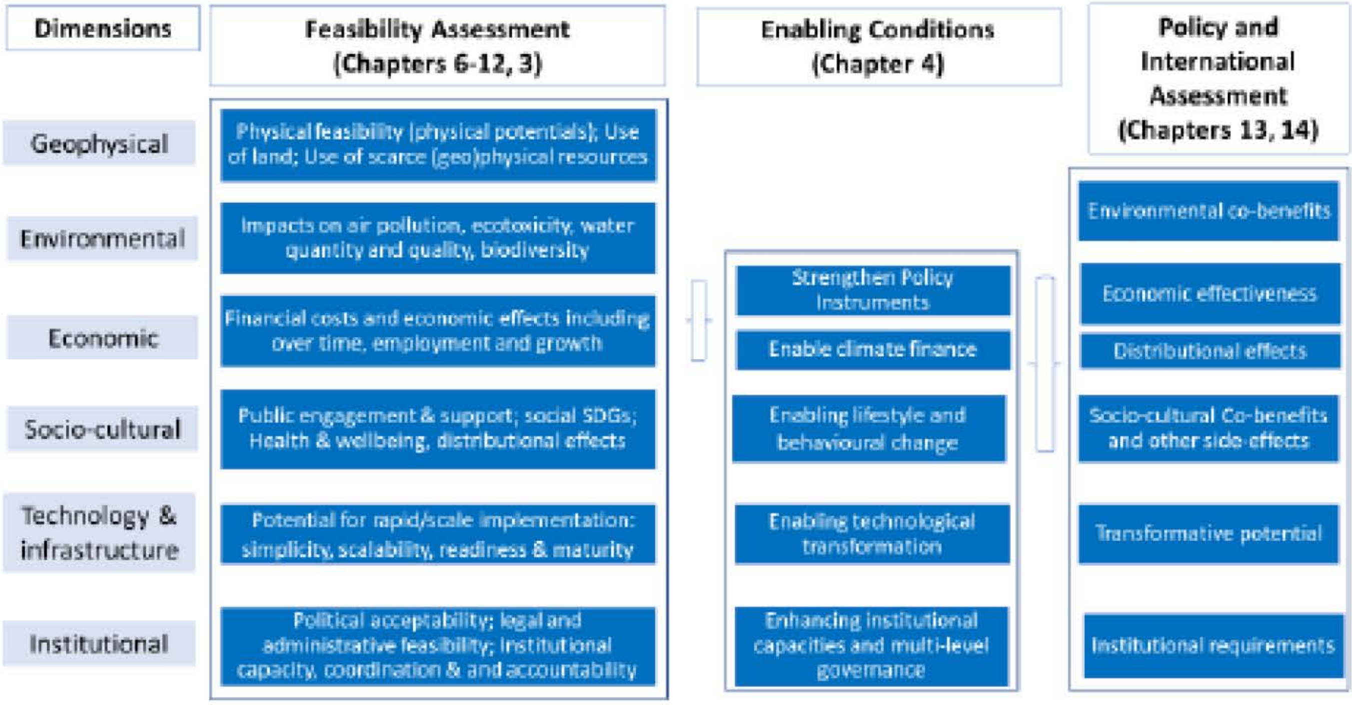


Figure 1.4: Feasibility and related dimensions of assessment

The SR1.5 (section 4.4) also introduced a framework of '*Enabling Conditions for systemic change*', as also listed in Figure 1.4, illustrating significant alignment with the dimensions of feasibility. In AR6 these enabling conditions are applied particularly in the context of shifting developments pathways (chapter 4), and used in introducing our review of Drivers and Constraints (1.5). The Figure 1.4 also illustrates, in a similar manner, key criteria used in chapters 13 and 14 for evaluating domestic and international policies.

Note that these dimensions are only a way of organising analysis and discussion. Some fundamental criteria may span across several dimensions. Most obviously, issues of ethics and equity are intrinsic to the economic, socio-cultural (values, including intergenerational justice) and institutional (e.g., procedural justice) dimensions. Geopolitical issues also clearly involve several dimensions, e.g., concerning the politics of international trade, finance and resource distribution (economic dimension); international vs nationalistic identity (socio-cultural); and multilateral governance (institutional). A more overtly action-focused structure is used in considering the role of demand and services in chapter 5, which organises key actions in a hierarchy of Avoid-Shift-Improve.

1.4 Sustainable Development and Climate Change Mitigation

Climate change and sustainable development are interwoven along multiple and complex lines of relationship (Fankhauser 2016; Gomez-Echeverri 2018; Okereke and Massaquoi 2017; Okereke et al. 2009). The close connection between sustainable development and climate change is highlighted in several previous IPCC reports (IPCC 2007a, 2011a, 2015, 2018a, 2019a). With its significant negative impact on food security and infrastructure, loss of lives and territories, species extinction, health, among several other risks, climate change poses a serious threat to development and wellbeing (IPCC 2007a, 2011a, 2015, 2018a, 2019a). Climate change is a multiple stressor that aggravates the effects of population growth, urbanisation, poor land management, overconsumption and weak institutions among others. Without serious efforts at mitigation and adaptation, climate change is likely to push millions further into poverty and limit the opportunities for sustainable development. It follows that ambitious climate mitigation is necessary to secure a safe climate within which development and wellbeing can be pursued and sustained. At the same time, some scholars emphasise that rapid and largescale economic development, the sort of which, at least historically, have resulted in climate change, seem to be needed to improve global wellbeing and lift millions in low- and middle-income countries out of poverty (Baarsch et al. 2020; Lu et al. 2019; Mugambiwa and Tirivangasi 2017; Chen et al. 2017; See Figure 1.6). Yet, others stress that climate change is caused by industrial development and more specifically, the character of social and economic development produced by the nature of capitalist society (Pelling and Manuel-Navarrete 2011; Koch 2012; Malm 2016), which they therefore view as ultimately unsustainable.

An obvious implication of the very close interaction between climate change and development as outlined above is that climate mitigation at local, national and global level cannot be effectively achieved by a narrow focus on 'climate-specific' sectors, actors and policies; but rather through a much broader attention to the mix of development choices and the resulting development paths and trajectories (O'Neill et al. 2014).

As a key staple of IPCC reports and global climate policy landscape (Gidden et al. 2019; Quilcaille et al. 2019; van Vuuren et al. 2017; IPCC 2014b, 2007b) (see also chapter 2), integrated assessment models and global scenarios (such as the "Shared Socio-Economic Pathways" – SSPs) highlight the interaction between development paths, climate change and emission stabilisation (see section 1.5.1 for in depth discussion on scenarios). The close link between and sustainable development is also recognised in policy circles. A part of the stated objective of the UNFCCC is to 'achieve the stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system and enable economic development to proceed in a sustainable manner' UNFCCC 1992, Art 2). Similarly, Article 2 of the Paris Agreement states that the aim is to 'strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty' (UNFCCC 2015).

Equity, inequality, justice, and poverty eradication, are important in conceptualising the relationship between sustainable development and climate change because of the wide variation in the contribution to, and impact of climate change within and across countries (Reckien et al. 2017; Diffenbaugh and Burke 2019; Okereke and Coventry 2016; Baarsch et al. 2020; Bos and Gupta 2019; Klinsky et al. 2017). Specifically, the impact of climate change in limiting development and wellbeing is most acutely felt by the world's poorest people, communities, and nations, who have the smallest carbon footprint, constrained capacity to respond and limited voice in important decision-making circles (Okereke and Ehresman 2014; Tosam and Mbih 2015; Mugambiwa and Tirivangasi 2017).

A common expression widely used in academic and policy circles is that climate action needs to be pursed in the context of sustainable development, equity and poverty eradication (IPCC 2018b, 2014b; Burton 2001; Smit and Pilifosova 2003; Klinsky and Winkler 2014; Tschakert and Olsson 2005). However, developing a better understanding of the relationship between climate mitigation, sustainable development and equity at both conceptual and practical levels remains an important but contentious aspect of climate mitigation policies.

1.4.1 Integrating Climate Mitigation and the Development Imperative: Relevant Concepts and their limitations

At one level, the concept of sustainable development can in fact be seen as an attempt to resolve the climate/environment-development tension with the basic aspiration and assumption being that economic growth and climate change as well as other environmental externalities can be decoupled (Antal and Van Den Bergh 2016; Casadio Tarabusi and Guarini 2013). Fundamentally, sustainable development recognises the interlinkages and interdependence of human and natural systems and implies the balancing of economic, social, and environmental (including climate) aspects in development planning and processes. However, despite the appeal of the concept, tensions remain over the interpretation and practical application, with acute disagreements regarding what the balancing entails in real life, which goals to set, and the means through which such goals might be pursued (Michelsen et al. 2016; Okereke, C. and Massaquoi and S. 2017; Shang et al. 2019). For example, the literature on degrowth, post growth, and post development question the sustainability and imperative of more growth especially in already industrialised countries and argue that prosperity and the Good Life are not immutably tied to economic growth (Escobar 2015; Asara et al. 2015; Kallis 2017; Latouche 2018) However, other scholars continue to emphasise the importance of economic growth in tackling climate change, pointing to the relationship between development and climate resilience as well as the role of industry-powered technologies such as electric vehicles, and even negative emission technologies in reducing GHG levels and promoting wellbeing (Heinrichs et al. 2014; Kasztelan 2017).

Moreover, countries differ enormously in their respective situation regarding their development path – a condition which affects their capability, goals, priorities and approach to the pursuit of sustainability (Shi et al. 2016; Ramos-Mejía et al. 2018; Okereke et al. 2019). Most climate and sustainable development literature recognise that despite its limitations, sustainable development with its emphasis on integrating social, economic and environmental goals, provides a comprehensive framework for the pursuit of human progress and wellbeing. This is more so the case when sustainable development is recognised not as a static objective but as a dynamic framework for measuring human progress (Costanza et al. 2016; Fotis and Polemis 2018). Sustainable development is therefore relevant for all countries even if different groups of nations experience the challenge of sustainability in different ways.

Much like Sustainable Development, concepts like low-carbon development (Mulugetta and Urban 2010; Yuan et al. 2011; Wang et al. 2017; Tian et al. 2019), climate-compatible development (CCD) (Mitchell and Maxwell 2010; Tompkins et al. 2013; Stringer et al. 2014) and more recently climate-resilient development (CRD) (Fankhauser and McDermott 2015; Henly-Shepard et al. 2018) have all emerged as ideas intended to bring together the goals of climate mitigation, development and poverty reduction (see Figure 1.5).

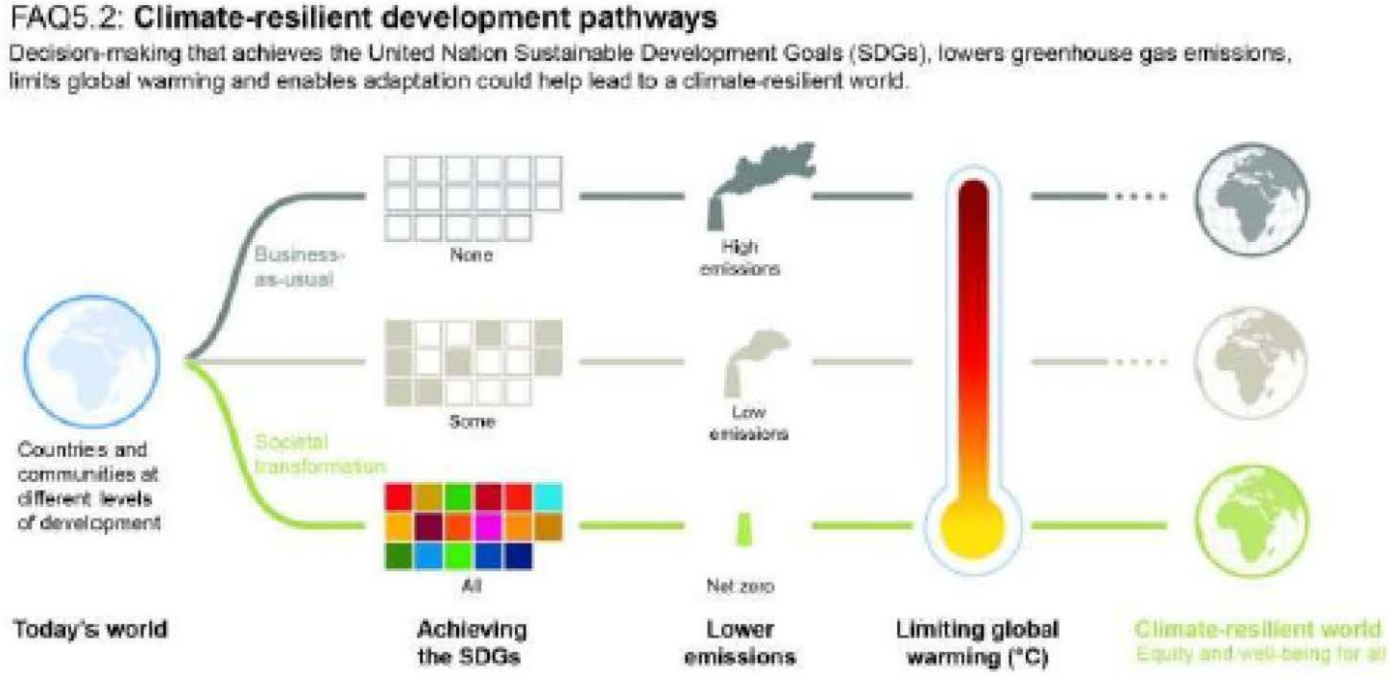


Figure 1.5 Links between climate mitigation, sustainable development, and equity
Source: (IPCC 2018a)

As indicated in Figure 1.5 above, development pathways that narrowly focus on climate mitigation or economic growth will not lead to the attainment of the SDGs and climate stabilisation objectives. Rather, the best chances of achieving both the SDGs and long-term climate goals lie in the development paths that maximises the synergy between climate mitigation and broader sustainable development.

In industrialised countries terms such as ecological modernisation, eco-modernism, the Green New Deal are often used to convey ideals of development pathways that take sustainability and environmental limits seriously (see e.g. Dale et. al (2015). The green economy has gained popularity in both developed and developing countries as an approach for harnessing economic growth to address environmental issues (Bina 2013; Georgeson et al. 2017). Under a green economy, countries would enhance economic growth while ensuring that it does not undermine ecological systems. Critics however argue that green economy ultimately emphasises economic growth to the detriment of other important aspects of human welfare such as social justice (Adelman 2015; Death 2014; Kamuti 2015). It is also argued that the central idea of the green economy that it is possible to decouple economic activity and growth (measured as GDP increment) from increasing use of biophysical resources (raw materials, energy) and GHG emissions is flawed (Jackson and Victor 2019; Parrique et al. 2019; Hickel and Kallis 2020). Furthermore, some have observed that while terms like the green economy and climate resilient development offer conceptual tools for imagining a synergistic relationship between development and climate mitigation, they generally offer limited practical guidelines for reconciling the tensions that are often present in policy making (Dale et al. 2015; Ferguson et al. 2015; Kasztelan, 2017 Kotzé 2018).

Increasingly, the central thought that underpins most literature on how to operationalise the link between sustainable development and climate mitigation is the concept of synergies and trade-offs (Dagnachew et al. 2018; Nerini et al. 2018; Thornton and Comberti 2017; Wüstemann et al. 2017; Klausbruckner et al. 2016; Mainali et al. 2018a). Climate mitigation can have co-benefits to other development aspirations. For example, energy efficiency and renewable energy programs can have positive effect in clean air and health, job creation, community cohesion and addressing inequities. At the same time, narrow climate focused policies can undermine sustainable development aspirations such as when large land-based mitigation such as re/afforestation takes the land and crops that can be used for food production or when regressive carbon tax policies exacerbates poverty and inequality. For its own part, development pathways that are sustainable can contribute to climate mitigation with examples including sustainable urban planning, conservation, agriculture, sustainable consumption, etc. In order to highlight the various ways that synergies can occur, it has been suggested to label "climate policy co-benefits", i.e. mitigation benefits in addition to avoided climate change, as Type 1, and "climate co-benefits", i.e. climate mitigation resulting from a measure in another policy field, as Type 2, and benefit synergies of policies with multiple objectives as Type 3 (Karlsson et al. 2020). The key insight is that pursuing climate stabilisation in the context of sustainable development requires decisions and choices that exploit and maximise the synergy and minimises the trade-off between climate mitigation and sustainable development.

Other concepts that aid the amalgamation of climate mitigation and sustainable development goals are integration and mainstreaming (Stringer et al. 2014). It could be that mainstreaming with its focus on incorporating climate change into development activities, such as the building of infrastructure and energy access expansion might have stronger resonance in developing countries (Wamsler and Pauleit 2016; Runhaar et al. 2018). Developed countries for their own part tend to emphasise the concept of just transition which stresses the need to ensure that societal transformation to low carbon pathways adequately integrate justice concerns of workers and unions, and do not result in the imposition of hardship on already marginalised populations within countries (Evans and Phelan 2016; Heffron and McCauley 2018; Goddard and Farrelly 2018; Smith, Jackie and Patterson 2018; McCauley and Heffron 2018).

1.4.2 Climate Mitigation, Equity and the Sustainable Development Goals (SDGs)

Climate action is one of the foci of the 17 Sustainable Develop Goals agreed by the world leaders in 2015 as a global framework for action to end hunger, protect the planet and ensure prosperity for all humans around the world (Ürge-Vorsatz et al. 2018). At the same time, several of the other goals such as ending poverty (Goal 1), zero hunger (Goal 2), good health and wellbeing (Goal 3), affordable and clean energy (Goal 7) among many others are related to climate change. Climate action can therefore be conceptualised as both a stand-alone and cross-cutting issue in the 2030 Development Agenda (Makomere and Mbeva 2018).

A major utility of the SDGs, apart from galvanising global collective action, is that they provide concrete themes as well as short to medium term metrics and targets for measuring human progress to sustainability (Kanie and Biermann 2017). The SDGs also help to sharpen the links and provide a concrete basis for exploring the synergies and trade-offs between sustainable development and climate mitigation as well as between different sustainable development goals (Makomere and Mbeva 2018; Mainali et al. 2018b; Nerini et al. 2018; Prajal et al. 2017a).

There has been a strong relationship between development and GHG emissions, as historically both per capita and absolute emissions have risen with industrialisation. A strong correlation also exists between Human Development Index and the per capita GHG emissions of regions and countries. Figure 1.6 below illustrates several important dimensions of the relationship between development and GHG emissions. It shows that while historically per capita GHG is strongly correlated to GDP, there is nevertheless a very wide range of national per capita GHG emissions and income levels even for countries with similar levels of development or industrialisation. Some countries have very low per capita GHG emissions and income even by historical standards, meanwhile others have very high per capita emissions and income. With the industrial revolution and industrialisation in recent times, has come increased income for some countries and people. With regards to income levels, up until GDP per capita income levels in the range USD10,000-20,000 there is clear relationship between GDP increase and almost every more direct indicator of welfare. However, at higher incomes the relationship becomes progressively less clear.

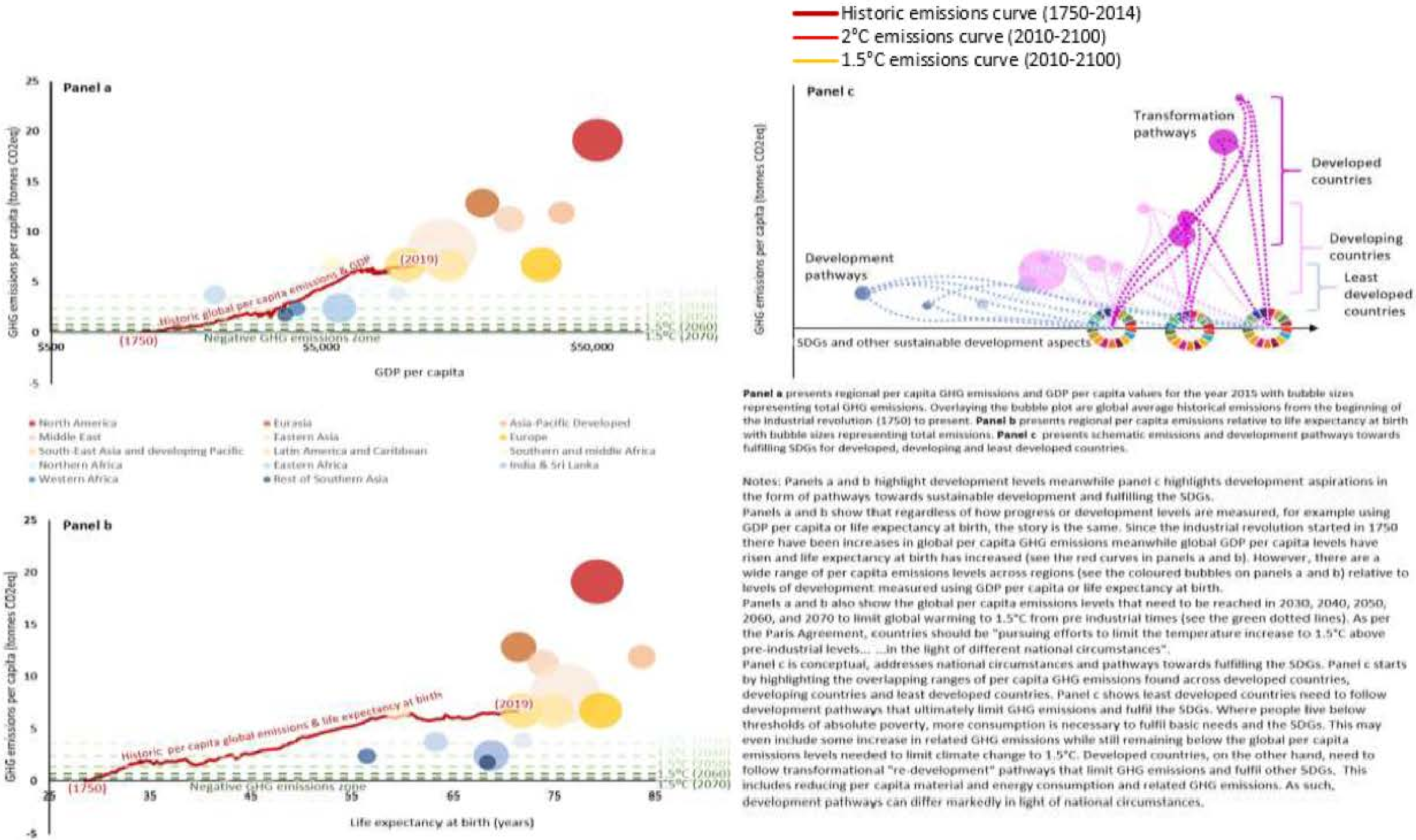
When it comes to LDCs, other developing economies, emerging industrial economies and industrialised economies, GDP per capita is an important metric but not the only metric defining these categories. Levels of agriculture and manufacturing are also defining characteristics, and in the case of LDCs so are levels of economic vulnerability (including the share of population in low elevated coastal zones) and human assets. As such, these development and industrialisation categories capture important characteristics of countries, their economies and possible pathways towards sustainability.

It is against this background that Dubash (2019) emphasises the importance of placing the need for urgent action on climate change in the context of the Paris Agreement framework, with its emphasis on sustainable development in the context of approaches that reinforce domestic political priorities and considerations as well as the institutions within which national frameworks are crystallised.

Concerns over equity in the context of growing global inequality and very tight remaining global carbon budgets (Peters et al. 2015; Kartha et al. 2018b; Matthews et al. 2019; van den Berg et al. 2019a) have led to the suggestion that the emphasis should be on equitable access to sustainable development. This literature emphasises the equity dimension and recognised the need for less developed countries to have sufficient room for development while addressing climate change (Pan et al. 2014; Winkler et al. 2013).

b) National per capita emissions and global per capita emissions curves

a) Regional per capita emissions and global per capita emissions curves



Panel a presents regional per capita GHG emissions and GDP per capita values for the year 2015 with bubble sizes representing total GHG emissions. Overlaying the bubble plot are global average historical emissions from the beginning of the industrial revolution (1750) to present. **Panel b** presents regional per capita emissions relative to life expectancy at birth with bubble sizes representing total emissions. **Panel c** presents schematic emissions and development pathways towards fulfilling SDGs for developed, developing and least developed countries.

Notes: Panels a and b highlight development levels meanwhile panel c highlights development aspirations in the form of pathways towards sustainable development and fulfilling the SDGs.
Panels a and b show that regardless of how progress or development levels are measured, for example using GDP per capita or life expectancy at birth, the story is the same. Since the industrial revolution started in 1750 there have been increases in global per capita GHG emissions meanwhile global GDP per capita levels have risen and life expectancy at birth has increased (see the red curves in panels a and b). However, there are a wide range of per capita emissions levels across regions (see the coloured bubbles on panels a and b) relative to levels of development measured using GDP per capita or life expectancy at birth.
Panels a and b also show the global per capita emissions levels that need to be reached in 2030, 2040, 2050, 2060, and 2070 to limit global warming to 1.5°C from pre industrial times (see the green dotted lines). As per the Paris Agreement, countries should be "pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels... ...in the light of different national circumstances".
Panel c is conceptual, addresses national circumstances and pathways towards fulfilling the SDGs. Panel c starts by highlighting the overlapping ranges of per capita GHG emissions found across developed countries, developing countries and least developed countries. Panel c shows least developed countries need to follow development pathways that ultimately limit GHG emissions and fulfil the SDGs. Where people live below thresholds of absolute poverty, more consumption is necessary to fulfil basic needs and the SDGs. This may even include some increase in related GHG emissions while still remaining below the global per capita emissions levels needed to limit climate change to 1.5°C. Developed countries, on the other hand, need to follow transformational "re-development" pathways that limit GHG emissions and fulfil other SDGs. This includes reducing per capita material and energy consumption and related GHG emissions. As such, development pathways can differ markedly in light of national circumstances.

Figure 1.6 Sustainable Development is relevant for all countries even if challenges differ

Notwithstanding, the SDGs clearly highlight the idea that attaining sustainable development is a challenge for all groups of countries – developed and developing – even though the challenge might manifest in different ways.

The figure also plots regional GHG per capita emissions by life expectancy with life expectancy at birth used as a proxy of development. It shows that regardless of the indices chosen, the relationship between per capita GHG emissions and development (including industrialisation) remains similar, though with a wide range of per capita emissions even for similar levels of development particularly at higher levels of GDP.

The important thing is that all countries need to move on to a pathway towards sustainability. Importantly, sustainability takes more than low GHG emissions, but also involves some level of industrialisation to support development aspirations and fulfilling the SDGs. Panel C of Figure 1.6 schematically plots a development pathway towards sustainability. For high per capita GHG emissions jurisdictions, a transition pathway towards sustainability involves rapid per capita GHG emissions reductions. For low emissions and development jurisdictions, a development pathway towards sustainability could take the form of an arc that allows for some increased per capita emissions while staying below the historic global per capita emissions curve and well below the 2°C emissions curve over time. However, it is important to note, low emissions alone are not adequate to fulfil the SDGs.

Literature consistently indicate that different countries will focus on different SDGs as priorities, at least in the medium term – the key determinant being the current development status and socio-economic conditions of countries. For example, the main concern of the Least Developed Countries (LDCs) might be economic development and how to cope with climate variability (adaptation), while developed countries which typically have more financial and technological capabilities could focus on climate mitigation and reducing unsustainable consumption. The countries falling in between those two categories can address both adaptation and mitigation actions at different degrees of combination and emphasis of different sectors depending on national circumstances.

The key basis for driving societal transformation is that while economic growth at least up to a level of broad industrialisation has been historically linked to greenhouse gas emissions growth, the correlation between CO_2 emission intensity, or absolute emission and gross domestic product growth, is not rigid, unambiguous and deterministic (Ojekunle et al. 2015). It cannot be taken that achieving a certain measure of economic growth inevitably demands a given amount of GHG emissions. As recent history has shown, investments in technology and the social innovation can result in countries attaining the sustainability corridor at a lower per capita GHG emissions. The developed countries may prioritise the environmental cluster of SDGs even if they are also concerned with addressing inequality and other social issues. It is also important to notice that the social cluster elements are closely interlinked as it is difficult to make the distinction between poverty, hunger, malnutrition, health, etc. It is apparent that below some thresholds of absolute poverty, more consumption is necessary for development to lead to well-being; whereas in contexts where there is overconsumption, less material consumption may increase well-being.

The need to think through the conceptual and practical relationship between climate change action and sustainable development remains very pressing especially in the context of Paris Agreement and the SDGs. First, while the Paris Agreement and the SDGs share the common goal of building a climate-safe future that is more sustainable, resilient and prosperous for humanity (Hellin and Fisher 2019) the integration between both agreement in terms of policy tools and timelines are limited. The SDGs have a timeline of 2030 while mitigation action has a much longer timeline. Second, there are synergies and tensions between climate mitigation and the other SGDs on the one hand, and among the other 16 SDGs on the other hand. Third, there are serious questions about the extent to which the SGDs can be met within planetary boundaries and the h, wealth of global ecosystems. Fourth, while the architecture of the Paris Agreement on Climate Change is based on an approach where countries submit NDCs and

One of the key controversies around Sustainable Development (SD) and development more broadly is attributed to the absence of a completely satisfactory way of measuring well-being or the Good Life. Well-being is still predominantly associated with increased levels of consumption of products and services (Roy et al. 2012) and consequently, the use of GDP has dominated the literature. However, GDP only measures economic activity and neglects inequality and services delivered by current capital stocks (Haberl et al. 2019) is therefore, a poor proxy for societal well-being (Ward et al. 2016) and suggests that economic growth, per se, is not the main problem for environmental pressures and impacts but that related on the quality of growth. Since the traditional approach is based on the neoclassical K-L (Solow-Swan) growth model, which considers the effects of merely the capital and the labour on the economic growth, the current empirical growth literature has recently addressed the role of human capital (skills) and institutional quality (Dasgupta et al. 2015; Sugiawan et al. 2019). In that sense, several indices have emerged to measure well-being (i.e. Human Development Index, OECD better life initiative, QoL Index, Gallup Health, Well-Being Index, Gross National Happiness, Happy Planet Index) but finding a single measure represents a challenge due to the lack of data (Sugiawan et al. 2019). Recently, measures such as inclusive wealth (the sum of capital assets that form the productive base of an economy) are proposed as an indicator to replace GDP for measuring well-being (UNEP 2018b; Arrow et al. 2011; Dasgupta et al. 2015; Sugiawan et al. 2019).

As previously indicated, achieving climate stabilisation in the context of sustainable development and efforts to eradicate poverty requires collective action and exploiting synergies between climate action and sustainable development, while minimising the impact of trade-offs (Makomere and Mbeva 2018; Najam 2005; Okereke, C. and Massaquoi and S. 2017). They also require a focus on equity considerations to avoid climate induced harm, as well as unfairness that can result from urgent actions to cut emissions (Kartha et al. 2018a; Pan et al. 2014; Robiou Du Pont et al. 2017). This is more so important as the diminishing carbon budget has intensified debates on which countries should be prioritised to access the remaining carbon budget (McGlade and Ekins 2015; Raupach et al. 2014). Moreover, concerns persist over the insufficiency of support for means of implementation, to support ambitious mitigation efforts (Pickering et al. 2015; Weikmans and Roberts 2019).

1.5 Drivers, and Constraints of Climate Mitigation and System Transitions/Transformation

This section provides brief assessment of some of the most important factors and dynamics that drive, shape and or limit climate mitigation in the context of sustainable development and system transformation. AR 5 introduced six "enabling conditions" for shifting development pathways which are presented in Chapter 4 of this report and some of which overlap with the drivers reviewed here. The key insight from the assessment of the system drivers and constraints undertaken below is twofold. The first is that none of the factors or conditions by themselves is more or less important than the others. All the factors matter in different measures with each exacting more or less force depending on prevailing social, economic, cultural and political context. The other insight is that these factors are in one sense neutral: each can serve as an enabling condition or a constraint to ambitious climate action depending, again, on the context and how they are deployed. Often one sees the factors exerting both push and pull forces at the same time in the same and across different scales. For example, finance and investments can serve as a barrier or an enabler to climate action. Similarly, political economy factors can align in favour of ambitious climate action or act in ways that inhibit strong co-operation and low carbon transition.

1.5.1 Sectors and services

Anthropogenic GHG emissions are a by-product of transforming resources to serve human needs and desires, as shaped by human culture, institutions and the physical world. This basic relationship has many and varied facets including for example technology (the methods by which the transformation proceeds), scale (number of humans), distribution of resources and the means to transport resources within societies, the goods and services that individuals and societies desire and in the choices that human societies make in terms of social organisation and institutions. A discussion of anthropogenic emissions by sector and their underlying drivers is provided in chapter 2 (see Chapter 2, Figure 2.7).

Human societies and individuals value a wide range of services for satisfying their needs and desires, ranging from nutrition to shelter to health to mobility and so forth (Chapter 5). The means by which services have been provided and for whom have varied substantially over time and space. Meeting sustainable development goals, including addressing climate change, primarily entails finding ways to provide the goods, services, and overall quality of life desired by human populations while protecting the Earth systems that enable sustainable development. Changing the composition of goods consumed, for example, shifting diet toward a more vegetarian balance, can reduce land-use emissions without comprising the quality of life (Stehfest et al. 2009; van Vuuren et al. 2018; van den Berg et al. 2019b). In the same vein, addressing climate change will require transforming the existing energy institutions that have been largely shaped around fossil fuels towards renewable energy. Systems do not evolve independently. They interact across sectors, scales, and time. For example interactions across systems are evident in the role of biodiversity in ecosystem integrity and provision of services (Mori et al. 2017). There has been considerable interest to better understand various co-evolution scales (Moss et al. 2016; USGCRP 2016; U.S. Department of Energy 2014) as well as the ways to transform systems and societies towards a low carbon future. The co-evolution of energy, water, land and economy is sometimes referred to as the "nexus" (U.S. Department of Energy 2014; Bazilian et al. 2011; Ringler et al. 2013; Smajgl et al. 2016; Albrecht et al. 2018; D'Odorico et al. 2018; Van Vuuren et al. 2019). A key perspective to note is that the fundamental paradigm of nexus is to assess trade-offs and unravel synergies between the various interlinked energy, water, food, land and climate dimensions (Brouwer et al. 2018). This is particularly important in the context of provision of services, such as energy, agriculture and land use and ecosystem services, as well as the role of cities in providing new systems of transformation.

To take another example, energy is not consumed for its own sake, but rather for the services that it provides (i.e., for economic activities). Energy provides a wide range of services including, for example, transport of people and freight, provision of sustenance, materials, space conditioning, lighting, communications, cooking, water-heating, military services and other (See Cullen and Allwood, 2010, Figure 2). The size of the global energy system has grown from roughly 11 exajoule (EJ) yr^{-1} in 1850, primarily in the form of traditional fuels (e.g. wood, straw, dung) (Grubler et al. 2014; Zou et al. 2016), to more than 600 EJ yr^{-1} in 2017, dominated by modern energy forms (BP 2018). Conversion losses in the transformation of primary energy forms to energy services are on the order of two-thirds (Grubler et al., 2014), leaving much room for improvement. There has been a long term trend to increasing the share of end-use energy that is in the form of electricity rather than fuels (Edmonds et al. 2006). A range of perspectives can be considered – there is evidently going to be an increased demand for services that provide satisfaction for human well-being. This perspective is different from simply considering energy and material inputs (see Chapter 5). The balance lies in identifying mitigation options, along with efficient provision of services for ensuring well-being. In terms of energy-return-on-investment, the ratios for fossil fuels are now much closer to those of renewables, and are expected to decline for the former in the future (Brockway et al. 2019). Land-energy-water and climate-land-energy-water are just one of many nexuses, which are relevant for understanding the complex nature of interdependencies and how these could either drive or constrain efforts at climate mitigation as drivers or constraints to low carbon system transformation. (Fajardy et al. 2018). Others interdependent sectors and services or nexuses where literature on systems transformation has grown include agriculture, forestry, land use and ecosystem services with a growing interest on the role that "nature-based solutions" (e.g. agro-forestry, land restoration, forest restoration (Chazdon 2008) can offer co-benefits for tackling climate change and for enhancing ecosystem services for sustainable development (Keesstra et al. 2018; Nesshöver et al. 2017; Torralba et al. 2016; Settele et al. 2016).

Another potent example is the interdependencies between patters of urbanisation, and the demand and supply of transportation, housing, water, food and medicare, recreational and other services. Here the role of urban planning and purposeful "experimentation" have been identified as critical for decarbonising old power and transport systems,, creating energy efficient and/or renewable energy synergies, and regenerating the atmosphere through carbon dioxide removal technologies (Newman et al. 2017). The green transformation of cites have also been identified as vital to address intense inequality, and to promote just transitions, and inclusive approaches to addressing climate vulnerabilities (Shi et al. 2016). In sum, it should be emphasised that effective mitigation strategies require an integrated approach that considers the trade-offs and synergies between various dimensions of nexus (Chapter 7; IPCC 2019b).

1.5.2 Trade, consumption and leakage

Emissions associated with the production of internationally traded goods and services account for 20-33 % of global emissions (Wiedmann and Lenzen 2018). Whether international trade drives increase or decrease in global GHG emissions depends on emissions intensity of traded products as well as the influence of international trade on the relocation of production, on the economic growth and income and on consumption patterns. While there are studies suggesting a general increasing effect of trade openness on territorial CO_2 emissions, there are studies indicating opposite effect (2.4.5). Tariff reduction of low carbon technologies could facilitate effective mitigation (de Melo and Vijil 2014; WTO 2018; Ertugrul et al. 2016; Islam et al. 2016). Carbon leakage offsetting the reduction in emissions by an increase outside the jurisdiction could occur through changes in the relative prices, relocation of industry, nested regulation and weak consumption leakage (see Box 5.4. AR5) (Naegele and Zaklan 2019). The magnitude of carbon leakage caused by early and unilateral mitigation policies in a fragmented climate policy world depends on trade and substitution patterns of fossil fuels and the design of policies (Bauer et al. 2013); Akimoto (2018) argue that differences in marginal abatement cost of NDCs could cause carbon leakage in energy-intensive, trade-exposed sectors, and could weaken effective global mitigation. Carbone and Rivers (2017) estimate that unilateral climate policy in such sectors could cause 10-30% leakage. See 13.2.6 for discussion.

While there could be a number of policy responses to cope with carbon leakage including border carbon adjustment (BCAs), they have limitations. Some options could potentially be incompatible with WTO, particularly those not focused on simply leveling the cost of carbon paid by consumers. Others could involve difficulty of tracing the carbon content of inputs (Onder 2012; Denis-Ryan et al. 2016); see chapter 13, and (Mehling et al. 2019) on context of trade law and the Paris Agreement.

Supply chains are increasingly becoming global (Hubacek et al. 2016), leading to a growth in trade volumes (Federico and Tena-Junguito 2017). Official inventories report territorial emissions. In recent years, other methods have been suggested as a way of accounting for emissions, such as shared responsibility (Lenzen et al. 2007), technology adjusted consumption based accounting (Kander et al. 2015), value added-based responsibility (Piñero et al. 2019) and exergy-based responsibility (Khajehpour et al. 2019). Consumption-based emissions (i.e. attribution of emissions related to domestic consumption and imports – final destination) are not officially reported in global emissions datasets (Afionis et al. (2017); see chapter 2 for discussion of these accounting perspectives). Understanding consumption-based emissions at multiple levels (see Chapter 2), is crucial for gaining insights into the trends in emissions, and for uncovering the socio-demographic drivers of emissions and unequal ecological exchange (Jorgenson 2012; Yu et al. 2014).

From a consumption perspective: high-income developed countries typically tend to be net importers of emissions, whereas low/middle income developing countries net-exporters (Peters et al. 2011).This trend is now shifting, with a growth in trade between non-OECD countries (Meng et al. 2018; Zhang et al. 2019), and a decline in emissions intensity of traded goods (Wood et al. 2019). An increase in international trade has resulted in a general shifting of fossil-fuel driven emissions-intensive production from developed to developing countries (Malik and Lan 2016; Iñaki Arto and Erik Dietzenbacher 2014), and between developing countries (Zhang et al. 2019).

Compilation of consumption-based GHG inventories has been suggested as a way of monitoring carbon leakage (Peters and Hertwich 2008). To this end, entire global supply chains must be considered (Peters et al. 2011), using well-established techniques such as multi-regional input-output tables that encompass information about trade between different sectors of nations (Tukker and Dietzenbacher 2013). These tables have been used extensively for consumption-based accounting of emissions at multiple levels (Wiedmann and Lenzen 2018; Malik et al. 2019).

Emissions from aviation and shipping are only considered in production-based accounting approaches, and not territorial and consumption-based approaches (Figure 2.8). These sectors emit approximately 1.6% and 2.6% of global CO_2 respectively (though the climate impact of the former is estimated to be 2 - 4 time higher due to indirect effects), with emissions growing rapidly at 3-5% per year before COVID-19. As the Paris Agreement primarily deals with NDCs, emissions from international aviation and shipping are not covered in the Agreement (chapter 10). Other emissions associated with shipping and aviation include black carbon and short-lived aerosols (e.g. sulphates), which have shown to be especially harmful for the Arctic (Qian et al. 2015; Ramanathan and Xu 2010; Stephenson et al. 2018; Pistone et al. 2019; Schaefer et al. 2014; Steffen et al. 2018; Lenton et al. 2019a) (chapter 10).

1.5.3 Technology

The rapid developments in technology over the past decade enhance potential for transformative changes, in particular to help deliver climate goals simultaneously with other SDGs. Technological change has enabled both emissions reductions and increases in emissions. The challenge will be to enhance the synergies and minimise the trade-offs and rebounds.

There have been large improvements in information storage, processing, including artificial intelligence, and communication over the last few years, see (chapter 16). In energy systems this can enhance energy-efficient control, reduce transaction cost for energy production and distribution, improve demand-side management (Raza and Khosravi 2015), and reduce the need for physical transport (Rosqvist et al. 2016) (see chapters 5, 6, 9-11). Information Technologies (IT) will have broad impacts on the patterns of work and leisure; they may accelerate trends to fewer or relocated working hours (Boppart and Krusell 2020) which – coupled with rising affluence – means that the emissions intensity of how people spend their leisure time will become (even) more important (see chapters 5, 9). However, IT may lead to rebound effects and higher needs for energy (Belkhir and Elmeligi 2018). Efficiency leads in general to lower cost and higher demand (Sudbury and Hutchinson 2016; Cohen and Cavoli 2019), and Information technologies, including blockchain, are electricity-intensive: as an example, cryptocurrencies may be a major global source of CO_2 if the electricity production is not decarbonised (Mora et al. 2018).

The fall in renewable energy costs, highlighted in section 1.3.3 and illustrated in Figure 1.7, has been accompanied by varied progress in many other technology areas such fuel cells for both stationary and mobile applications (Dodds 2019) (chapters 6, 9, 12) and battery and other storage technologies

(Crabtree et al. 2015). The latter may help manage variability in electricity from renewable energy (chapters 6, 9) and facilitate electric transport (chapter 10), (Freeman et al. 2017; Greaker et al. 2019; Wangsness and Halse). Also, Generation III light water nuclear fission reactors could be ready for large scale deployment contributing as an economical base load for energy (Knapp and Pevec 2018), but may fail if potential financial, safety, fuel cycle and regulatory risks are not properly managed (Abd Manan et al. 2015).

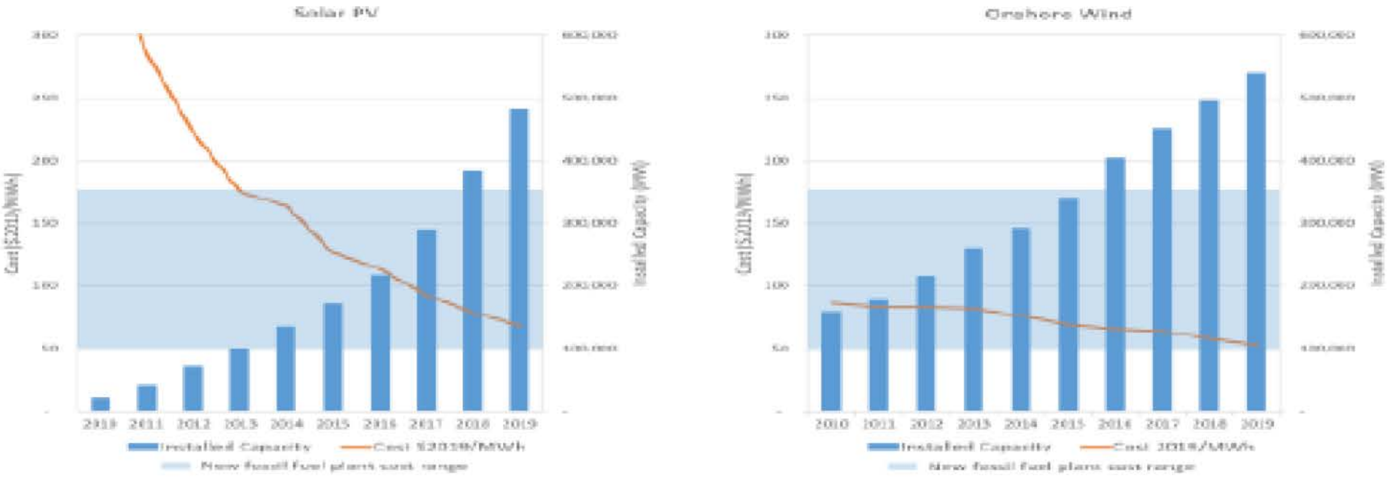


Figure 1.7 Cost reductions and adoption in solar PV and onshore wind energy

Source: IRENA (2020), with fossil fuel LCOE indicated as shaded blue at USD 50-177/MW (p.12 note 4)

Like electricity, hydrogen (H_2) is a zero-carbon energy vector with multiple applications. It is a zero-carbon candidate for replacing hydrocarbon fuels (gas, liquid and coke) for high-temperature heat in industrial processes such as iron, steel industry and non-metallic mineral production, for long-range transportation (IEA 2019b), power generation and for low-temperature heat in residential and commercial buildings (Staffell et al. 2019). Deploying H_2 delivery infrastructure economically is a challenge when the future scale of hydrogen demand is so uncertain: in this transition period, H_2 from natural gas (NG) with CO_2 capture and storage (CCS) may help to kick-start the H_2 economy (Sunny et al. 2020).

In addition to hydrogen, CO_2-based fuels (or e-fuels or Power-to-X) provide important low-carbon alternatives to fossil fuels if produced using low-carbon energy sources (Ch 10). CO_2-based fuels such as synthetic methane, methanol, diesel, jet fuel and other hydrocarbons, represent drop-in solutions as no major changes of infrastructure are necessary for their use (Artz et al. 2018; Bobeck et al. 2019; Yugo and Soler 2019).

Another concern is that energy production and conversion systems involve materials use, such as rare earth materials for electronics or lithium for batteries (Wanger 2011; Flexer et al. 2018), stressing the importance of recycling (Rosendahl and Rubiano 2019; IPCC 2011b). Innovation is enabling greater recycling and re-use of energy-intensive materials (e.g. Milford et al. (2013)) and introducing radically new and less carbon-intensive materials. Deployment and development of CCS technologies have been much slower than projected in previous Assessments. Nineteen full scale commercial facilities were operating in 2019 (Global CCS Institute 2019), but the capacity is low compared to projections of volumes needed, even if it is increasing every year (International Energy Agency (IEA) 2019).

Terrestrial systems play an increasingly important role as fossil fuel and industrial emissions are reduced to low levels. Terrestrial systems provide a pathway to offsetting residual, hard-to-reduce emissions in other sectors via afforestation, soil carbon management, and other strategies. However, there are limits to their potential and large-scale deployment could increase risks for desertification, land degradation, food security and sustainable development (SRCCL SPM B.3.2). Still, continued improvements in crop and livestock yields reduce land demand for agriculture enabling it to be used for other purposes including bioenergy production (Wise et al. 2009; Köberle et al. 2020; Havlík et al. 2014; Popp et al. 2017). By removing carbon from the atmosphere during growth, modern bioenergy can provide both energy and negative emissions when coupled with CCS (BECCS), and net zero emissions scenarios tend to project bioenergy production in millions of km^2 (IPCC 2019d, 2018b). Since AR5, several modelled scenarios have explored the adverse side effects of gigaton-scale deployment of bioenergy such as higher risk of food insecurity and higher water withdrawals (Hasegawa et al. 2018; Fuhrman et al. 2020). Until recently, the only carbon dioxide removal (CDR) options available in models were BECCS and afforestation and the introduction in models of other CDR options like CO_2 direct air capture with CCS (DACCS) reduces reliance on bioenergy to deliver negative emissions (Realmonte et al. 2019; Köberle 2019). In agriculture, a recent spur in both technological and knowledge innovation show potential for meeting demand for food, feed, fiber and bioenergy while keeping within planetary boundaries (Chapter 7). One example is plant-based meat innovation which could also help drastically reduce meat consumption (Eshel et al. 2019). Innovation in spatial data and monitoring systems can also help reducing deforestation rates (Seymour and Harris 2019).

Geoengineering typically refers to a broad class of speculative technological proposals that either capture carbon dioxide from the atmosphere or directly modify the Earth's energy balance. Carbon dioxide removal (CDR) technologies, which include direct air capture, ocean iron fertilisation, enhanced weathering and ocean alkalinisation (National Research Council 2015a), are appealing because they present an opportunity to draw down atmospheric CO_2 at rates that far exceed those associated with the Earth's natural carbon cycle, but are currently more expensive per ton CO_2 than renewables and other forms of mitigation. SRM, which would cool the planet by reflecting incoming sunlight, is appealing for its low estimated direct costs and rapid timescales for cooling (National Research Council 2015b). The two primary proposals are stratospheric aerosol injection and marine cloud brightening, both of which entail significant, uncertain side effects and extremely thorny international equity and governance challenges (Chhetri et al. 2018). Geoengineering proposals are in early stages of technological development and have not been tested or deployed beyond the pilot stage. Understanding of the climate response to SRM remains subject to large uncertainties (AR6 WG1).

Innovation in low carbon technologies comes partly from direct public and private investments in research and development, but also through learning effects and scale economies as new products and technologies are developed and deployed (Chapter 16). Private sector incentives to low carbon innovation are limited by many factors. One example is that the full benefits of innovation often extend beyond the original innovators ('spill-overs' to other companies and countries). Governments anyway have an important role in most major innovations and associated industrial innovations (Mazzucato 2013), suggesting a significant role for governments in fostering low carbon industrial developments (Roberts and Geels 2019a). Another obstacle is that innovations tend to be driven from a few global centres, and other regions may fear technology dependence. International initiatives, combined with funding from the Green Climate Fund, may help to alleviate such concerns (1.2; Chapters 15, 16).

1.5.4 Finance and investment

Since AR5, there has been growing recognition that the financial sector has an important role to play in the mitigation of climate change. Major shifts in current investment patterns are required to realise the objectives of the Paris Agreement (15.2.2), particularly the goal enshrined in Article 2c for "Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development" (UNFCCC 2015). There is a persistent but uncertain gap in mitigation finance (Table 15.15.1). Climate finance draws from the same pool of resources to fund both mitigation and adaptation projects meaning they must be examined together (Box 15.1).

Climate finance is a multi-actor, multi-objective domain that includes central banks, commercial banks, asset managers, underwriters, development banks, and corporate planners. Climate change presents both risks and opportunities for the financial sector. Climate related financial risk is often divided into physical risks related to the impacts of climate change itself and transition risks related to the exposure to policy and technology changes in line with a low-carbon transition, and liability risks from litigation for climate-related damages (Box 15.2). Both could potentially lead to stranded assets (the loss of economic value of existing assets before the end of their useful lifetimes (Bos and Gupta 2019). The continuing expansion of fossil fuel infrastructure capacity and lack of transparency on how these are valued in corporate balance sheets raises concerns that systemic risk may be accumulating in the financial sector in relation to a potential low-carbon transition that may already be under way (15.6.3).

The Financial Stability Board chartered the Task Force on Climate-related Financial Disclosure (TCFD) in 2016 (15.6.3) out of concern that inadequate information about potential climate-related financial risk (physical and transition) could lead to financial instability (recessions) (Carney 2015). The TCFD recommends that investors and companies consider climate change risks in their strategies and capital allocation, so investors can make informed decisions (TCFD 2018). Transparency alone may be insufficient to enable the required asset reallocation. There is an unmet need for metrics and indicators of assets risk exposure (Campiglio et al. 2018; Monasterolo 2017). The Network for Greening the Financial Sector (NGFS), is a collective of central banks and supervisors working voluntarily to help strengthen the global response required to meet the goals of the Paris agreement and to enhance the role of the financial system to manage risks and to mobilise capital for green and low-carbon investments in the broader context of environmentally sustainable development. Climate-related institutional stress tests have been commissioned by some central banks (especially in Europe) to assess the exposure of regulated financial institutions under their auspices (Bank of England, Dutch Central Bank, Banque de France etc.).

The international community agreed in 2015 through the Addis Ababa Action Agenda (AAAA) "to address the challenge of financing and creating an enabling environment at all levels for sustainable development" (UNDESA 2015). The AAAA recognises the significant potential of regional cooperation and provides a forum for discussing the solutions pathways to common challenges faced by developing countries (15.6.4). At COP16 in Cancun, countries "established the Green Climate Fund (GCF) "as an operating entity of the Financial Mechanism" under Article 11 of the UNFCCC to help finance developing countries' efforts to "reduce their greenhouse gas emissions and enhance their ability to respond to climate change (GCF 2020). Advanced economies pledged USD100 billion a year by 2020, but so far this target has not been met (15.6.4). Confronting the problem of insufficient funding remains a challenge (Cui and Huang 2018). Recent increase in green bond issuance has happened in parallel with efforts to reform the international financial system by supporting development of local capital markets (15.6.4).

Development bank and climate funds are inadequate to provide the scale of financial flows to achieve sustainable development. Long-term sources of private capital are required to meet financing needs across sectors and geographies. Requisite North-South financial flows are impeded by both geographic and technological risk premiums (Buhr et al. 2018; Iyer et al. 2015) (15.2.1). Climate-related investments in developing countries also suffer from structural barriers such as sovereign risk and exchange rate volatility (Farooquee and Shrimali 2016; Guzman et al. 2018) which affect not only climate-related investment but investment in general (Yamahaki et al. 2020) including in needed infrastructure development consistent with meeting the SDGs (Gray and Irwin 2003).

In deep decarbonisation scenarios, investments into fossil power generation technologies (including those with CCS) decrease by more than half by 2030 (IEA 2019c). Policies would need to facilitate a shift toward low-carbon solutions and increase investment levels (15.6.2). However, there was a surge of coal investments across 56 recipient countries in Asia and Africa, almost entirely supported by foreign State-Owned Enterprises, whilst private investment has flowed almost entirely into renewables

(Zhou et al. 2018). Steffen and Schmidt (2019) also found that even within Multilateral Development Banks, 'public- and private-sector branches differ considerably', with public-sector lending used mainly in non-renewable and hydropower projects. Political leadership is therefore essential to steer financial flows to support low carbon transition (15.6). Voituriez et al. (2019) identify significant mitigation potential if financing countries simply applied their own environmental standards to their overseas investments.

1.5.5 Political economy

The politics of interest (most especially economic interest) of key actors at subnational, national and global level can be an important determinants of climate (in) action (O'Hara 2009; Lo 2010; Tanner and Allouche 2011; Sovacool et al. 2015; Clapp et al. 2018; Lohmann 2018; Newell and Taylor 2018; Lohmann 2019). Political economy approaches can be crudely divided into the term as used by economists, which can be referred to as "economic approaches to politics", and those by other social scientists (Paterson and P-Laberge 2018). The latter literature emphasises the intimate relation between industrial economic growth and climate change and more specifically the central role of structures of power, production, and a commitment to economic growth in either facilitating or hindering ambitious climate action. An important aspect of this is the historically central role of fossil fuels to economic development and especially in enabling the exponential expansion and globalisation of economic activity, as well as the deep embedding of fossil energy in daily life (Malm 2015; Huber 2012; Di Muzio 2015; Newell and Paterson 2010).

The centrality of fossil energy to economic development over the last two hundred years raises obvious questions regarding the possibility of decarbonisation. Economically, this is well understood as a problem of decoupling. But the constraint is also political, in terms of the power of incumbent fossil fuel interests to block initiatives towards decarbonisation (Newell and Paterson 2010; Geels 2014; Jones and Levy 2009). In climate change, one sees both that the effects of policy on GDP growth are key considerations in deciding the level of policy ambition and direction and strategies of states (Lo 2010; Alam et al. 2013; Ibikunle and Okereke 2014), regions (Goldthau and Sitter 2015); and business actors (Wittneben et al. 2012). Decarbonisation strategies are often centred around projects to develop new sources of economic activity: carbon markets creating new commodities to trade and windfall profit for big businesses (Newell and Paterson 2010); the investment generated in new urban infrastructure (Whitehead 2013); innovations in a range of new energy technologies (Fankhauser et al. 2013; Lachapelle et al. 2017; Meckling and Nahm 2018), for example.

One factor limiting the ambition of climate policy has been the ability of incumbent industries to shape government action on climate change (Newell and Paterson 1998; Breetz et al. 2018; Jones and Levy 2009; Geels 2014). Campaigns by oil and coal companies against climate action in the US and Australia are perhaps the most well-known and largely successful of these (Brulle et al. 2020; Stokes 2020; Mildenberger 2020) although similar dynamics have been demonstrated for example in Brazil and South Africa (Hochstetler 2020). In other contexts, resistance by incumbent companies is more subtle but nevertheless has weakened policy design on emissions trading systems (Pinkse and Kolk 2012), limited the development of alternative fuelled automobiles (Wells and Nieuwenhuis 2012; Levy and Egan 2003), for example.

Political economy suggests one part of the key to countering this is in the building of coalitions of actors to legitimise policy in the face of such opposition (Meadowcroft 2005; Levin et al. 2012; Meckling 2011). The interaction of politics, power and economics is central in explaining why countries with higher per-capita emissions, which logically have more opportunities to reduce emissions, in practice often take the opposite stance. This can arise from the vested interest of State-owned Enterprises (Wittneben et al. 2012; Polman 2015; Wright and Nyberg 2017), the alignment and coalitions of countries in climate negotiations (Gupta 2016; Okereke and Coventry 2016), and the patterns of opposition to or support for climate policy among citizens (Swilling et al. 2016; Heffron and McCauley 2018; Ransan-Cooper et al. 2018; Turhan et al. 2019; Baker 2015) (with the "yellow vest" demonstrations in France in 2018 being one recent example). Balancing such forces typically involves building coalitions of actors to legitimise climate policy in the face of such opposition (Meadowcroft 2005; Levin et al. 2012; Meckling 2011).

1.5.6 Equity and fairness

Considerations of equity and fairness can serve as both driver and barrier to climate mitigation at different scales of governance. Literature regularly highlight equity and justice issues as critical components in local politics and international diplomacy regarding all SDG, such as goals for no poverty, zero hunger, gender equality, affordable clean energy, reducing inequality, but also for climate action (Goal 13) (Marmot and Bell 2018; Spijkers 2018). Equity issues are important reasons why it is difficult to reach a significant global agreement, as it is hard to agree on the optimal level of greenhouse gas mitigation (or emissions) and how mitigation should be distributed among countries (Kverndokk 2018). There are at least two reasons for this. First, an optimal trade-off between mitigation costs and damage costs of climate change depends on ethical considerations. Examples follow from simulations made on integrated assessment models (see, e.g., chapters 3 and 4). As these models use different ethical parameters such as the time preference rate and the valuation of consumption between agents with different consumption levels, they also produce different optimal mitigation paths see (IPCC 2018a) and Chapter 3. Second, treaties that are considered unfair may be hard to implement (Klinsky et al. 2017; Liu et al. 2017). Lessons from experimental economics show that people may not accept a distribution that is considered unfair, even if there is a cost of not accepting (Gampfer 2014). As equity issues are important for reaching deep decarbonisation, the transition towards a sustainable development (Evans and Phelan 2016; Heffron and McCauley 2018; Okereke 2018) is also dependent on taking equity seriously in climate policies and international negotiations (Okereke and Coventry 2016; Martinez et al. 2019; Klinsky et al. 2017).

Both climate change and climate policies affect countries and people differently. Rich and poor countries will not be affected in the same way by climate change, and the highest impacts will likely be felt in the poor countries (Burke et al. 2015). For example, low-income countries tend to be more dependent on primary industries (agriculture, fisheries, etc.) than high- and middle-income countries, and their infrastructure is also in a poorer condition. There is also a lack of political representation at world stage for many of these communities (see also 1.6.3.2 below). Also, within a country, the burden may not be equally distributed. For instance, gender matters, and women, especially in poor countries, are often less adaptive to climate change (Jost et al. 2016; Rao et al. 2019). Costs of mitigation also differ across countries. Studies show there are large disparities of economic impacts of NDCs across regions, and also between relatively similar countries when it comes to the level of development, due to large differences in marginal abatement cost for the emission reduction target of NDCs (Akimoto et al. 2018; Fujimori et al. 2016; Edmonds et al.).

However, taking equity into account in designing an international climate agreement is complicated as there is no single universally accepted equity criteria, and countries may strategically choose a criterion that favours them (Lange et al. 2007, 2010). Still, several studies analyse the consequences of different social preferences in designing climate agreements, such as for instance inequality aversion, sovereignty and altruism (Anthoff and Tol 2010; Kverndokk et al. 2014).

A climate treaty may help meeting some of the SDGs, but there may also be trade-offs between mitigating climate change and meeting some SDGs (see section 1.4 above and chapter 17). Such a treaty will likely involve transfers from rich to poor countries, as agreed upon in the (UNFCCC 2010) (see section 1.4.5 above and chapter 15). The transfers will typically be transfers of mitigation and adaptation capital, or financial resources (from public and private funds) to support mitigation and adaptation activities, and may be motivated by strategical reasons as well as equity reasons (Kverndokk 2018). However, transfers of mitigation technology should be carefully designed to ensure additivity and not crowding out of mitigation effort in the poor regions (Sarr and Swanson 2017; Glachant et al. 2017).

1.5.7 Social innovation and behaviour change

In addition to economic barriers to the adoption of clean technologies, there may be other obstacles based on individual and collective behaviours. Religion, values, culture, identity, social status and habits strongly influence individual behaviours and choices and therefore, climate friendly consumption, see also section 1.6.3.1 and chapter 5. The required behavioural changes are not always aligned with these key driving factors. Identity, or a person's sense of self, affects their behaviour. Identity can mean that you identify with a certain social category of people (Akerlof and Kranton 2000), that you behave in accordance with some sort of ideal behaviour (Brekke et al. 2003), or that values are based on past choices (Bénabou and Tirole 2011).

One example may be changes in diets, as diets have an impact on greenhouse gas emissions (Willett et al. 2019). Moving towards plant-based alternatives to meat could be an important way of cutting into emissions from diets, see e.g. (Eshel et al. 2019) for a study on the U.S. However, diets are deeply entrenched in cultures and identities and hard to change (Fresco 2015). Henceforth, some behaviours that are harder to change will only be transformed by the transition itself: triggered by policies, the transition will bring about technologies that, in turn, will make new green behaviours entrenched (as in the case of a tax on red meat that facilitates the diffusion of meat alternatives that gain the favour of new generations).

Behaviour can be changed through a number of mechanisms besides economic policy and regulation, such as information campaigns, advertising and nudging. In addition, innovations and infrastructure have impacts on behaviour. For instance, to reduce road traffic, biking lines make it easier to choose to bike. But several social innovations may also have impacts on greenhouse gas emissions. Education is increasing across the world, and higher education will have impacts on fertility, consumption and the attitude towards the environment (Osili and Long 2008; McCrary, Justin and Royer 2011; Hamilton 2011). Further, a fall in poverty and an improvement in health will also have implications for fertility, energy use and consumption globally. Finally, social capital and the ability to work collectively may have large consequences for mitigation and the ability to adapt to climate change (Adger 2009). See also section 4.3.5 in IPCC (2015).

Climate change perception and how policies can affect this perception and then act accordingly is studied through different lenses from psychology (Weber 2016) to sociology (Guilbeault et al. 2018) and experimental economics (Allcott 2011). These disciplines and studies also are of great help in better understanding of demand-side of mitigation solution. In chapter 5, a transdisciplinary approach to identify demand-side climate solutions is introduced, investigating for each behavioural-based solution its mitigation potential, what policy measures may trigger the change and their implications for well-being. A key shift to introduce these behavioural measures is to depart from the notion of sectors and introducing the idea of services. The focus shifts from the economic activity itself to the benefits it brings to human well-being: we don't need the transport sector per se, but we do need a set of transport services to fulfil our lives. This is the first IPCC assessment report using services, rather than sectors, as a meaningful unit to explore mitigation options and with particular attention to well-being. Avoid, Shift and Improve are the three dimensions along which it is useful to articulate mitigation options for each of the services that individuals need to meet their needs.

1.5.8 Legal framework and institutions

Institutions are rules and norms held in common by social actors that guide, constrain and shape human interaction (IPCC 2018a). Institutions can be formal, such as laws and policies, or informal, such as norms and conventions. It became obvious that institutions can both facilitate or constrain climate policy-making and implementation in multiple ways. Institutions set the economic incentives for action or inaction on climate change both at national, regional and individual levels (Dorsch and Flachsland 2017; Rory Sullivan 2017).

A lot is often said about how price or cost influence how much nations, companies and individuals are willing to adopt renewable energy technologies and lifestyle (Creutzig et al. 2017; Tol 2018). However, the cost of low-carbon technologies are often themselves products of specific institutional constructs and practices, such as the pattern of subsidies or investment (Andrews-Speed 2016). Institutions entrench specific political decision-making processes, often empowering some interests over others. Several scholars have traced delay and sluggishness by states to pursue ambition climate mitigation policies to the activities of powerful interest groups who have vested interest in maintaining the current high carbon economic structures (Sullivan et al. 2018; Okereke and Russel 2010; Wilhite 2016).

Some suggest that societal transformation towards low a carbon future requires new politics that involves thinking in intergenerational time horizons, as well as new forms of partnerships between private and public actors (Westman and Broto 2018), which may imply the need for new institutions and social innovation that entail greater involvement of non-state actors in climate governance (Fuhr et al. 2018). Some scholars insist that the democratisation of climate politics, with greater emphasis on equity and community participation, is a much-needed condition for this (Dryzek 2016; Dryzek and Niemeyer 2019; Nico Stehr 2015). Others suggest that democracy may actually hinder radical climate action in some circumstances (Povitkina 2018).

At the global level, the UN institutions have been a major force driving climate action mostly through persuasion, rule setting, building coalitions and the promotion of accountability (Torney and Cross 2018). National action may be spurred by international process while national consensus may enhance global collective action (Iacobuta and Höhne 2017). By 2017, 70% of global GHG emissions are covered with either nationally binding climate legislation or climate strategies. In accordance with the development of NDCs, the share of global GHG emissions covered with national GHG emissions targets increased from 69% in 2014 to 89% in 2017.

A common criticism of international institutions is their limited (if any) powers of compliance (Zahar 2017). As a global legal institution, the Paris Agreement has little enforcement mechanism (Sindico 2015), but enforcement is not a necessary condition for an instrument to be legally binding (Bodansky 2016a). In reality compliance tends to be high once countries have ratified and a Treaty or an Agreement is in force. Often, the problem is not so much of non-compliance, but the level of ambition.

The Paris Agreement requires Parties to submit their Nationally Determined Contributions and to have these updated periodically. The Periodic update is seen as a way of ratchet up ambition overtime. The Paris Agreement also requires Parties to pursue domestic mitigation measures, providing clear, transparent and understandable information on the NDCs, accounting for anthropogenic emissions and removals, and providing information, no less frequently than biennially, on a national inventory as well as on progress in implementing and achieving the NDC. At the same time, the Paris Agreement obliges that developed country Parties shall provide financial resources to assist developing country Parties. Legally bindingness of the Paris Agreement is undeniable since it is justiciable based on the consent of States in its implementation as contracting states (Bodansky 2016b). The bindingness of an agreement also depends on the costs (e.g., loss of reputation) to a state of nonparticipation, noncompliance, or withdrawal. Strong norms with high costs of violation are sometimes called 'binding' (IPCC 2015; Hoffmann 2004, 2011).

It remains unclear whether harder or softer legal norms are more capable of enhancing ecological reflexivity. The combination of harder procedural commitments with softer substantive provisions of the Paris Agreement could encourage flexible responses to changing conditions while its softer transparency-based framework could limit assurance to ambitious commitments and their fulfilment (Pickering et al. 2018). Numerous international climate governance initiatives engage national and subnational governments, NGOs and private corporations, constituting a "regime complex" (Keohane and Victor 2011). They may have longer-run and second-order effects if commitments are more precise and binding (Kahler 2017). However, without targets, incentives, defined baseline or monitoring, reporting, and verification, they are not likely to fill the "mitigation gap" (Michaelowa and Michaelowa 2017).

1.5.9 Policy drivers

The literature finds that transformation to different systems will hinge on conscious policy to change the direction in which energy, land-use, agriculture and other key sectors develop (Bataille et al. 2016). Policy plays a central role in in land-related systems (Chapter 7), urban development (Chapter 8), improving energy efficiency in buildings (Chapter 9) and transport (Chapter 10), and decarbonising industrial systems (Chapter 11).

The role of policy in shifting towards a low-carbon system to date has been most evident in energy efficiency (Chapter 5) and electricity (Chapter 6). The IPCC Special Report on Renewable Energy (2011a) already found that "Government policies play a crucial role in accelerating the deployment of RE technologies", as "an increasing number and variety of RE policies - motivated by many factors - have driven escalated growth of RE technologies" (SRES, p.24). With continued expansion of policies, the SR1.5 (IPCC 2018a) noted the "dramatic improvement in the political, economic, social and technical feasibility of solar energy, wind energy and electricity storage" summarised above.

Policy has been and will be central not only because greenhouse gas emissions are almost universally under-priced in market economies (Stern and Stiglitz 2017; World Bank 2019b), and because of inadequate economic incentives to innovation (Jaffe et al. 2005) but also due to multiple sources of path-dependence and lock-in to existing systems (Section 5.2 below). AR5 found that "Infrastructure developments and long-lived products that lock societies into GHG-intensive emissions pathways may be difficult or very costly to change, reinforcing the importance of early action for ambitious mitigation (robust evidence, high agreement)." (AR5 p.18).

Synergies and trade-offs arise partly because of the nexus of GHG emissions with other adverse impacts (e.g. local air pollution) and critical resources (e.g. water and food) (Conway et al. 2015; Andrews-Speed and Dalin 2017), which also imply interacting policy domains.

The literature shows increasing emphasis on policy packages, including those spanning the different levels of niche/behaviour; existing regimes governing markets and public actors; and the landscape level of strategic decision-making and regime changes (section 5.4). Chapter 13 conducts a thorough appraisal of policies for transformation in the context of sustainable development. Such assessment indicates the importance of policy as a driver of change for sustainable development at multiple levels and across many actors, with potential for benefits as well as costs at many levels.

National-level legislation may be particularly important to the credibility and long-term stability of policy to reduce the risks and hence cost of finance (chapter 15) and for encouraging private sector innovation at scale (chapter 16). Nash and Steurer (2019) find that seven national Climate Change Acts in European countries all act as 'living policy processes, though to varying extents'. As one significant example, the halving of CO_2 emissions in UK power generation reflects multiple policies, particularly since the UK's Climate Change Act (2008), which drew upon the Kyoto structure of binding commitments but requires domestic emission caps to be set 15 years ahead to enhance certainty. The energy regulator's duties were amended to protect 'present and future consumers', leading on to the

UK's Electricity Market Reform, which both strengthened carbon pricing and supported a surge in renewable energy, which along with energy efficiency policies at EU, UK and sub-national levels led to these unprecedent reductions (Grubb and Newbery 2018).

The important of policy at multiple levels does not lessen the importance of international policy, for reasons include long-term stability, equity, and scope, but examples of effective implementation policy at international levels remain fewer and governance weaker (Chapter 14).

1.5.10 International cooperation

The need for collective and urgent action on climate change is often mentioned as an important reason for strong international co-operation in the 21st century (Bodansky et al. 2017; Cramton et al. 2017b; Falkner 2016a; Keohane and Victor 2016).

International cooperation is essential for tackling climates action because of the structure of the climate change problem (Bodansky and Lavanya, 2017; Keohane and Victor, 2016). First, the benefits of GHG emissions reduction are global and non-excludable, making anthropogenic climate change a global commons problem (Falkner 2016a; Wapner and Elver 2017). Second, mitigation costs are only borne by countries taking action while the benefit of such action is not limited to them. Moreover, there is a tendency among governments to think that mitigation efforts will raise energy cost and adversely affect national economic competitiveness. All these create strong incentives for free riding where states may wish to benefit from GHG reduction without taking their fair share of action (Keohane and Victor, 2016; Herman 2019). International cooperation has the potential to address these challenges by offering a platform for collaboration for multiple actors with diverse perceptions of the costs and benefits of collective action. International institutions offer opportunity for actors to engage in meaningful communication, and exchange of ideas about potential solutions (Cole 2015).

One of the roles of international institution set up to address ozone layer depletion was the promotion of trust between emitters which was needed to reduce the threat of free-riding (Falkner 2016b; Keohane and Victor 2016). International cooperation is vital for the creation and diffusion of norms and the framework for stabilising expectations among actors (Pettenger 2016). The United Nations Framework Convention for Climate Change for example, has generated or reinforced several important norms for global climate action including the principles of equity, common but differentiated responsibility, respective capabilities and the precautionary principles. These principles have been vital for helping to maintain global cooperation among states with unevenly distributed emissions sources, climate impacts, and varying mitigation cost across countries (Keohane and Victor, 2016). International cooperation could increase awareness on climate change, motivate ambitious actions through for example the formation of coalitions of the willing and provide a structure for measuring and monitoring action towards a global goal (Milkoreit and Haapala 2019). It can also promote technology development and transfer, capacity building; mobilise finance for mitigation and adaptation, and address climate justice (Chan et al. 2018; Okereke and Coventry 2016).

However, it has been noted that international cooperation can be characterised by 'organised hypocrisy' where proclamations are not matched with corresponding action (Egnell 2010). Some have argued that international co-operation for the climate change certainly displays this problem given that over 20 years of co-operation has not resulted in level of reduction which scientists say are necessary to avoid climate change. International cooperation can also seem to be a barrier to ambitious action when negotiation is trapped in relative-gains calculus where states are seeking to game the regime or gain leverage over one another (Purdon 2017). Moreover, the politics of self-interest can lead the least common dominator logic where ambition is lowered to accommodate participation of the least ambitious states (Falkner 2016a).

Scholars suggest that international collaboration works best when the agreement is self-reinforcing with incentives for mutual gains and joint action (Keohane and Victor 2016). However, the structure of the climate challenge makes such an arrangement hard to achieve. The negotiation of Paris Agreement was done in the context of serious questions about how best to structure international climate cooperation to achieve better results given the limited progress made under Kyoto in terms of emission reduction (Bodansky 2016a; Okereke and Coventry 2016; Scavenius and Rayner 2018). The central component of the Paris Agreement is a pledge and review system of Nationally Determined Contributions (NDC) which seeks to combine top-down centralised elements (e.g. procedural obligations to prepare and communicate successive NDCs, compliance with international transparency requirements) and bottom-up voluntary NDCs, the Paris Agreement as having a hybrid structure (Chan et al. 2018). This new agreement is designed to side-step the fractious bargaining which characterised international climate cooperation (Marcu 2017). However, the extent to which this new arrangement will drive ambitious climate policy in the long run remains to be seen (Chapter 14).

Outside the UNFCCC many other platforms and metrics for comparing mitigation efforts have emerged (Aldy 2015). Countries may assess others' efforts in determining their actions through several platforms, such as Climate Change Cooperation Index (C3-I), Climate Change Performance Index (CCPI) 'Climate Laws, Institutions and Measures Index' (CLIMI) (Bernauer and Böhmelt 2013). International cooperative initiatives between and among non-state (e.g., business, investors, civil society) and subnational (e.g., city, state) actors have also been emerging, taking the forms of public-private partnerships, private sector governance initiatives, NGO transnational initiatives, and subnational transnational initiatives (Bulkeley and Schroeder 2012; Roelfsema et al. 2018). Literature is mostly positive about the role of these transnational initiatives in stives in facilitating climate action across scales although some strong voices of criticism and caution about their accountability and effectiveness remain (Chan et al. 2016; Roger et al. 2017; Michaelowa and Michaelowa 2017; Widerberg and Pattberg 2017)(chapter 14).

1.6 Four Analytical Frameworks

1.6.1 Introduction

Climate change is unprecedented in its scope (sectors, actors and countries), depth (major transformations) and timescales (over generations). As such, it creates unique challenges for analysis. It has been called "the greatest market failure in history" (Stern 2007a); the Perfect Moral Storm (Gardiner 2006) and a "super wicked problem" (Lazarus 2008; Levin et al. 2012) - one which appears difficult to solve through the traditional tools and assumptions of social organisation and analysis. This wide context for analysis flows directly from the previous sections: the risks, uncertainties, and the breadth of scenarios (1.3); the location of climate mitigation in the wider context of sustainable development (1.4); and the diverse and sometimes conflicting drivers of emissions and policy (1.5).

In its chapter devoted to decision-making under uncertainty, the IPCC Fifth Assessment extended previous IPCC reports "in four ways". [4] This section summarises insights from subsequent developments in key analytic frameworks and tools. We organise these partly as reflected in the quotes above – broadly: economic, ethical and system complexity perspectives – noting relationship with the

FOOTNOTE [4] AR5 Chapter 2: By "expanding climate-related decisions to other levels of decision making" [Figure 2.2]; in "moving beyond primarily rational-economic" appraisal by "reviewing the psychological and behavioural literature on perceptions and responses to risk and uncertainty"; by "considering the pros and cons of alternative methodologies and decision aids from the point of view of practitioners;" and by "expanding the scope of the challenges associated with developing risk management strategies".

"three types of effects" noted in SR1.5 as relevant to assessing feasibility of implementation, namely *systemic, spatial and distributional*, and *dynamic*, effects.

Specifically, we review advances in *aggregated economic* frameworks to evaluate system-level choices; *distributional and ethical* perspectives to reflect disaggregated concerns related to both stages of development and distributional concerns; and *transition dynamic* frameworks which focus on the processes and actors involved in major technological and social transitions. We find that these need to be complemented by a fourth, which shines more light on the psychological and political factors which have impeded progress to date. We emphasise that all these frameworks are relevant, and together they point to the multiple perspectives and actions required if the positive drivers summarised in our previous section are to outweigh the barriers and overcome the constraints.

1.6.2 Aggregated approaches: cost-benefit, cost-effectiveness and dynamic efficiency

1.6.2.1 Evaluating global pathways under uncertainty

Economic perspectives have coalesced around two main approaches: cost-benefit, striving to balance monetised costs and benefits of mitigation (Nordhaus 2008); and cost-effectiveness, minimising mitigation costs given a climate target. Many studies reviewed in Chapter 3 analyse the long-term mitigation goal in the Paris Agreement, which was informed by scientific assessment of 'avoiding dangerous anthropogenic interference' (UNFCCC 1992). Both approaches recognise that resources are limited, and climate change competes with other priorities in government policymaking. For at least 10-15 years after the first computed global cost-benefit estimate (Nordhaus 1992), the dominant conclusions from these different approaches seemed to yield very different recommendations, with cost-benefit studies suggesting lenient mitigation compared to the climate targets typically recommended from scientific risk assessments (Weyant 2017). Over the past 10-15 years, literature has made important strides towards reconciling these two approaches, both in the analytic methods and the conclusions arising.

Damages and risks Incorporating impacts which may be extremely severe but are uncertain (known as "fat tails", e.g. Weitzman (2009, 2011)), strengthens the economic case for ambitious action, to avoid risks of extreme climate impacts (Ackerman et al. 2010; Fankhauser et al. 2013; Dietz and Stern 2015). The salience of risks has also been amplified by improved understanding of climate 'tipping points' (Lontzek et al. 2015; Lenton et al. 2019b).

One review considered "the best estimate of the optimal [near-term] carbon tax still ranges from a few tens to a few hundreds of dollars per ton of carbon (Tol 2018)." Similarly, a new generation of Cost Benefits analysis based on projections of actual observed damages result in mitigation effort that are very much in line with the targets currently discussed in the Paris Agreement (Glanemann et al. 2020; Hänsel et al. 2020).

Discounting. The role of time-discounting, in weighting future climate change impacts against today's costs of mitigating emissions, has been long recognised (Weitzman 1994, 2001; Nordhaus 2007; Dasgupta 2008; Stern 2007a). Its importance is underlined in analytical Integrated Assessment Models (IAMs) (Golosov et al. 2014; van der Ploeg and Rezai 2019; van den Bijgaart et al. 2016). Economic literature suggests applying risk-free, public, and long-term interest rates when evaluating climate change (Weitzman 2001; Dasgupta 2008; Arrow et al. 2013; Groom and Hepburn 2017). Expert elicitations indicate values around 2-3% (Drupp et al. 2018), lower than in many of the studies reviewed in earlier IPCC Assessments, hence increasing the weight accorded to the future. The U.S. Interagency Working Group on the Social Cost of Carbon used 3% as its central value (IAWG 2016; Li and Pizer 2018; Adler et al. 2017)

Hybrid cost-benefit approaches that extend the objective of the optimisation beyond traditional welfare, adding some form of temperature targets as in (Llavador et al. 2015; Held 2019) represent a step in bridging the gap between the two approaches and result in proposed strategies much more in line with those coming from the cost-effectiveness literature. Approaching from the opposite side, cost-effectiveness studies have looked into incorporating benefits from avoided climate damages (Drouet et al. 2020), to improve the assessment of net costs.

Overall the combination of improved damage functions with the wider consensus on low discount rates (as well as lower mitigation costs due to innovation) has increasingly yielded 'optimal' results from benefit-cost studies in line with the range established in the Paris Agreement (see Cross-Working-Group Box 1 in Chapter 3).

Inefficient implementation would raise mitigation costs (Homma et al. 2019) ; conversely, **co-benefits** – most extensively estimated for air-quality, valued at a few tens of USD/tCO_2 across sixteen studies (Karlsson et al. 2020) - would further strengthen the conclusion.

Whereas many of these factors affect primarily cost-benefit evaluation, discounting also determines the cost-effective trajectory: Emmerling et al. (2019) find that, for a remaining budget of 1000GtCO_2, reducing the discount rate from 5% to 2% would more than double current efforts, limit 'overshoot', and greatly reduce a late rush to negative emissions.

Distribution of impacts. The empirical climate economic impacts literature generally indicates a robust heterogeneity in the distribution of climate damages at the nationally aggregated and subnational level (Moore et al. 2017; Ricke et al. 2018; Carleton et al. 2020). A 'global damage function' necessarily implies aggregating impacts across people and countries with different levels of income, and over generations, a process which obscures the strategic considerations that drive climate policy making (Keohane and Oppenheimer 2016). Economics acknowledges there is no single, objectively-defined such 'social welfare function' (IPCC 1995, 2015), underlining the relevance of equity (next section) and global negotiations to determine collective objectives.

Integrated Assessment Models. IAMs are the primary tool for evaluating the implications and metrics of such aggregate economic reasoning. They broadly divide into 'stylized aggregate benefit-cost models', and more complex, 'detailed process' IAMs (Weyant 2017) mirroring the two approaches presented above; see Appendix C for details. Farmer et. al (2015) highlighted the importance of uncertainty, aggregation, and realistic damage functions, on which significant progress has been made as above, along with technological change considered below. IAMs and other whole-system models mostly assume optimisation, which makes it hard to represent cost-effective efficiency options, but they may better reflect associated 'rebound' at system level (Saunders 2021).

Cost-benefit IAMs utilise damage functions to derive a social cost of CO_2 emissions' (SCC - the additional cost to society of a pulse of CO_2 emissions. This metric accounts for the external damages for evaluating CO_2-emitting and mitigation investments. Obvious limitations arise from the difficulties in assessing an objective, globally-acceptable single estimate of climate change damages as discussed above; (Pezzey 2018) argues that agreement on this can never be expected.

Calculating cost-effective trajectories towards given goals typically uses more detailed process IAMs, which calculate the 'cost of carbon' trajectory that would be associated with a given climate target. Translated to a 'shadow price', this (like the SCC) also offers a benchmark to assess the cost-effectiveness of investments, as used by some governments and companies (1.6.2.4).

Care is required to clarify what is optimised (Dietz and Venmans 2019). Very long-run cost-benefit carries the challenges noted. Optimising a path towards a given temperature goal *by a fixed date* (e.g. 2100) gives time-inconsistent results backloaded to large, last-minute investment in negative emission technologies. 'Cost-effective' optimisations generate less initial effort than *equivalent* cost-benefit models (Gollier et al. 2019; Dietz and Venmans 2019) as they do not incorporate benefits of reducing impacts earlier.

1.6.2.2 Dynamic efficiency

'Efficient pathways' are affected by inertia and innovation. Inertia implies amplifying action on long-lived investments and infrastructure that could otherwise lock in emissions for many decades (Vogt-Schilb et al. 2018; Baldwin et al. 2020). To the extent that early action induces low carbon innovation, it 'multiplies' the optimal effort (for given damage assumptions), because it facilitates subsequent cheaper abatement. For example, a 'learning-by-doing' analysis concludes that early deployment of expensive PV was of net global economic benefit, due to induced innovation (Newbery (2018).

Research thus increasingly emphasises the need to understand climate transformation in terms of dynamic, rather than static, efficiency (Gillingham and Stock 2018). This means taking account of inertia, learning and various additional sources of 'path-dependence'. Including induced innovation in stylised IAMs can radically change the outlook (Acemoglu et al. 2012, 2016), albeit with limitations (Pottier et al. 2014); many more detailed-process IAMs now do (as reviewed in Yang et al. (2018) and Grubb et al. (2020))

These dynamic effects typically justify greater up-front effort (Kalkuhl et al. 2012; Bertram et al. 2015), including accelerated international diffusion (Schultes et al. 2018), and strengthen optimal initial effort in benefit-cost models (Grubb et al. 2020, Baldwin et al. 2020). Mercure et al. (2019) illustrate that different representations of innovation and financial markets together can explain why estimated impacts of mitigation on GDP can differ very widely (potentially even in sign), between different model types (Chapter 15).

1.6.2.3 Economic Instruments – pricing CO_2 and other greenhouse gas emissions

Stern's (2007b) reference to climate change as "the greatest market failure in history" highlights that damages inflicted by climate change are not properly costed in our economic decision-making. Economic perspectives emphasise the value of removing fossil-fuel subsidies, and pricing emissions to 'internalise' in economic decision-making the 'external' damages imposed by GHG emissions.

Economics generally sees carbon pricing (on principles which extends to other gases) as the most cost-effective way to reduce emissions, given certain assumptions. Stern (2015) identifies six market failures which complicate this logic, but along with most economists, insists that it remains important to effective policy.[5] Taking account of the wide uncertainties noted and combining approaches, the High Level Commission on carbon pricing (Stern and Stiglitz 2017) estimated an appropriate range as USD40-80/tCO_2 in 2020, rising steadily thereafter. The benefits from induced innovation may also affect carbon pricing design (Cason and de Vries 2019). In economic theory, negotiations on a common carbon price (or other common policies) may have benefits (less subject to 'free riding') than a focus on negotiating national targets (Cramton et al. 2017a).

Because carbon pricing creates winners and losers, it must also contend with distributional effects (domestic and international) and political viability (Klenert et al. 2018; Prinn et al. 2017), though (Rennkamp 2019) finds rich incumbents were often most vocal in using arguments about impacts on the poor. A major review (Maestre-Andrés et al. 2019) finds persistent distributional concerns, which may be addressed by combining redistribution of revenues with support for low carbon innovation. The realities of political economy have to date limited the implementation of carbon pricing, leading some social scientists to ask '*Can* we price carbon?' (Rabe 2018). The evidence of slowly growing adoption (World Bank 2019b) is "yes", but only slowly over time: a study of 66 implemented carbon pricing

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FOOTNOTE [5] Beyond GHG externalities these market failures are; inadequate R&D; failures in risk/capital markets; network effects creating coordination failures; wider information failures; and co-benefits.

policies show important effects of regional clustering, international processes, and seizing political windows of opportunity (Skovgaard et al. 2019).

Carbon pricing concepts can be important outside of the traditional market ('tax or trading') applications. A 'social cost of carbon' can be used to evaluate government and regulatory decisions, to compensate for inadequate carbon prices in actual markets, and by companies to reflect the external damage of their emissions and strategic risks of future carbon controls (Zhou and Wen 2020). An agreed 'social value of mitigation activities' could form a basic index for underwriting risks in low carbon investments internationally (Ghersi et al., in review). In practice, a wide range of policy instruments are used (Chapter 13).

1.6.3 Ethical approaches

Climate change has been described as "The Perfect Moral Storm" (Gardiner 2011) combining three 'tempests'. Its *global* dimension, in a world of sovereign states which have only fragmentary responsibility and control, makes it 'difficult to generate the moral consideration and necessary political will'. Its impacts are *intergenerational* but future generations have no voice in contemporary affairs, the usual mechanism for addressing distributional injustices: 'The future whispers while the present shouts.' He claims these challenges – together with the intrinsic inequity of wealthy big emitters impacting particularly poorer victims – are then exacerbated by as yet inadequate theoretical perspectives to 'allow moral sensitivity, compassion, transnational and transgenerational care, and other forms of ethical concern to rise to the surface and provide guidance for meaningful and effective climate action.'

1.6.3.1 Ethics and values

A large body of literature examines the critical role of values, ethics, attitudes, and behaviours as foundational frames for understanding and assessing climate action, sustainable development and societal transformation (IPCC WGIII (2015) Chapter 3). Most of this work is offered as a counter point or critique to mainstream literature's focus on safe-guarding of economic growth of nations, corporations and individuals (Castree 2017; Gunster 2017). These perspectives highlight the dominance of economic utilitarianism in western philosophical thought as a key driver for unsustainable consumption and global environmental change (Hoeing et al. 2015; Popescu 2016).

Entrenching alterative values that promote deep decarbonisation, environmental conservation and protection across all levels of society is viewed as foundational component of climate resilient and sustainable development and for achieving human rights, and a safe climate world (Jolly et al. 2015; Evensen 2015; Popescu 2016; Tàbara et al. 2019). While acknowledging the role of policy, technology, and finance, some scholars point out that 'managerialist' approaches that emphasise 'technical governance' and fail to challenge the deeper values that underpin societies will not secure the deep change required to avert dangerous climate change and other environmental challenges (Hartzell-Nichols 2014; Groves et al. 2016).

Several authors stress the centrality of a commitment to social justice, particularly regarding the distribution of responsibilities, rights, and mutual obligations between nations in navigating societal transformations (Patterson et al. 2018; Gawel and Kuhlicke 2017; Leach et al. 2018). Some scholars suggest that current approaches to climate action fail to match what is required by science because they tend to circumvent constraints on human behaviour, especially constraints on economic interest and activity. The alternative often proposed are governance models that are centred on environmental limits, planetary boundaries and the moral imperative to prioritise the poor in earth systems governance (Carley and Konisky 2020; Kashwan et al. 2020). With regards to global climate diplomacy, it has been suggested that a key requirement for stronger action lies in finding ways to moderate the economic interests of states which tend to be stronger than general interests for urgent climate action (Bain 2017). One concrete idea is to renew emphasis on trust and solidarity as foundations for global co-operation on climate change (Jolly et al. 2015).

Research focused on the national level has found that a sense of short-term interest among stakeholders could block thought reflection and deliberation needed for climate mitigation and adaptation planning (Hackmann 2016; Herrick 2018; Sussman et al. 2016; Schlosberg et al. 2017). It has been argued that proper management of self-perceptions guided by virtuous ethics and values is necessary to create situationally appropriate mitigation and adaptation policy regime at both national and international level (Herrick 2018). It has been noted that individuals, communities and countries that have strong altruistic concern about climate change impact on future generations tend to be more proactively engaged in climate mitigation and adaption. Similarly, literature suggests that self-transcendent values such as universalism and benevolence, and moderation are positively related to pro-environmental behaviours (Howell and Allen 2017; Jonsson and Nilsson 2014; Katz-Gerro et al. 2015; Braito et al. 2017).

Another strong theme in ethical perspectives to climate governance is the perceived need for a greater recognition of interdependence including the intimate relationship between humans and the non-human world (Hannis 2015; Howell and Allen 2017; Gupta and Racherla 2018), which is argued as offering an organising principle for enduring sustainable transformation. A key policy implication of this is moving away from valuing nature only in market and monetary terms to strongly incorporating existential and non-material value of nature in natural resource accounting (Neuteleers and Engelen 2015; Himes-Cornell et al. 2018; Shackleton et al. 2017).There has been increasing attention on ways to design climate policy frameworks to promote the reconciliation of ecological virtue with its emphasis on the collective, and individual freedoms, and personal autonomy (Kasperbauer 2016; Nash et al. 2017; Xiang et al. 2019). In such a framework, moderation, fairness, and stewardship are all understood and promoted as directly contributing to the good life. Such approaches are deemed vital to counteract the tendency to free ride and to achieve the much-needed behavioural restraints required to tackle the threat of climate change.

Some literature suggests that attention to emotions especially with regards to climate communication could help societies and individuals act in ways that focus less on monetary gain and more on climate and environmental sustainability (Bryck and Ellis 2016; Chapman et al., 2017; Nabi et al., 2018; Zummo et al. 2020).

1.6.3.2 Equity, just transition, and representation: international public choice across time and space

Climate change raises important equity issues, which underline concepts of 'just transition' (Harlan et al. 2015; Klinsky et al. 2017; Kemp-Benedict 2018). Equity perspectives highlight three asymmetries relevant for climate change (Okereke 2017; Okereke and Coventry 2016) (see also 1.5.6 above). The *asymmetry in contribution* highlights different contributions to climate change both in historical and current terms, and apply both within and between states as well as between generations (Caney 2016; Heyward and Roser 2016). *Asymmetry in impacts* highlight the fact that the damages will be borne disproportionately across countries, regions, communities, individuals and gender; moreover, it is often those that have contributed the least that stand to bear the greatest impact of climate change (Shi et al. 2016; IPCC 2015). *Asymmetry in capacity* highlights differences of power between groups and nations to participate in climate decision and governance.

If attention is not paid to consideration of equity, efforts designed to tackle climate change may end up exacerbating inequities among communities and between countries (Heffron and McCauley 2018). The implication is that to be sustainable in the long run, mitigation strategy should have a central place for consideration of justice. Some critical scholars suggest that injustice following from climate impacts and climate policies is asymptotic of a more fundamental structural injustice that characterise social relations. On this view, the starting point for tackling climate change is to address the deeper inequities within societies (Routledge et al. 2018).

Avoiding adverse distributional consequences of mitigation policies underpins emphasis upon the need for a 'just transition' (see subsection 4.5 in Chapter 4, and subsection 1.6.5 below). A just transition can be defined as a transition from a high-carbon economy to a low-carbon economy which is considered sufficiently equitable for the affected individuals, workers, communities, sectors, regions and countries (Newell and Mulvaney 2013; Jasanoff 2018). Thus, the aim is to ensure that nobody is left behind in the transition and several studies are conducted on national levels (Sovacool 2013; Sovacool et al. 2019). Different policy instruments can be used to make the transition to a low-carbon economy, but the choice of policy instrument to mitigate greenhouse gas emissions may give different distributional consequences (Millar et al. 2017; IPCC 2015). Measures to reduce the regressivity of carbon prices could include redistributing the tax revenue to favour of low-income groups, lump sum redistribution of tax revenues or differentiated carbon taxes (Metcalf 2009; Klenert and Mattauch 2016; Stiglitz 2019).

While just transition often has a national focus in the literature, a just transition also requires that the asymmetries between rich and poor countries do not increase. Climate change and climate policies affect countries and people differently, with the poor likely to be impacted more (section 1.5.6). A just transition will therefore be a transition where these distributional affects will be reduced. The choice of underlying ethical assumptions when defining welfare, will give very different outcomes when it comes to mitigation (Anthoff and Tol 2010). International climate finance in which rich countries finance mitigation and adaptation in poor countries is also important for reducing the asymmetries between rich and poor countries (1.5.4 and chapter 15).

Issues in intergenerational equity are concerned with the distribution between the present and future generation. One important aspect is discounting as mentioned in 1.6.2.1. Another approach to this debate has been to study the burdens on each generation that follow from the transition to low-carbon economies, in particular the possibility that no generation has to reduce their wellbeing from climate mitigation, see (IPCC 2015 Chapter 3). If climate mitigation is beneficial to the world from an intergenerational perspective, all generations should in principle be able to benefit from this by sharing this welfare benefit.

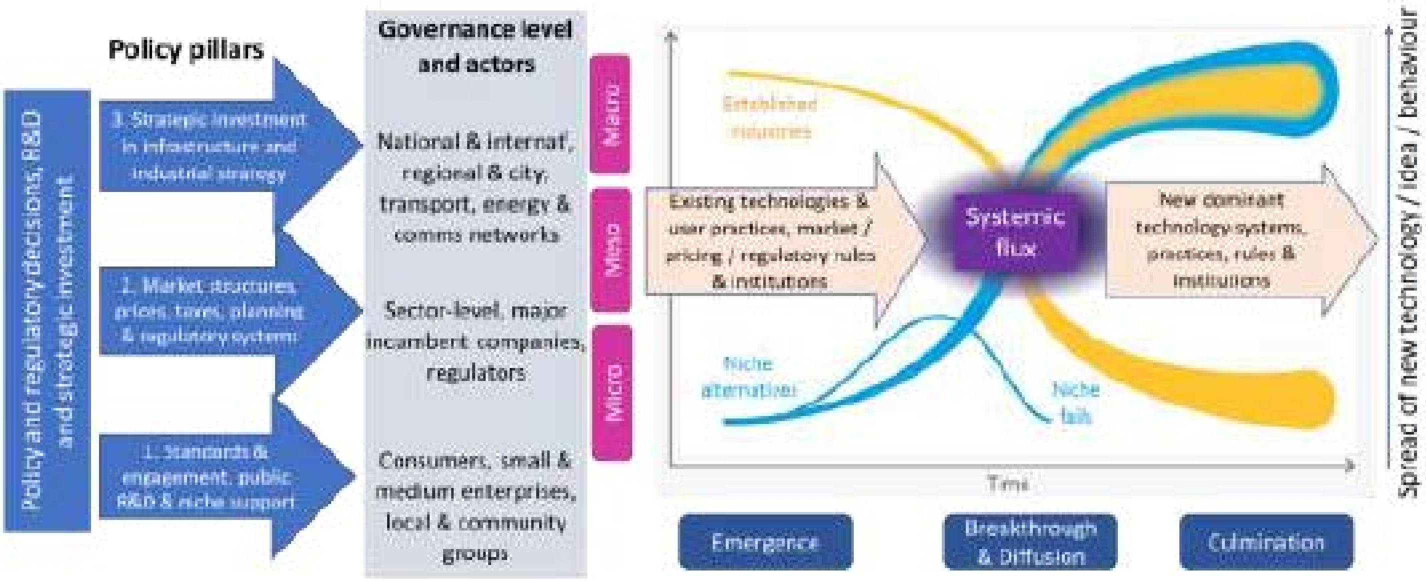
Thus, it should be possible to design mitigation policies that can benefit all generations. Suggestions have been made in the literature on how to do this such as a change today from real capital investments to investments in natural capital so that future generations will inherit less real capital but a better environment, or financing mitigation efforts today using governmental debt redeemed by future generations, see for instance (Broome 2012; Heijdra et al. 2006; Karp and Rezai 2014; Hoel et al. 2019). Note however that this approach violates the 'polluter pays principle' as the present generation does not take the burden of mitigation.

One strong implication of the discussion is the importance of policies to drive transitions - like those associated with deep decarbonisation - integrating consideration of distribution and justice, hence 'just transitions' is part of a larger framework of transition and transformation.

1.6.4 Analytic frameworks of transition and transformation

This report uses the term *transition* as the process, and *transformation* as the outcome or objective, of large-scale changes in technological, economic and social systems. Typically, new technologies, ideas and associated systems initially grow slowly in absolute terms, but may then 'take-off' in a phase of exponential growth as they emerge from a position of niche into mainstream diffusion, as indicated by the 'S-curve' growth in Figure 1.8. These dynamics arise from interrelationships between innovation (in technologies, companies and other organisations), markets, infrastructure and institutions, at multiple levels (Geels et al. 2017; Kramer 2018). Consequently, multiple disciplinary perspectives are needed (Turnheim et al. 2015; Geels et al. 2016; Hof et al. 2019).

In addition to dynamic economic perspectives (6.2.2), dedicated theories of technological transitions and social science perspectives emphasise the different actors in socio-economic systems. These highlight different processes that tend to dominate at different scales, across three main levels, with the most general terminology as *micro, meso and macro* (Rotmans et al. 2001) (Figure 1.8).



Note: The graphic panel illustrates growth of innovative technologies or practices, which if successful tend to emerge from niches into an S-shape dynamic of exponential growth, levelling off to linear growth before slowing as the market saturates. This displaces incumbent industries which decline, initially slowly but then at accelerating pace. The literatures typically identify three main levels (micro, meso and macro) with different characteristics. Transitions can be accelerated by policies appropriately targeted at these different levels. The middle (established 'socio-technical regime') tends to resist major change and may often have to undergo reform, driven by pressures from the other two levels. Incumbent industries have to adapt if they are to thrive within the growth of new systems.

Figure 1.8 Transition dynamics: levels, policies and processes

In contrast to standard economic perspectives with metrics of marginal or smooth change (e.g. elasticities), transition theories emphasise the non-linearity of transition processes, which explain for example persistent tendencies to underestimate the exponential pace of change now being observed in renewable energy (2, 6) and emerging in mobility (10).

A dominant theoretical framework has emerged as the 'Multi-Level Perspective' or MLP (Geels 2002; Grin et al. 2010). A common feature across theories is that transitions often start with niche alternatives (Grin et al. 2010; Köhler et al. 2019), which under some conditions can then break through to wider diffusion Sustainability requires purposeful actions at the different levels to foster the growth of sustainable technologies and practices.

Such transition frameworks explain how and why large-scale change in socio-technical systems is difficult, involving a co-evolutionary process between technologies, market demand, policy and culture at the different levels. This requires an interdisciplinary approach and analysis that addresses the non-linear dynamics, social, economic and environmental aspects of transitions to sustainability (Köhler et al. 2018; Cherp et al. 2018).

Levels, actors and decision-making domains. Socio-technical (ST) systems change is a co-evolutionary process between three main levels. In the middle (meso-level) is the established '*ST regime*', analysed as a set of interrelated sub-systems: scientific, engineering, market, policy and culture. At the micro level is an ecosystem of varied niche alternatives. Overlaying the ST regime structures is a macro 'landscape' level. Each level can involve different actors and decision-characteristics.

With some clear parallels, recent decades have seen broadening of economic perspectives and theories. Grubb et al. (2014, 2015) classify these into three 'domains of economic decision-making', which they associate with different branches of economic theory, respectively (1) *behavioural and organisational*; (2) *neoclassical and welfare*, and (3) *evolutionary and institutional*. These are presented not as alternatives but rather descriptions of processes which occur at different social and temporal scales, including to actors in climate finance and applied by (Hall et al. 2017) to studying 'adaptive finance' in the UK electricity transition

These interrelated 3-level perspectives help to clarify the agents and processes of transformative changes. There are significant differences (notably, the latter suggests governments as actors at the macro/strategic level, which in the MLP is typically seen as a broader exogenous 'landscape'). But both point to understanding the characteristics of different actors in society, namely individuals/communities; larger corporate organisations (public or private); and (mainly) public authorities, at different levels.

Complementary frameworks and methods. Related transition frameworks include *Strategic Niche Management* (Rip and Kemp 1998; Geels and Raven 2006), and *Transition Management* (Rotmans et al. 2001; Loorbach 2010) which applies MLP to practical application for governance and policy, discussed further in chapter 16.4. *Socio-ecological systems (SES)* analysis, developed from natural resources modelling, aims to model interlinked dynamics of social and ecological systems. (Christensen et al. 2011; Fletcher and Hilbert 2007; Haberl et al. 2016) - as complex, co-evolutionary adaptive processes in which macroscale patterns emerge from micro drivers of human behaviour, with variables and their interaction explicit. The technical transitions literature however has limited interactions with the developmental literature (Mealy and Hepburn 2020).

Regime stability and resistance to change. Stable ST regimes imply that basic rules and regulatory structures are known and reliable as a basis for decision-making by the principal economic actors (whether public or private). This provides foundations for the 'economically rational' tools of cost-benefit analysis, risk-return assessment, and cost and performance preferences of consumers, to dominate the behaviour of markets. The ST regime is a mature system and tends to resist change, because it has strong lock-in to its technologies and practices through established institutions, mature production systems, a supporting social culture and existing market structures. Radical innovations which do not fit these structures struggle, even if they provide potentially a more suitable alternative. Therefore, support for the niche alternatives is a vital aspect of policy and governance to support transitions to sustainability (Grin et al. 2010).

Forces for change. There are continual interactions between landscape, regime and niches. Consumer preferences evolve, and growing inequities arising from the accumulation of capital and power of incumbents can breed dissent, as will external damages which are not reflected in market prices. In addition to bottom-up innovations, niches can break through if external landscape developments 'create pressures on the regime that lead to cracks, tensions and windows of opportunity' (Geels 2010; Rotmans et al. 2001); an example is scientific knowledge about climate change putting sustained pressure on current regimes of energy production and consumption (Kuzemko et al (2016)).

Social transformation. There is always a social dimension to such transitions, which are part of a complete transformation. Key elements of social transformation include capacity to transform (Folke et al. 2010), planning, and interdisciplinarity (Woiwode 2013). The Second World War demonstrated the extent to which crises can motivate (sometimes positive) change across complex social and technical systems, e.g. as blockades forced transformative modernisation of the UK's agricultural system, which then doubled its productivity over 15 years (Roberts and Geels 2019b). Feola (2015) distinguished transformational adaptation (reactive) from societal transformation (proactive). The former seeks to find ways of responding to the growing scale of the impacts of climate change, whilst the latter seeks ways in which societies can reorient themselves (including their values and norms, see previous section) in a sustainable direction (Chapter 5).

Uncertainty and policy. Transitions can only be effectively governed by addressing the plurality of actors, processes and interests (Köhler et al. 2019). Different policies can influence actors at different levels, the foundations for "three pillars of policy" (Figure 2.8; Grubb et al.2014). One challenge is to balance support of existing socio-technical systems with strategic investment and institutional development of the emerging niches (e.g. the maintenance of energy provision and energy security with the development of renewables). Another is to manage decline of industries such as coal in power generation.

Integration: risks, tipping points and opportunities. Transition theories tend to come from very different disciplines and approaches compared to either economics or other social sciences, with less quantification for policy evaluation. Given inherent uncertainties, there are obvious risks (e.g. Alic and Sarewitz 2016). Business change management principles could be relevant to support positive social change (Stephan et al. 2016). For policy evaluation, transitions can be viewed as processes in which dynamic efficiency (1.6.2.2) dominates over static allocative efficiency, particularly in the context of potential 'positive intervention points' (Farmer et al. 2019). This may make an evaluation framework of *risks and opportunities* more appropriate than traditional cost-benefit (Mercure et al. in review), and (drawing on lessons from renewables and electric vehicles), create foundations for sector-based international 'positive sum cooperation' in climate mitigation (Sharpe and Lenton 2020).

1.6.5 Psychology and politics of changing course

Despite three decades of scientific warnings of ever-greater clarity and urgency, global emissions were still rising to 2018. Part of the reason can be ascribed to various factors which create 'carbon lock-in' (Unruh 2000); an interdisciplinary review by Seto et. al (2016) identifies a dozen main components organised into three types, as summarised in Table 1.1. Whilst each of the three analytic frameworks above sheds some light on these, this section focuses on additional psychological and institutional/political dimensions.

Table 1.1 Summary of three types of carbon lock-in and their key characteristics

Lock-in type	Key characteristics
Behavioural	- Lock-in through individual decision making (e.g., psychological processes) - Single, calculated choices become a long string of non-calculated and self-reinforcing habits - Lock-in through social structure (e.g., norms and social processes) - Interrupting habits is difficult but possible (e.g., family size, thermostat setting)
Institutional	- Powerful economic, social, and political actors seek to reinforce status quo that favours their interests - Institutions are designed to stabilise and lock in - Beneficial and intended outcome for some actors - Not random chance but intentional choice (e.g., support for renewable energy in Germany)
Infrastructural and technological	- Technological and economic forces lead to inertia - Long lead times, large investments, sunk costs, long-lived effects - Initial choices account for private but not social costs and benefits - Random, unintentional events affect final outcomes (e.g., QWERTY)

Source: Seto et al (2016)

1.6.5.1 Psychological and behavioural dimensions

Frustration with inadequate progress on mitigation motivates attention to the psychological 'faults of our rationality' (Bryck and Ellis (2016), p.642). AR5 emphasised that decision processes often include both deliberative ('calculate the costs and benefits') and intuitive thinking, the latter utilising emotion- and rule-based responses that are conditioned by personal past experience, social context, and cultural factors (e.g. (Kahneman 2003), and that laypersons tend to judge risks differently than experts - for example, 'intuitive' reactions are often characterised by biases to status quo and aversion to perceived risks and ambiguity (Kahneman and Tversky 2018).

Many of these features of human reasoning create 'psychological distance' from climate change (Spence et al. 2012; Marshall 2014). These can impede adequate personal responses, in addition to the collective nature of the problem, where such problems (as with COVID-19) can take the form of 'Unknown knowns' (Sarewitz 2020).

Behavioural biases and many other factors can also help explain why cost-effective energy efficiency measures or other mitigation technologies are not taken up as fast or as widely as the benefits might suggest: "People procrastinate; attention wanders. Peripheral factors subconsciously influence perceptions and decisions … we often resist actions with clear long-term benefits if they are unpleasant in the short run." Allcott and Mulainathan (2010, p. 1204). Modelling by Safarzyńska (2018) shows how behavioural factors change responses to carbon pricing relative to other instruments. A key perspective is to eschew 'either/or' between economic and behavioural frameworks, as the greatest effects often involve combining behavioural dimensions (e.g. norms, social influence networks, convenience and quality assurance) with financial incentives and information (Stern et al. 2010).

Randomised, controlled field trials in a representative population are increasingly used to predict the effects of behavioural interventions (Levitt and List 2008; McRae and Meeks 2016; Gillan 2017).

1.6.5.2 Socio-political and institutional approaches

Political and institutional dynamics shape climate change responses in important ways, not least because incumbent actors have frequently blocked climate policy (1.5.5). Institutional perspectives emphasise that their ability to do this - as well as the ability of others to foster low carbon transitions - are structured by specific institutional forms across countries (Lamb and Minx 2020). National institutions have widely been developed to promote traditionally fossil-fuel based sectors like electricity and transport as key to national economic development, contributing to carbon lock-in (Seto et al. 2016).

The influence of interest groups on policy-making varies across countries. Comparative political economy approaches distinguish different patterns of state-economy relations, showing that, as a generalisation, countries where interests are closely coordinated by governments ('coordinated market economies'), have been able to generate transformative change more than those where a more arms-length, even combative relationship between interest groups and governments ('liberal market economies') (Lachapelle and Paterson 2013; Meckling 2018; Ćetković and Buzogány 2016; Zou et al. 2016). 'Developmental states' often have the capacity for strong intervention but any low-carbon interventions may be overwhelmed by very rapid rates of economic growth.

The ability to generate successful climate policy is also affected by specific institutional features. These include levels and types of democracy (Povitkina 2018), electoral systems, or levels of institutional centralisation (federal vs unitary states, presidential vs parliamentary systems) (Lachapelle and Paterson 2013; Steurer and Clar 2018; Clulow 2019). Countries that have constructed an overarching architecture of climate governance institutions (e.g. cross-department and multilevel coordination, and semi-autonomous climate agencies), are more able to develop strategic approaches to climate governance needed to foster transformative change (Dubash, forthcoming).

A key feature of such institutions is how they respond to social movement and NGO action: NGO access to policy processes enables new ideas to be adopted, but too close an NGO-government relation stifles innovation and transformative action (Dryzek et al. 2003). NGO campaigns on fracking (Neville et al. 2019) or divestment (Mangat et al. 2018) have helped the adoption of new ideas, for example 'stranded assets', in policy arenas (Piggot 2018; Newell et al. 2020; Paterson 2020). Attempts to treat climate change as 'post-political' result in poor policy responses (Swyngedouw 2010). Some institutional innovations have more directly targeted enhanced public deliberation and participation, notably in citizens' climate assemblies (Howarth et al. 2020) and in the use of legal institutions to litigate against those opposing climate action (Peel and Osofksy 2020). This literature shows that transformative pathways are possible within a variety of institutional settings, although institutional innovation will be necessary everywhere, to pursue zero carbon transitions.

The pursuit of low carbon transitions therefore entails constructing coalitions that can sustain policy momentum over time. Policy stability is critical to enabling long-term investments in decarbonisation (Rietig and Laing 2017; Rosenbloom et al. 2018). Policy design can enable coalitions to form that generate policy feedback enabling further policy development to accelerate decarbonisation (Roberts et al. 2018).

To do this, policy design needs to generate concentrated benefits to coalition members so that they actively support the policy (Millar et al. 2020; Bernstein and Hoffmann 2018; Meckling 2019). Policy design may also provoke coalitions to oppose climate policy, as in the FT programme in Ontario (Stokes 2013) or the *gilets jaunes* protests against carbon taxation in France (Berry and Laurent 2019). Appropriate policy design for coalition-building will be different at different stages of the transition process (Meckling et al. 2017; Breetz et al. 2018).

Coalitions may also be sustained by overarching framings, especially to involve actors (e.g. NGOs) for whom the benefits of climate policy are not narrowly economic. While a just transitions frame can be viewed through ethical lenses (see 1.6.3.2), it can also be understood in terms of coalition-building. It emphasises the importance of low carbon transitions as ones that spread the economic benefits broadly, through 'green jobs', and the redistributive policies embedded in them both nationally and globally, most notably (Healy and Barry 2017; Winkler 2020).

1.6.6 Integrating Frameworks, co-benefits and 'Just Transitions'

In combination, these frameworks offer ways to understand the multiple perspectives, processes and challenges involved in accelerating mitigation alongside wider sustainable development. No one framework is adequate to such a broad-ranging goal, nor are single tools. Holistic analysis needs to bridge modelling, qualitative transition theories illuminated by case studies, and practice-based action research (Geels et al. 2016). Effective policy needs to build on understandings which combine economic efficiency, ethics and equity, the dynamics and processes of large-scale transitions, and the role of psychology and politics.

These analytic frameworks also point to arenas of potential synergies and trade-offs (when broadly known), and opportunities and risks (when uncertainties are greater), associated with mitigation. This offers theoretical foundations for mitigation strategies which can also generate co-benefits, by focusing on options for which the positives outweigh the negatives, or can be made to through smart policy.

One factor that emerges across several of these frameworks is the relevance of disaggregated perspectives: the diverse conditions and distributional consequences within and between countries; the natural resistance from incumbents (including employment concerns) in existing systems; and the underlying psychological and political obstacles to major transformations.

This motivates discourses on both avoiding stranded assets and enabling 'just transitions' (section 1.6.2.3; boxes TS-8 and TS-9). As noted, sufficient equity is not only an ethical issue but an enabler of deeper ambition for accelerated mitigation (Hoegh-Guldberg et al. 2019; Klinsky and Winkler 2018; Urpelainen and Van de Graaf 2018). The literature suggests that the perception of fairness influences the effectiveness of cooperative action (Winkler et al. 2018), and this can apply to affected individuals, workers, communities, sectors, regions and countries (Newell and Mulvaney 2013; Jasanoff 2018). A just transitions framing can also enable coalitions which integrate low carbon transformations with concerns for climate adaptation (Patterson et al. 2018). All this explains the emergence of 'just transition Commissions' in several of the more ambitious developed countries and complex social packages for coal phase-out in Europe (Chapter 4 section 4.5), as well as reference to the concept in the Paris Agreement and its emphasis in the Talanoa dialogue and Silesia declaration (1.2.2).

Whilst the broad concepts of Just Transition have roots going back decade, its specific realisation in context of climate change is of course complex: chapter (4.5) identifies at least eight distinct elements proposed in the literature, even before considering the international dimensions.

1.7 Multi-Level Governance

Previous sections have highlighted the complex interconnection between climate mitigation and the multiple factors that can both facilitate ambitious climate action and the diversity of analytical frames for interpreting the challenge, constructing and assessing response options. An overriding impression is that achieving the transition to a low carbon, climate resilient and sustainable world requires purposeful and largely coordinated planning and decisions at many scales of governance including municipal, subnational, national and global levels. This implies a need for multi-level governance of climate change to manage the complex economic, ethical, social and political systems required to address climate change. (Hooghe and Marks 2001; Betsill and Bulkeley 2006; Amundsen et al. 2010; Fuhr et al. 2018).

1.7.1 Concept of multi-level governance

Multi-level governance refers to the dispersion of governance across multiple levels of jurisdiction and decision-making (Hooghe and Marks 2003), including, regional, national and local, as well as trans-regional and trans-national levels. The concept emphasises that modern governance generally consists of, and is more flexible when there are, vertical linkages of governance processes at different levels. Choices and decisions made in several other aspects of life often have implications for climate change (Cole 2015; Jordan et al. 2018a).

The concept of governance encompasses the ability to plan and create the organisations needed (Güney 2017) to achieve a desired goal. It also illuminates that processes involved in making and implementing decisions on climate change is no longer the exclusive preserve of government actors but rather involve a range of non-nation state actors such as cities, businesses, and civil society organisations (AR5 Chapter 13, 13.3.1 and 13.5.2; Bäckstrand et al. 2017; Jordan et al. 2018b).

Although domestic and international climate governance have made some progress, climate change presents strains upon multilateral cooperation, to an extent, reflecting the 'globalisation paradox' (Rodrik 2011), an 'ineluctable tension' between national self-determination (sovereignty), democracy, and the economic benefits of globalisation.' With climate change, the trade-off is not only against the collective economic benefits of globalisation, but also the planetary risks arising from resistance to effective, co-operative governance. In this sense, governance is seen as "steering mechanisms" by which actors and institutions seek to shape action and outcomes (Dingwerth and Pattberg 2006). Good and effective governance and strong institutional arrangements are key to the success of the Paris Agreement and the 2030 Agenda for Sustainable Development (Gomez-Echeverri 2018).

1.7.2 Key factors of Multi-level governance

At the international level, implementation of the Paris Agreement is proceeding in parallel with other activities in increasingly diverse landscape of loosely coordinated institutions, constituting "regime complex" (Keohane and Victor 2011), and new cooperative efforts demonstrate an evolution in the shifting authority given to actors at different level of governance (Chan et al. 2018).

At national and subnational levels, climate change policies and actions are interwoven with and embedded in the context of much broader social, economic and political goals. The governance required to address climate change have to navigate the political, economic, ethical, and transitional dynamics perspectives outlined in this section 1.5 (Iacobuta et al. 2018).

There are some key factors as drivers or constraints of multi-level governance.

The first is power dynamics. Climate governance is driven mainly by power relations, operating at global, national and local context. Lacking of supranational authority to coordinate responses across sovereign states, effective global rules and institutions to govern climate change are more likely to emerge when those national interests can sufficiently align with the global interest (Victor 2011). Furthermore, widespread cooperation would only be expected when the additional (short term) costs implied by full cooperation are small, otherwise finding the temptation to 'free ride' on the actions of others to be fatal (Barrett 1994).

Economists have explored many solutions to such 'free-riding' and other coordination problems (Finus 2008), including the potential for joint climate-SD benefits (e.g. reduced air pollution) to motivate stronger action (e.g. Finus and Rübbelke 2011). Another strand considers the use of trade measures to encourage participation (Nordhaus 2015). However retaliatory measures could also make this unstable, irrespective of other considerations (Barrett and Dannenberg 2016). A focus on short-term national self-interest potentially makes the approach even more limited if it empowers national lobbies.

If self-interest is the only thing that drives state behaviour, combined with the traditional conception of climate change as entailing significant mitigation burdens for a long-term, collective, benefit (a "global public good"), the prospects for effective cooperation to solve the problem seem slim (Barrett and Dannenberg 2014). Nevertheless there are clear benefits from strengthened cooperation, including the synergies with more sustainable development (e.g. Mainali et al. 2018; Hoghton 2009).

A second key factor is the quality and role of institutions. The interests of states, businesses and other actors are powerful motivations for (in)action, but in the meantime, institutions at international and national levels have the ability to mediate and sustain cooperation based on equity and fair rules and outcomes. The challenge is how to engender high quality and equitable participation from all stakeholders mostly necessary to ensure broad-based and effective outcomes.

Equity has always been a multi-faceted principle that needs to be applied in a dynamic context in climate governance (Klinsky and Winkler 2018). The discussion of mitigation tends to bring a focus on "equitable burden sharing" with various metrics including responsibility, capacity, the right to development and measures of equality (Höhne et al. 2014), but equity debates have also widened to include distributional aspects of impacts, adaptation, and support mechanisms such as finance and technology.

The third factor is ideas, along with experimentation. Climate change governance is projected as self-consciously transformation at unprecedented scale and speed, seeking process involving a context of ideas and experimentation across scales of authority, jurisdiction and scales (Hildén et al. 2017; Laakso et al. 2017; Gordon 2018; van der Heijden 2018; Kivimaa et al. 2017). Through multiple largely uncoordinated searches for change and development in technologies, economies, value and behaviour at multiple places, it entails significant innovation in governance. The focus should be the ways how to foster transitions in energy, food, transport or other systems (Berkhout et al. 2010; Hoffmann 2011;

Bulkeley et al. 2015; Bernstein and Hoffmann 2018) and how to govern at a range of scales (local to global) and types of location (factories, schools, streets, etc). Such experiments represent a significant new source of innovation and capability-formation, linked to global knowledge and technology flows, which could reshape emergent socio-technical regimes and so contribute to alternative development pathways (Berkhout et al. 2010; Roberts et al. 2018; Turnheim and Kivimaa 2018; Lo & Castán Broto, 2019).

1.7.3 Innovation in Multi-level governance

Even before the Paris Agreement, climate change governance had evolved into a complex polycentric structure that spans from the global to national and sub-national levels, relying on both formal and informal networks and policy channels (Bulkeley et al. 2014; Jordan et al. 2015). Increased multi-level participation of subnational actors, along with a diversity of other actors contributed to an extremely polarised discussion and policy blockage rather than enabling policy innovation (Fisher and Leifeld 2019). Investigating the distribution of hard and soft power resources, capacities and power relations within and across different jurisdictional levels enables systematic understanding the role of power in climate governance (Marquardt 2017).

On one hand, such fragmented governance landscape may lead to coordination and legitimacy gaps undermining the regime (Nasiritousi and Bäckstrand 2019). On the other hand, given divided authority in world politics, diverse national preferences and pervasive suspicion of free riding, it should be sought how to incrementally deepen cooperation in a polycentric global system rather than seeking a single, integrated governance (Keohane and Victor 2016).

Rayner et al. (2019) emphasise that *implementing* the Paris Agreement will require different governance structures, beyond the multilateral system, adapted to sectoral needs. They find that whilst the power sector and international transport have plausible international governance, for other key sectors international governance is weak or non-existent. However, given the embedding of fossil energy not only in production but in consumption and thus daily life (Paterson 2007; Bulkeley et al. 2016; Szeman and Petrocultures Research Group), much of the resistance to climate policy is not necessarily only by incumbent industries but from threats to established habits and practices taking account of geography and domestic politics etc. (Chandrashekeran 2016). Governance helps to align and moderate the interests of actors as well as to shift perceptions, including the negative, burden-sharing narratives that often accompany discussion about climate action especially in international negotiations. Roberts et al. (2018) identify three roles for integrating governance with political economy and transition dynamics: '1) the role of coalitions in supporting and hindering acceleration; 2) the role of feedbacks, through which policies may shape actor preferences which, in turn, create stronger policies; and 3) the role of broader contexts (political economies, institutions, cultural norms, and technical systems) in creating more (or less) favourable conditions for deliberate acceleration.' These approaches go well beyond the normal focus of governance analysis on public authorities and companies and may serve to engage the wider public and international networks in imagining low carbon societies (e.g. Levy and Spicer, 2013; Milkoreit, 2017; Nikoleris, Stripple and Tenngart, 2017; Wapner and Elver, 2017; Sonesson et al., 2019; Fatemi, Okyere, Diko, & Kita, 2020).

1.8 Conclusions

Global conditions have changed substantially since the IPCCs Fifth Assessment in 2014. The Paris Agreement and the SDGs provided a new international context, but global intergovernmental cooperation has been under intense stress. Growing direct impacts of climate change are unambiguous and movements in society – in countries and transnational organisations at many levels – have grown. Global emissions growth had slowed but not stopped up to 2018/19, albeit with more diverse national trends. Growing numbers of countries have adopted 'net zero' emission goals, but 'nationally declared contributions' to 2030 are inconsistent with the agreed Paris goals. An unfolding technology revolution is making significant contributions in some countries, but as yet its global impact is limited.

Global climate change can only be tackled within, and if integrated with, the wider context of sustainable development, and related social goals including equity concerns. Countries and their populations have many conflicting priorities. Developing countries in particular have multiple urgent needs associated with earlier stages of sustainable development as reflected in the non-climate SDGs. Developed countries are amongst the most unsustainable in terms of overall consumption, but also face social constraints particularly arising from distributional impacts of climate policies.

Multiple frameworks of analytic assessment, adapted to the realities of climate change mitigation, are therefore required. We identified four main groups.. *Aggregate economic* frameworks – including environmental costs or goals, and with due attention to implied behavioural, distributional and dynamic assumptions - can provide insights about trade-offs, cost-effectiveness and policies for delivering agreed goals. Ethical frameworks are equally essential to inform both international and domestic discourse and decisions, including relating to international (and intergenerational) responsibilities, related financial systems, and domestic policy design in all countries. Explicit frameworks for analysing transition and transformation across multiple sectors need to draw on both socio-technical transition literatures, and those on social transformation. Finally, literatures on psychology, behaviour and political sciences can illuminate obstacles that have impeded progress to date, and suggest ways to overcome them.

No single analytical framework, or single discipline, on its own can offer a comprehensive assessment of climate change mitigation. Together they point to the relevance of growing literatures and discourses on 'just transitions', and the role of governance at multiple levels. Ultimately all these frameworks are needed to inform the decisions required to deepen and broaden the scattered elements of progress to date, and hence accelerate progress towards agreed goals and multiple dimensions of climate mitigation in the context of sustainable development.

1.9 Knowledge gaps

Despite huge expansion in the literature (Callaghan et al. 2020), knowledge gaps remain. Modeling gaps include analysis bringing together detailed physical and economic climatic impacts, whilst improving representation of transition dynamics and financial and distributional considerations. Interdisciplinary tools remain limited, and uncertainties remain concerning the role of new technological sets, international instruments, policy and political evaluation as well as long-term impacts of the COVID-19 pandemic Timmons Roberts et al. (2020) suggest 'four agendas' for research on the relationship of mitigation and wider well-being, based on empirics of countries in qualitatively different situations.

Policy evaluation and international cooperation pose knowledge gaps, for example, in the interactions between international agreements and local level instruments, constituencies and implementation. Literature on the potential for supply side agreement, in which producers agree to restrict the supply of fossil fuels (e.g., Asheim et al. (2019), is limited but gaining increasing academic attention.

Nature is under pressure both at land and at sea as demonstrated by declining biodiversity. Climate policies could increase the pressure on land and oceans (see SRCCL and SROCC); however, with plans for a major biodiversity summit, there has been insufficient attention to relationships between biodiversity and climate agreements, and associated policies particularly in the light of 'nature based solutions'; agriculture-related options remain under-researched.

The relative roles of short-term mitigation policies and long-term investments, including government and financial decision-making tools, remains inadequately explored. Strategic investments may include in city planning, public transport, EV charging networks, CCS etc. Understanding how international treaties can increase incentives to make such investments is all the more salient in the aftermath of COVID-19, on which research is necessarily young but rapidly growing. Finally, the economic, institutional and political strategies to close the gap between NDCs, actual implementations, and mitigation goals and needs – a gap supposed to be narrowed by the UNFCCC Global Stocktake – require much further research.

1.10 Roadmap to the Report

This Sixth Assessment Report covers Mitigation in five main parts (Figure 1), namely: introduction and frameworks; emission trends, scenarios and pathways; sectors; institutional dimensions including national and international policy, financial and technological mitigation drivers; and conclusions.

Chapters 2-5 cover the big picture trends, drivers and projections at national and global levels. (2) analyses emission trends and drivers to date. (3) presents the results of long-term global scenarios, including the projected economics and other characteristics of mitigation through to balancing of sources and sinks through the second half this century, and the implications for global temperature change and risks. (4) explores the shorter-term prospects including NDCs, and the possibilities for accelerating mitigation out to 2050 in the context of sustainable development at the national, regional and international scales. (5), a new chapter for IPCC Assessments, focuses upon the role of services and derived demand for energy and land use, and the social dimensions.

Chapters 6-12 examine sectoral contributions and possibilities for mitigation. (6) summarises characteristics and trends in the energy sector, specifically supply, including the remarkable changes in the cost of some key technologies since AR5; (7) examines the roles of AFOLU, drawing upon and updating the recent Special Report, including the potential tensions between the multiple uses of land; (8) presents a holistic view of the trends and pressures of urban systems, as both a challenge and an opportunity for mitigation for the first time in ARs; Chapters 9 and 10 then examine two sectors which entwine with, but go well beyond, urban systems: buildings (9) including construction materials and zero carbon buildings; and transport (10), including shipping and aviation and a wider look at mobility as a general service; (11) explores the contribution of industry, including supply chain developments, resource efficiency/circular economy, and the cross-system implications of decarbonisation for industrial systems; finally, in this section, (12) takes a cross-sectoral perspective and explores options which are inherently more cross-cutting, like the interactions of biomass energy, food and land, and aspects of mitigation not covered in the sector chapters including carbon dioxide removal.

Four chapters then look at cross-cutting issues in implementation and governance of mitigation. (13) explores national and sub-national policies and institutions, bringing together lessons of policies examined in the sectoral chapters, as well as insights from service and demand-side perspectives (5), and compares governance approaches including integrated analysis of sectoral and cross-sectoral governance and capacity-building, and the role and relationships of sub-national actors. (14) then considers the roles and status of international cooperation, including international institutions, sectoral agreements and multiple forms of international partnerships, and the ethics and governance challenges of Solar Radiation Modification. (15) explores investment and finance in mitigation and adaptation, including current trends, the investment needs for deep decarbonisation, and the complementary roles of public and private finance. This includes climate-related investment opportunities and risks (e.g. 'stranded assets'), linkages between finance and investments in adaptation and mitigation; and the impact of COVID-19. A new chapter on innovation (16) looks at technology development, accelerated deployment and global diffusion as systemic issues that hold potential for transformative changes, and the challenges of managing such changes at multiple levels including the role of international cooperation.

Finally, (17) seeks to bring together the threads of the report, in terms of Accelerating the transition in the context of sustainable development, including practical pathways for joint responses to climate change and sustainable development challenges. This include major regional perspectives, mitigation-adaptation interlinkages, and enabling conditions including the roles of technology, finance and cooperation for sustainable development.

Frequently asked questions

FAQ 1.1 What is climate change mitigation?

Climate change mitigation involves implementation of actions or activities that limit emissions of greenhouse gases from entering the atmosphere and/or reduce levels of existing greenhouse gases from the atmosphere. The actions that inform mitigation vary from implementation of new and improved renewable energy technologies to enhancing energy efficiency to addressing consumer practices and behaviour. Mitigation also includes actions that facilitate removal of gases from the atmosphere by greenhouse sinks. The ultimate goal of mitigation is to prevent anthropogenic greenhouse gas emissions to interfere with the climate system, in turn reducing the rate of climate change. In the context of mitigation, a range of sources of emissions (such as land-use change) are addressed. Effective mitigation strategies require an understanding of mechanisms that underpin release of emissions.

FAQ 1.2 What human activities cause Greenhouse Gas (GHG) emissions?

Anthropogenic GHGs such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (e.g. hydrofluorocarbons, perfluorocarbons, Sulphur hexafluoride) are released from various sources. CO_2 makes the largest contribution to global GHG emissions; fluorinated gases (F-gases) contribute a few per cent in CO_2 equivalents. However, F-gases have extremely long atmospheric lifetimes, some extending to tens of thousands of years. They have also grown at the fastest rate for any GHG (440%, (chapter 2)) and now contribute a few per cent in CO_2 equivalents.

The largest source of CO_2 is combustion of fossil fuels in energy conversion systems like boilers in electric power plants, engines in aircraft and automobiles, and in cooking and heating within homes and businesses. While most GHGs come from fossil fuel combustion, about one quarter comes from land-related activities like agriculture (mainly CH_4 and N_2O) and deforestation (mainly CO_2), with additional emissions from fossil fuel production (mainly CH_4), industrial processes (mainly CO_2, N_2O and F-gases), and municipal waste and wastewater (mainly CH_4) (2).. In addition to these emissions, black carbon – an aerosol that is, for example, emitted during incomplete combustion of fossil fuels – contributes to warming of the Earth's atmosphere.

FAQ 1.3 What do 'net zero emissions' and similar terms mean in relation to holding global temperature increase below a given level?

For the long-lived GHGs, like CO_2, N_2O, and some industrial gases (of which CO_2 dominates anthropogenic global warming), atmospheric concentrations and hence global warming will continue to increase as long as emissions exceed the processes of removal. Achieving a given long-term temperature goal thus requires (in the language of the Paris Agreement) a 'balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases.' This relates broadly to concepts of 'net zero emissions' and 'carbon (or climate) neutrality', terms which are defined more precisely in the IPCC Glossary (Annex A in this report).

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