Chapters

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Introduction and Framing

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Executive Summary

Global greenhouse gas (GHG) emissions continued to rise to 2019: the aggregate reductions implied by current Nationally Determined Contributions (NDCs) to 2030 would still make it impossible to limit warming to 1.5°C with no or limited overshoot, and would only be compatible with *likely limiting warming* below 2°C if followed by much steeper decline, hence limiting warming to either level implies accelerated mitigation actions at all scales (*robust evidence*, *high agreement*). Since the IPCC's Fifth Assessment Report (AR5), important changes that have emerged include the specific objectives established in the Paris Agreement of 2015 (for temperature, adaptation and finance), rising climate impacts, and higher levels of societal awareness and support for climate action. The growth of global GHG emissions has slowed over the past decade, and delivering the updated NDCs to 2030 would turn this into decline, but the implied global emissions by 2030 exceed pathways consistent with 1.5°C by a large margin, and are near the upper end of the range of modelled pathways which keep temperatures *likely* limit warming to 2°C (with >65% probability). Continuing investments in carbon-intensive activities at scale will heighten the multitude of risks associated with climate change and impede societal and industrial transformation towards low-carbon development. Meeting the long-term temperature objective in the Paris Agreement therefore implies a rapid turn to an accelerating decline of GHG emissions towards 'net zero', which is implausible without urgent and ambitious action at all scales. The unprecedented COVID-19 pandemic has had far-reaching impacts on the global economic and social system, and recovery will present both challenges and opportunities for climate mitigation. {1.2, 1.3, 1.5, 1.6, Chapters 3 and 4}

While there are some trade-offs, effective and equitable climate policies are largely compatible with the broader goal of sustainable development and efforts to eradicate poverty as enshrined in the 17 Sustainable Development Goals (SDGs) (*robust evidence*, *high agreement*). Climate mitigation is one of many goals that societies pursue in the context of sustainable development, as evidenced by the wide range of the SDGs. Climate mitigation has synergies and/or trade-offs with many other SDGs. There has been a strong relationship between development and GHG emissions, as historically both per capita and absolute emissions have risen with industrialisation. However, recent evidence shows countries can grow their economies while reducing emissions. Countries have different priorities in achieving the SDGs and reducing emissions as informed by their respective national conditions and capabilities. Given the differences in GHG emissions contributions, degree of vulnerabilities and impacts, as well as capacities within and between nations, equity and justice are important considerations for effective climate policy and for securing national and international support for deep decarbonisation. Achieving sustainable global development and eradicating poverty as enshrined in the 17 SDGS would involve effective and equitable climate policies at all levels from local to global scale. Failure to address questions of equity and justice over time can undermine social cohesion and stability. International cooperation can enhance efforts to achieve ambitious global climate mitigation in the context of sustainable development. {1.4, 1.6, Chapters 2, 3, 4, 5, 13 and 17}

The transition to a low-carbon economy depends on a wide range of closely intertwined drivers and constraints, including policies and technologies where notable advances over the past decade have 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*). Drivers for and constraints against low-carbon societal transition comprise *economic and technological* factors (the means by which services such as food, heating and shelter are provided and for whom, the emissions intensity of traded products, finance, and investment), *socio-political issues* (political economy, equity and fairness, social innovation and behaviour change), and *institutional factors* (legal framework and institutions, and the quality of international cooperation). In addition to being deeply intertwined all the factors matter to varying degrees, depending on the prevailing social, economic, cultural and political context. They often exert both push and pull forces at the same time, within and across different scales. The development and deployment of innovative technologies and systems at scale are important for achieving deep decarbonisation. In recent years, the cost of several low-carbon technologies has declined sharply, alongside rapid deployment. Over 20 countries have also sustained emission reductions, and many more have accelerated energy efficiency and/or land-use improvements. Overall, however, the global contribution is so far modest, at a few billion tonnes (tCO_2-eq) of avoided emissions annually. {1.3, 1.4, Chapters 2, 4, 13 and 14}

Accelerating mitigation to prevent dangerous anthropogenic interference within the climate system will require the 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 entails integration of multiple analytic frameworks. Approaches to risk assessment and resilience, established across IPCC Working Groups, are complemented by frameworks for probing the challenges in implementing mitigation. *Aggregate frameworks* include cost-effectiveness analysis towards given objectives, and cost-benefit analysis, both of which have been developing to take fuller account of advances in understanding risks and innovation, the dynamics of emitting systems and of climate impacts, and welfare economic theory including growing consensus on long-term discounting. *Ethical frameworks* consider the fairness of processes and outcomes which can help ameliorate distributional impacts across income groups, countries and generations. *Transition and transformation frameworks* explain and evaluate 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* outline the constraints (and opportunities) arising from human psychology and the power of incumbent interests. A comprehensive understanding of climate mitigation must combine these multiple frameworks. Together with established risk frameworks, collectively these help to explain potential synergies and trade-offs in mitigation, 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. {1.2.2, 1.7, 1.8}

The speed, direction and depth of any transition will be determined by choices in the, environmental, technological, economic, socio-cultural and institutional realms (*robust evidence*, *high agreement*). Transitions in specific systems can be gradual or rapid and disruptive. The pace of a transition can be impeded by 'lock-in' generated by existing physical capital, institutions, and social norms. The interaction between power, politics and economy is central in explaining why broad commitments do 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, as the impacts have become more salient. Both public and private financing and financial structures strongly affect the scale and balance of high- and low-carbon investments. COVID-19 has strained public finances, and integrating climate finance into ongoing recovery strategies, nationally and internationally, can accelerate the diffusion of low-carbon technologies and also help poorer countries to minimise future stranded assets. Societal and behavioural norms, regulations and institutions are essential conditions to accelerate low-carbon transitions in multiple sectors, whilst addressing distributional concerns endemic to any major transition. {1.3.3, 1.4, 1.8, Chapters 2, 4 and 15, and Cross-Chapter Box 1 in this chapter}

Achieving the global transition to a low-carbon, climate-resilient and sustainable world requires purposeful and increasingly coordinated planning and decisions at many scales of governance including local, sub-national, national and global levels (*robust evidence*, *high agreement*). Accelerating mitigation globally would imply strengthening policies adopted to date, expanding the effort across options, sectors, and countries, and broadening responses to include more diverse actors and societal processes at multiple – including international – levels. Effective governance of climate change entails strong action across multiple jurisdictions and decision-making levels, including regular evaluation and learning. Choices that cause climate change as well as the processes for making and implementing relevant decisions involve a range of non-nation state actors such as cities, businesses, and civil society organisations. At global, national and sub-national levels, climate change 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. Effective climate-governing institutions, and openness to experimentation on a variety of institutional arrangements, policies and programmes can play a vital role in engaging stakeholders and building momentum for effective climate action. {1.4, 1.9, Chapters 8, 15 and 17}

1.1 Introduction

This report (AR6 WGIII) aims to assess new literature on climate mitigation including implications for global sustainable development. In this Sixth Assessment Cycle the IPCC has also published three Special Reports,[1] all of which emphasise the rising threat of climate change and the implications for more ambitious mitigation efforts at all scales. At the same time, the Paris Agreement (PA) and the UN 2030 Agenda for Sustainable Development with its 17 Sustainable Development Goals (SDGs), both adopted in 2015, set out a globally agreed agenda within which climate mitigation efforts must be located. 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 the Fifth Assessment Report (AR5).

Since (IPCC 2014a), climate mitigation policies around the world have grown in both number and shape (Chapter 13). However, while the average rate of annual increase of CO_2 emissions has declined (Section 1.3.2), GHG emissions globally continued to rise, underlining the urgency of the mitigation challenge (Chapters 2 and 3). Over 20 countries have cut absolute emissions alongside sustained economic growth, but the scale of mitigation action across countries remains varied and is generally much slower than the pace required to meet the goals of the Paris Agreement (Sections 1.3.2 and 2.7.2). Per capita GHG emissions between countries even at similar stages of economic development (based on GDP per capita) vary by a factor of three (Figure 1.6) and by more than two on consumption basis (Section 2.3).

The Special Report on Global Warming of 1.5°C (SR1.5) underlined that humanity is now living with the 'unifying lens of the Anthropocene' (IPCC 2018a, pp. 52–53), that requires a sharpened focus on the impact of human activity on the climate system and the planet more broadly given 'planetary boundaries' (Steffen et al. 2015) including interdependencies of climate change and biodiversity (Dasgupta 2021). Recent literature assessed by Working Groups I and II of this AR6 underlines the urgency of climate action as cumulative CO_2 emissions, along with other greenhouses gases (GHGs), drives the temperature change. Across AR6, global temperature changes are defined relative to the period 1850–1900, as in SR1.5 and collaboration with WGI enabled the use of AR6-calibrated emulators to assure consistency across the three Working Groups. The remaining 'carbon budgets' (see Annex I: Glossary) associated with 1.5°C and 2°C temperature targets equate to about one (for 1.5°C) to three (for 2°C) decades of current emissions, as from 2020, but with significant variation depending on multiple factors including other gases (Figure 2.7, and Cross-Working Group Box 1 in Chapter 3). For an outline of the WGIII approach to mitigation scenarios, emission pathways implied by the Paris goals, and the timing of peak and 'net zero' (see Glossary and FAQ 1.3), see Section 1.5 and Chapter 3.

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 role of collective action in achieving urgent and ambitious global climate mitigation in the context of sustainable development, with attention to issues of equity and fairness as highlighted in several chapters of the report (Chapters 4, 5, 14, 15 and 17).

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 energy efficient technologies and behavioural changes (Chapters 5 and 9–11), can enable societies to provide services with much lower emissions. However, there are still significant differences in the ability to access and utilise low-carbon technologies across the world (Chapters 4, 15 and 16). New actors, including cities, businesses, and numerous non-state transnational alliances have emerged as important players in the global effort to tackle climate change (Chapters 13–16).

Along with continued development of concepts, models and technologies, there have been numerous insights from both the successes and failures of mitigation action that can inform future policy design and climate action. However, to date, policies and investments are still clearly inadequate to put the world in line with the PA's aims (Chapters 13 and 15).

The greater the inertia in emission trends and carbon-intensive investments, the more that CO_2 will continue to accumulate (Hilaire et al. 2019; IPCC 2019a). Overall, the literature points to the need for a 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 chapter introduces readers to the AR6 WGIII Report and provides an overview of progress and challenges, in three parts. Part A (1.1–1.5) introduces the climate mitigation challenge, provides key findings and developments since previous assessment, and reviews the main drivers for, and constraints against accelerated climate action. Part B (1.6–1.8) provides an assessment of the key frameworks for understanding the climate mitigation challenge covering broad approaches such as sustainable development and more specific economic, political and ethical framings. Part C (1.9–1.12) briefly highlights the role of governance for steering and coordinating efforts to accelerate globally effective and equitable climate mitigation, notes the gaps in knowledge that have been identified in the process of assessment, and provides a road map to the rest of the report.

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[1] These are the Special Report on Global Warming of 1.5°C (SR1.5) (IPCC 2018b); the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (IPCC 2019b); and the Special Report on Climate Change and Land (SRCCL) (IPCC 2019c).

1.2 Previous Assessments

1.2.1 Key Findings from Previous Assessment Reports

Successive WGIII 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 2018b, 2019b, 2019c) are summarised below.

The AR5 projected that in baseline scenarios (i.e., based on prevailing trends without explicit additional mitigation efforts), agriculture, forestry and other land use (AFOLU) would be the only sector where emissions could fall by 2100, with some CO_2 removal (IPCC 2014b, p. 17). Direct CO_2 emissions from energy were projected to double or even triple by 2050 (IPCC 2014b, p. 20) 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. The AR5 noted that mitigation effort and the costs associated with ambitious mitigation differ significantly across countries, and in 'globally cost-effective' scenarios, the biggest reductions (relative to projections) occur in the countries with the highest future emissions in the baseline scenarios (IPCC 2014b, p. 17). 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 (IPCC 2014b, p. 18).

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 2018b, 2019b, 2019c). 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 examined pathways limiting warming to 1.5°C, compared to the historical baseline of 1850–1900, finding that 'in pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030, reaching net zero around 2050' (2045–2055 interquartile range); with 'overshoot' referring to higher temperatures, then brought down by 2100 through 'net negative' emissions. It found this would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (*high confidence*) (IPCC 2018b).

The SR1.5 found that the Nationally Determined Contributions (NDCs) as declared under the Paris Agreement (PA) would not limit warming to 1.5°C; despite significant updates to NDCs in 2020/21, this remains the case, although delivery of these more ambitious NDCs would somewhat enhance the prospects for staying below 2°C (Section 1.3.3).

The AR5 WGIII 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, technology availability, and 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 three to four 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, which highlights the need to consider trade-offs alongside benefits. Examples include synergies between climate policy and improved air quality, reducing premature deaths and morbidity (IPCC 2014b, Figure SPM.6) (AR6 WGI Sections 6.6.3 and 6.7.3), 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 (IPCC 2019a).

Previous Assessment Reports (ARs) have detailed 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 (Figure 2.14), though the magnitude of these emissions can vary widely between countries. These – together with the energy and urban systems which feed and shape end-use sectors – define the sectoral chapters in this AR6 WGIII report.

Estimates of emissions associated with production and transport of internationally traded goods were first presented in AR5 WGIII, which estimated the 'embodied emission transfers' from upper-middle-income countries to industrialised countries through trade at about 10% of CO_2 emissions in each of these groups (IPCC 2014a, Figure TS.5). The literature on this and discussion on their accounting has grown substantially since then (Chapters 2 and 8).

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. *Inter alia*, international cooperation to tackle ozone depletion and acid rain offer useful examples. The 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. (IPCC 2014a 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). International cooperation and collective action on climate change alongside local, national, regional and global policies will be crucial to solve the problem, and this report notes cooperative approaches beyond simple 'global commons' framings (Chapters 13 and 14).

The AR5 (all Working Group reports) also underlined that climate policy inherently involves risk and uncertainty (in nature, economy, society and individuals). To help evaluate responses, 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 have pros and cons, and have been further developed in subsequent literature and in AR6 (Sections 1.2.2 and 1.7).

Recent assessments (IPCC 2014a, 2018b) 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, lifestyle 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 underlying drivers of energy demand, food choices and social aspects.

1.2.2 Developments in Climate Science, Impacts and Risk

The assessment of the Physical Science Basis (IPCC AR6 WGI) 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 (AR6 WGI SPM A.2, B.3 and B.4). Oceanic changes include rising sea level, acidification, deoxygenation, and changing salinity (WGI 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.

In defining the objective of international climate negotiations as being to 'prevent dangerous anthropogenic interference' (UNFCCC 1992, Art. 2), the UNFCCC underlines the centrality of risk framing in considering the threats of climate change and potential response measures. 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.

In AR6 the IPCC employs a common risk framing across all three working groups and provides guidance for more consistent and transparent usage (AR6 WGI Cross-Chapter Box 3 in Chapter 1; AR6 WGII Section 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' (Annex I), encompassing risks from both potential impacts of climate change and human responses to it (Reisinger et al. 2020). The risk framing includes steps for identifying, evaluating, and prioritising current and future risks; for understanding the interactions among different sources of risk; for distributing effort 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 mischaracterise risks and pay insufficient attention to the potential for surprises (Weitzman 2011; Aven and Renn 2015; Stoerk et al. 2018). Concepts of resilience and vulnerability provide overlapping, alternative entry points to understanding and addressing the societal challenges caused and exacerbated by climate change (AR6 WGII, Section 1.2.1).

The AR6 WGII devotes a full chapter (Chapter 17) to 'Decision-Making Options for Managing Risk', detailing the analytic approaches and drawing upon the *Cynefin* classification of *known, knowable, complex* and *chaotic* systems (Section 17.3.1). 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 (AR6 WGII Chapter 17 Cross-Chapter Box DEEP; also Marchau et al. (2019); Doukas and Nikas (2020)).

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' (AR6 WGII, Cross-Working Group Box ECONOMIC in Chapter 16, and Section 16.6.2). This, along with other developments strengthen foundations for calculating a 'social cost of carbon'. This informs a common metric for comparing different risks and estimating benefits compared to the costs of GHG reductions and other risk-reducing options (Section 1.7.1); emissions mitigation itself also involves multiple uncertainties, which alongside risks can also involve potential opportunities (Section 1.7.3).

Simultaneously, the literature increasingly emphasises the importance of multi-objective risk assessment and management (e.g., representative key risks in AR6 WGII Chapter 16), which may or may not correlate with any single estimate of economic value (AR6 WGII, Section 1.4.1; IPCC risk guidance). Given the deep uncertainties and risks, the goals established (notably in the Paris Agreement and SDGs) reflect negotiated outcomes informed by the scientific assessment of risks.

1.3 The Multilateral Context, Emissions Trends and Key Developments

Since AR5, there have been notable multilateral efforts which help determine the context for current and future climate action. This section summarises key features of this evolving context.

1.3.1 The 2015 Agreements

In 2015 the world concluded four major agreements that are very relevant to climate action. These include: the Paris Agreement under 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 Sustainable Development Goals (SDGs).

The Paris Agreement (PA). The Paris Agreement 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), alongside goals for adaptation (IPCC AR6 WGII), and 'aligning financial flows' (see 'finance goal', below) , so as 'to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty.'

The Paris Agreement is predicated on encouraging progressively ambitious climate action from all countries on the basis of Nationally Determined Contributions (Clémençon 2016; Rajamani 2016). 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 (Bodansky 2016; Falkner 2016a). The PA entered into force in November 2016 and as of February 2021 it already had 190 Parties (out of 197 Parties to the UNFCCC).

The PA also underlines 'the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances' (PA Art. 2, para. 2), and correspondingly that 'developed country Parties should continue taking the lead by undertaking economy-wide absolute emission reductions'. It states that 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.

In order to achieve the its long term temperature goal, the Paris Agreement aims 'to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century' (PA Art. 4 para. 1). The PA provides for five-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 Art. 14). The first global stocktake is scheduled for 2023 (PA Art. 14, para. 3).

The Paris Agreement's finance goal aims to make 'finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development' (PA Art. 2.1C). In keeping with the acknowledged context of global sustainable development and poverty eradication, and the corresponding aims of aligning finance and agreed differentiating principles as indicated above, '…the developed country parties are to assist developing country parties with financial resources' (PA Art. 9). The Green Climate Fund (GCF), an operating entity of the UNFCCC Financial Mechanism to finance mitigation and adaptation efforts in developing countries (GCF 2020), was given an important role in serving the Agreement and supporting PA goals. The GCF gathered pledges worth USD10.3 billion, from developed and developing countries, regions, and one city (Paris) (Antimiani et al. 2017; Bowman and Minas 2019). Financing has since increased but remains short of the goal to mobilise USD100 billion by 2020 (Chapter 15).

Initiatives contributing to the Paris Agreement goals include the Non-State Actor Zone for Climate Action (NAZCA: now renamed as Global Climate Action) portal, launched at COP20 (December 2014) in Lima, Peru, to support city-based actions for mitigating climate change (IISD 2015) and Marrakech Partnership for Global Climate Action which is a UNFCCC-backed series of events intended to facilitate collaboration between governments and the cities, regions, businesses and investors that must act on climate change.

Details of the Paris Agreement, evaluation of the Kyoto Protocol, and other key multilateral developments since AR5 that are relevant to climate mitigation including the CORSIA aviation agreement adopted under ICAO, the IMO shipping strategy, and the Kigali Amendment to the Montreal Protocol on hydrofluorocarbons (HFCs), are discussed in Chapter 14.

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, peace, prosperity, partnerships and the planet. While climate change is explicitly listed as SDG 13, the pursuit of the implementation of the UNFCCC is relevant for a number of other goals including SDG 7 (clean energy for all), SDG 9 (sustainable industry), and SDG 11 (sustainable cities), SDG 12 (responsible consumption and production) as well as those relating to life below water (SDG 14) and on land (SDG 15) (Biermann et al. 2017). Mitigation actions could have multiple synergies and trade-offs across the SDGs (Pradhan et al. 2017) (Chapter 17) and their net effects depend on the pace and magnitude of changes, the specific mitigation choices and the management of the transition. This suggests that mitigation must be pursued in the broader context of sustainable development as explained in Section 1.6.

Finance. The Paris Agreement's finance goal (above) reflects a broadened focus, beyond the costs of climate adaptation and mitigation, to recognising that a structural shift towards low-carbon climate-resilient development pathways requires large-scale investments that engage the wider financial system (Sections 15.1 and 15.2.4). The SR1.5 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' (Rozenberg and Fay 2019).

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 cooperation and provides a forum for discussing the solutions to common challenges faced by developing countries (Section 15.6.4).

Alongside this, private and blended climate finance is increasing but is still short of projected requirements consistent with Paris Agreement goals (Section 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 (Section 15.6.3). To date, the most significant governance development is the Financial Stability Board's Task Force on Climate-related Financial Disclosures (TCFD) and its recommendations that investors and companies consider climate change risks in their strategies and capital allocation, so investors can make informed decisions (TCFD 2018), welcomed by over 500 financial institutions and companies as signatories, albeit with patchy implementation (Sections 1.4. 4 and 15.6.3).

Talanoa Dialogue and Just Transition. As mandated at Paris COP21 and launched at COP23, the 'Talanoa Dialogue' (UNFCCC 2018a) emphasised holistic approaches across multiple economic sectors for 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). This underlined the importance of aiming for Just Transitions in reducing emissions, at the same time preserving livelihoods and managing economic risks for countries and communities that rely heavily on emissions-intensive technologies for domestic growth (Markkanen and Anger-Kraavi 2019), and for maintaining ecosystem integrity through nature-based solutions.

1.3.2 Global and Regional Emissions

Global GHG emissions have continued to rise since AR5, though the average rate of emissions growth slowed, from 2.4% (from 2000–2010) to 1.3% for 2010–2019 (Figure 1.1). After a period of exceptionally rapid growth from 2000 as charted in AR5, global fossil fuel- and industry-related (FFI) CO_2 emissions almost plateaued between 2014 and 2016 (while the global economy continued to expand (World Bank 2020), but increased again over 2017–19, the average annual growth rate for all GHGs since 2014 being around 0.8% yr^{-1} (IPCC/EDGAR emissions database; see also Chapter 11, Figure 11.2)). Important driving factors include population and GDP growth, as illustrated in panels (b) and (c) of Figure 1.1 respectively. The pause in emissions growth reflected the interplay of strong energy efficiency improvements and low-carbon technology deployment, but these did not expand fast enough to offset the continued pressures for overall growth at global level (UNEP 2018a; IEA 2019a). However, since 2013/14, the decline in global emissions intensity (GHG/GDP) has accelerated somewhat, and global emissions growth has averaged slightly slower than population growth (Figure 1.1d), which if sustained would imply a peak of global CO_2 (GHG) emissions per capita, at about 5 tCO_2 per person (7 tCO_2-eq per person) respectively.

Due to its much shorter lifetime, methane has a disproportionate impact on near-term temperature, and is estimated to account for almost a third of the warming observed to date (AR6 WGI SPM; AR6 WGIII Chapter 2, Figure 2.4). Methane reductions could be particularly important in relation to near- and medium-term temperatures, including through counteracting the impact of reducing short-lived aerosol pollutants which have an average cooling effect.[2]

The land-use component of CO_2 emissions has different drivers and particularly large uncertainties (Figures 2.2 and 2.5), hence is shown separately. Also, compared to AR5, new evidence showed that the AFOLU CO_2 estimates by the global models assessed in this report are not necessarily comparable with national GHG inventories, due to different approaches to estimate the 'anthropogenic' CO_2 sink. Possible ways to reconcile these discrepancies are discussed in Chapter 7.

Regional trends have varied. Emissions from most countries continued to grow, but in absolute terms, 32 countries reduced energy and industry CO_2 emissions for at least a decade, 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).[3] In total,

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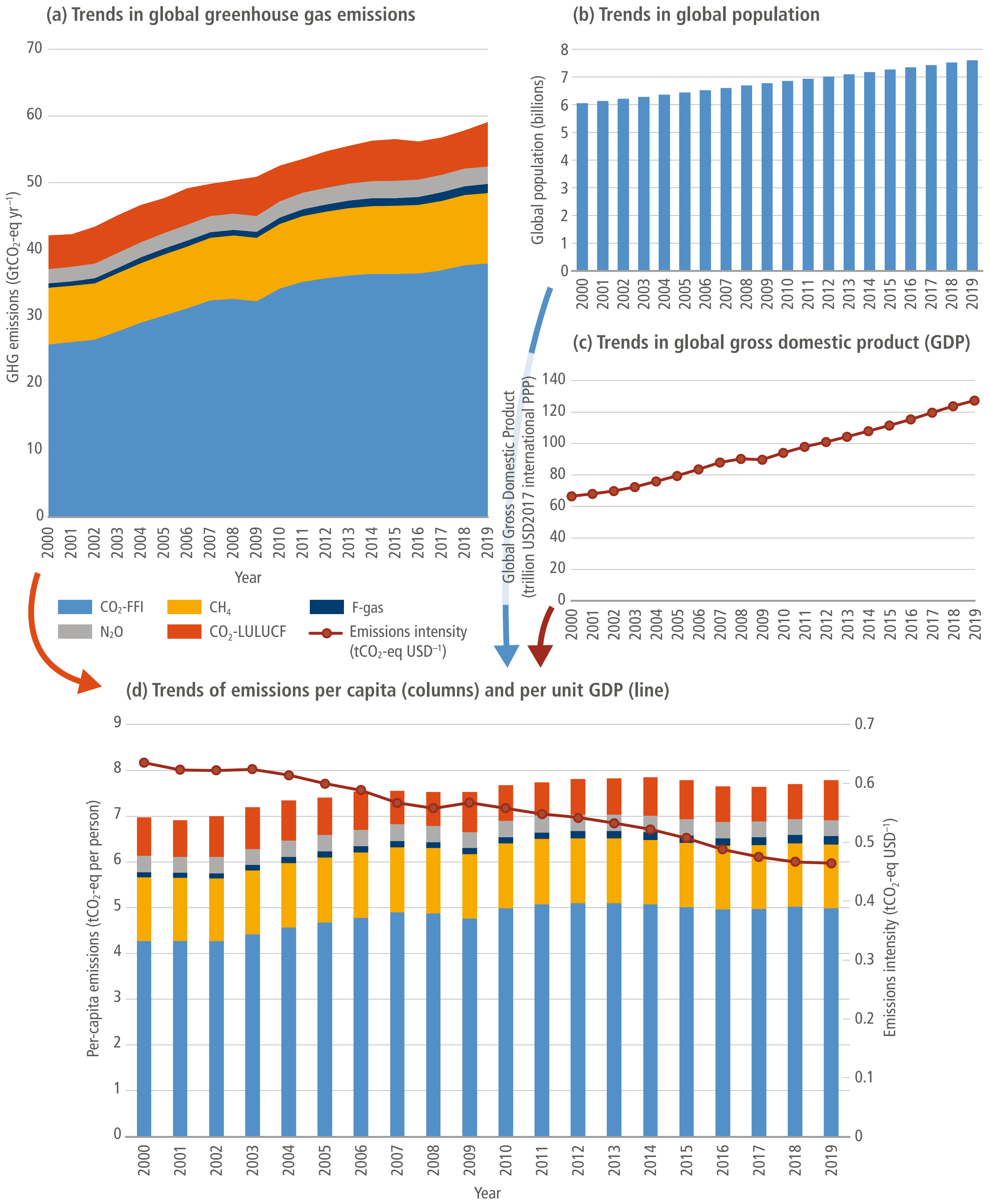
[2] Indeed, cooling effects of anthropogenic aerosols (organic carbon, black carbon, sulphates, nitrates), which are also important components of local air pollution (Myhre et al. 2013) (AR6 WGI SPM D1.7) may in global average be of similar magnitude to warming from methane at present. Mitigation which reduces such aerosol masking could thereby increase global temperatures, and reducing methane emissions would offset this much more rapidly than reducing CO_2 because of its relatively short lifetime, with the combined effects which could counterbalance each other (AR6 WGI SPM D1.7). Methane is thus particularly important in determining whether or when 1.5˚C is reached for example.

[3] With some exclusions for countries which were very small or undergoing economic collapse: fossil-fuel-and industry (CO_2-FFI) emissions in 2018 were below 2008 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 Section 2.2.3, as analysed in Lamb et al. (2021). An earlier study found 18 developed countries that had reduced CO_2-FFI emissions over 2005–2015 (Le Quéré et al. 2019). Decomposition analysis of national trends in Xia et al. (2021), identified 23 industrialised countries (UNFCCC Annex I) with CO_2-FFI emissions in 2017 lower than in 2000 (Figure 1.3), of which 22 had increased GDP over the period. 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 for CO_2-FFI up to 2018 (Section 2.3). See Chapter 3 for reduction rates associated with 1.5°C and 2°C.



(a) Trends in global greenhouse gas emissions

(b) Trends in global population

(c) Trends in global gross domestic product (GDP)

(d) Trends of emissions per capita (columns) and per unit GDP (line)

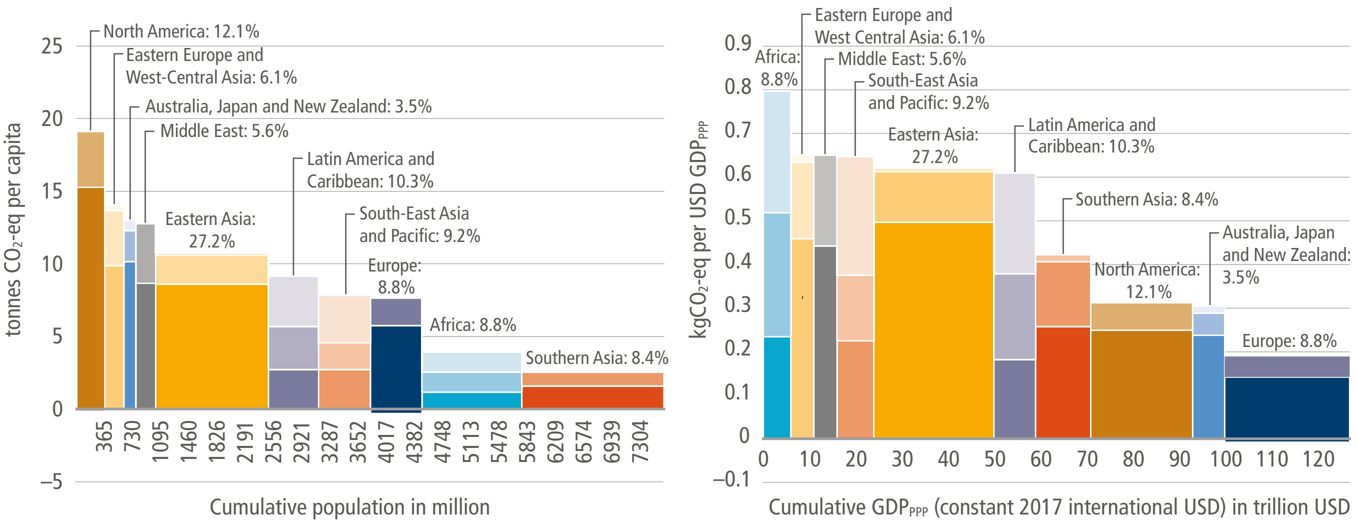
Figure 1.1 | Global emission trends since 2000 by groups of gases: absolute, per capita, and intensity. Note: shows CO_2 from fossil fuel combustion and industrial processes (FFI); CO_2 from agriculture, forestry and other land use (AFOLU); methane (CH_4); nitrous oxide (N_2O); fluorinated gases (F-gases). Gases reported in $GtCO_2$-eq converted based on AR6 global warming potentials with a 100-year time horizon (GWP100).

developed country emissions barely changed from 2010, whilst those from the rest of the world grew.

Figure 1.2 shows the distribution of regional emissions (a) per capita and (b) per GDP based on purchasing power parity (GDP_{ppp}) of different country groupings in 2019. Plotted against population and GDP respectively, the area of each block is proportional to the

(a) Distribution of regional emissions (territorial, 2019): CO_2-FFI (bottom-bar above x-axis, darker), plus non-CO_2 GHGs (top bar, lighter), plus CO_2-LULUCF (top-most or below-axis (negative) bars)

(b) Distribution of regional emissions (territorial, 2019): CO_2-FFI (bottom-bar above x-axis, darker), plus non-CO_2 GHGs (top bar, lighter), plus CO_2-LULUCF (top-most or below-axis (negative) bars)



(c) Distribution of regional emissions (consumption-based footprint, 2018): CO_2-FFI only

(d) Distribution of regional emissions (consumption-based footprint, 2018): CO_2-FFI only

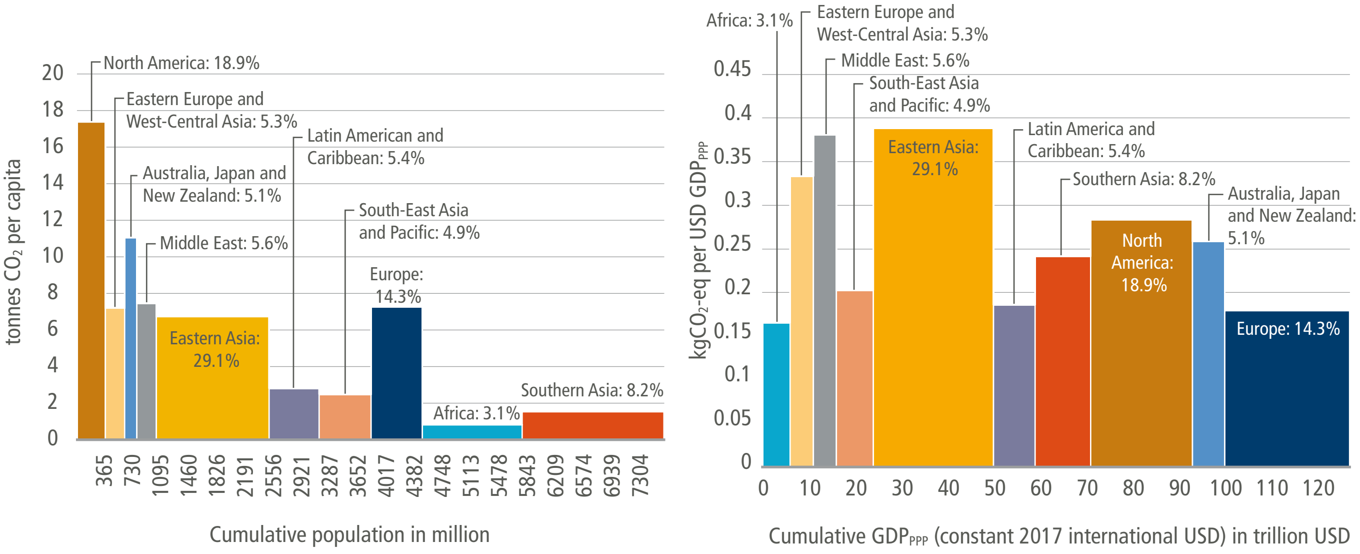


Figure 1.2 | Distribution of regional greenhouse gas (GHG) emissions for 10 broad global regions according to territorial accounting (panels (a) and (b), GHG emissions) and consumption-based accounting (panels (c) and (d), CO_2-FFI emissions only). GHG emissions are categorised into: fossil fuel and industry (CO_2-FFI); land use, land-use change and forestry (CO_2-LULUCF); and other greenhouse gases (methane, nitrous oxide and F-gas – converted to 100-year global warming potentials). Per-capita GHGs for territorial **(panel a)** and CO_2-FFI emissions vs population for consumption-based accounting **(panel c)**. Panels **(b)** and **(d)**: GHG emissions per unit GDP_{ppp} vs GDP_{ppp}, weighted with purchasing power parity for territorial accounting (panel b), CO_2-FFI emissions per unit GDP_{ppp} for consumption-based accounting (panel d). The area of the rectangles refers to the total emissions for each regional category, with the height capturing per-capita emissions (panels a and c) or emissions per unit GDP_{ppp} (panels (b) and (d)), and the width proportional to the population of the regions and GDP_{ppp}. Emissions from international aviation and shipping (2.4% of the total GHG emissions) are not included.

region's emissions. Compared to the equivalent presentations in 2004 (AR4 WGIII Figure SPM.3) and 2010 (AR5 WGIII Figure 1.8), East Asia now forms substantially the biggest group, whilst at about 8 tCO_2-FFI (/10 tCO_2-eq all GHGs) per person, its emissions per capita remain about half that of North America. In contrast, a third of the world's population, in Southern Asia and Africa, emit on average under 2 (2.5 tCO_2-eq) per person, little more than in the previous assessments. Particularly for these regions, there continue to be substantial differences in GDP, life expectancy and other measures of well-being (Figure 1.6).

Emissions per unit GDP are much less diverse than per capita and have also converged significantly. Poorer countries tend to show higher 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.

Many developed country regions are net importers of energy-intensive goods, and emissions are affected by the accounting of such 'embodied emissions'. Panels (c) and (d) show results (only available for CO_2-FFI, to 2018) on the basis of consumption footprints which include emissions embodied in traded goods. This makes modest changes to the relative position of different regions (for further discussion see Section 2.3).

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 USD1.90 a day), reflecting large income inequality (Laborde Debucquet and Martin 2017; Rozenberg and Fay 2019). Diffenbaugh and Burke (2019) find that global warming already has increased global economic inequality, even if between-country inequalities have decreased over recent decades. The distributional implications between regional groups in the Shared Socio-economic Pathways (SSPs) diverge according to the scenario (Frame et al. 2019).

An important recent development has been commitments by many countries, now covering a large majority of global emissions, to reach net zero CO_2 or greenhouse gas emissions (Chapter 3).[4] Furthermore, globally, net zero targets (whether CO_2 or GHG) have been adopted by about 823 cities and 101 regions (Chapter 8).

1.3.3 Some Other Key Trends and Developments

The COVID-19 pandemic profoundly impacted economy and human society, globally and within countries. As detailed in Cross-Chapter Box 1 in this chapter, some of its impacts will be long-lasting, permanent even, and there are also lessons relevant to climate change. The direct impact on emissions projected for rest of this decade are modest, but 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.

The COVID-19 aftermath consequently also changes the economic context for mitigation (Sections 15.2 and 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 'economic multiplier' benefits, especially if they help to build the industries and infrastructures for further clean growth (Hepburn et al. 2020). However, the capability to mobilise low-interest finance varies markedly across countries and large public debts – including bringing some developing countries close to default – undermine both the political appetite and feasibility of large-scale clean investments. In practice 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 (Cross-Chapter Box 1 in this chapter).

Cross-Chapter Box 1 | The COVID-19 Crisis: Lessons, Risks and Opportunities for Mitigation

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The COVID-19 pandemic triggered the deepest global economic contraction as well as CO_2 emission reductions since the Second World War (Le Quéré et al. 2020b), (AR6 WGI, Box 6.1) (Section 2.2.2.1). While emissions and most economies are expected to rebound in 2021–2022 (IEA 2021), some impacts of the pandemic (e.g., aspects of economy, finance and transport-related emission drivers) may last far longer. COVID-19 pushed more than 100 million people back into extreme poverty, and reversed progress towards some other SDGs including health, life expectancy and child literacy (UN DESA 2021). Health impacts and the consequences of deep economy-wide shocks may last many years even without significant future recurrence (Section 15.6.3). These changes, as well as the pandemic response actions, bring both important risks as well as opportunities for accelerating mitigation (Chapters 1, 5, 10 and 15).

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[4] Continually updated information on net zero commitments is available at https://www.zerotracker.net.

Cross-Chapter Box 1 (continued)

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 (Chapter 5 and Section 1.3). 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). This echoes long-standing climate literature on potential 'high impact' events, including those *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. Overall, global CO_2 FFI emissions declined by about 5.8% (5.1–6.3%) from 2019 to 2020, or about 2.2 (1.8–2.4) $GtCO_2$ in total (Section 2.2.2). Analysis from previous economic crises suggest significant rebound in emissions without policy-induced structural shifts (Jaeger et al. 2020) (Section 2.2.2.1 and Figure 2.5). Initial projections suggest the COVID aftermath may reduce emissions by 4–5% over 2025–2030 (Shan and Et.al 2020; Reilly et al. 2021), below a 'no-pandemic' baseline. The long-term impacts on behaviour, technology and associated emissions remain to be seen, but may be particularly significant in transport – lockdowns reduced mobility-related emissions, alongside two major growth areas: electronic communications replacing many work and personal travel requirements (Chapter 10 and Section 4.4.3.4); and revitalised local active transport and e-micromobility (Earley and Newman 2021). 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 (Section 8.7), with evidence also indicating that air pollution itself amplified vulnerability to COVID-19 (Gudka et al. 2020; Wu et al. 2020). The significant impacts on passenger aviation are projected to extend not just through behavioural changes, but also fleet changes from retiring older planes, and reduced new orders indicating expectations of reduced demand and associated GHG emissions until 2030 (Sections 5.1.2 and 10.5) (AR6 WGI Box 6.1 in Chapter 6). However, air cargo has recovered more rapidly (IATA 2020), possibly enhanced by online ordering.

Fiscal, growth and inequality impacts. Aspects of the global and regional economic crises from COVID-19 may prevail much longer than the crisis itself, potentially compromising mitigation. Most countries have undertaken unprecedented levels of short-term public expenditures. The International Monetary Fund (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 (Sections 15.2.3 and 15.6.3). COVID-19 further lowered interest rates which should facilitate low-carbon investment, but pandemic responses have increased sovereign debt across countries in all income bands (IMF 2021), and, particularly in some developing economies and regions, it has caused debt distress (Bulow et al. 2021), widening the gap in developing countries' access to capital (Hourcade et al. 2021b) (Section 15.6.3). 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 (Section 5.1.2 and 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 (Section 1.6).

Impacts on profitability and investment. COVID-19-induced demand reduction in electricity disproportionally affected coal power plants, whilst transport reduction most affected oil (IEA 2020a). This accelerated pre-existing decline in the relative profitability of most fossil fuel industries (Ameli et al. 2021). Renewables were the only energy sector to increase output (IEA 2020a). Within the context of a wider *overall* reduction in energy investment this prompted a substantial *relative* shift towards low-carbon investment particularly by the private sector (IEA 2020b; Rosembloom and Markard 2020) (Sections 15.2.1, 15.3.1 and 15.6.1).

Post-pandemic recovery pathways provide an opportunity to attract finance into accelerated and transformative low-carbon public investment (Sections 15.2 and 15.6.3). In most countries, COVID-19 has increased 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. During deep crises like that of COVID-19, economic multipliers of stimulus packages can be high (Hepburn et al., 2020), so much so that fiscal injections can then generate multipliers from 1.5 to 2.5, weakening the alleged crowding-out effect of public stimulus (Auerbach and Gorodnichenko 2012; Blanchard and Leigh 2013) (Section 15.2.3).

Cross-Chapter Box 1 (continued)

Recovery packages are motivated by assessments of the macroeconomic effectiveness ('multipliers') of public spending in ways that can crowd-in and revive private investment (Hepburn et al. 2020). 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 environmental, social and governance (ESG) and green bond markets (Section 15.6)), this can boost the effectiveness of public spending (IMF 2020). Stern and Valero (2021) argue that investment in low-carbon innovation and its diffusion, complemented by investments in sustainable infrastructure, are key to shaping environmentally sustainable and inclusive growth in the aftermath of the COVID-19 pandemic crisis. This would be the case both for high-income economies on the global innovation frontier, and to promote sustainable development in poorer economies.

A study with a global general equilibrium model (Liu et al. 2021) 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 post-Keynesian model of wider 'green recovery' policies (Pollitt et al. 2021) finds a short-run benefit of around 3.5% GDP (compared to 'no policy'), and even about 1% above a recovery boosted by cuts in consumption taxes, the latter benefit sustained through 2030 – outperforming an equivalent conventional stimulus package while reducing global CO_2 emissions by 12%.

Orientation of recovery packages. The large public spending on supporting or stimulating economies, exceeding USD12 trillion 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 and have not been much linked to climate action, (Sections 15.2.3 and 15.6.3): in the G20 counties, 40% of energy-related support spending went to the fossil fuel industry compared to 37% on low-carbon energy (EPT 2020). Recovery packages are also at risk of being 'colourless' (Hepburn et al., 2020), though some countries and regions have prioritised green stimulus expenditures for example as part of a 'Green New Deal' (Rochedo et al. 2021) (Sections 13.9.6 and 15.6.3).

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 (Section 1.7). 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). '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. 2021). This illustrates the role of Just Transition approaches to global responses including the value of integrated, multi-level governance (Sections 1.7, 4.5 and 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, and may distract 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 (Roberts and Geels 2019a) (Section 1.6.5). 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 (Section 5.1.2). COVID-19 appears to have accelerated the emergence of renewable power, electromobility and digitalisation (Newman 2020) (Sections 5.1.2, 6.3 and 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 (Section 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 (Obergassel et al. 2021). Noting the critical global post-COVID-19 challenge as the double impact of heightened credit risk in developing countries, along with indebtedness in developed countries, Hourcade et al. (2021a) estimate that a 'multilateral' sovereign guarantee structure to underwrite low-carbon investments could leverage projects up to 15 times its value, contributing to shifting development pathways consistent with the SDGs and Paris goals.

COVID- 19 can thus be taken as a reminder of the urgency of addressing climate change, a warning of the risk of future stranded assets (Rempel and Gupta 2021) (Chapter 17), but also an opportunity for a cleaner recovery.

In addition to developments in climate science, emissions, the international agreements in 2015, and the recent impact of COVID-19, a few other key developments have strong implications for climate mitigation.

Cheaper renewable energy technologies. Most striking, the cost of solar photovoltaic (PV) has fallen by a factor of 5 to 10 in the decade since the IPCC Special Report on Renewable Energy (IPCC 2011a) and other data inputting to the AR5 assessments. The SR1.5 reported major cost reductions, the IEA (2020) World Energy Outlook described PV as now 'the cheapest electricity in history' for projects that 'tap low cost finance and high quality resources.' Costs and deployment both vary widely between different countries (Chapters 6, 9 and 12) but costs are still projected to continue falling (Vartiainen et al. 2020). Rapid technological developments have occurred in many other low-carbon technologies including batteries and electric vehicles (Section 1.4.3), IT and related control systems, with progress also where electrification is not possible (Chapters 2, 6 and 11).

Civil society pressures for stronger action. Civic engagement increased leading up to the Paris Agreement (Bäckstrand and Lövbrand 2019) and after. Youth movements in several countries show young people's awareness about climate change, evidenced by the school strikes for the climate (Hagedorn et al. 2019; Buettner 2020; Thackeray et al. 2020; Walker 2020). Senior figures across many religions (Francis 2015; IFEES 2015) stressed the duty of humanity to protect future generations and the natural world, and warned about the inequities of climate change. Growing awareness of local environmental problems such as air pollution in Asia and Africa (Karlsson et al. 2020), and the threat to indigenous people's rights and existence has also fuelled climate activism (Etchart 2017). Grassroots movements (Cheon and Urpelainen 2018; Fisher et al. 2019), build political pressure for accelerating climate change mitigation, as does increasing climate litigation (Setzer and Vanhala 2019) (Chapters 13 and 14).

Climate policies also encounter resistance. However, there are multiple sources of resistance to climate action in practice. Corporations and trade associations often lobby against measures they deem detrimental (Section 1.4.6). The emblematic 'yellow vest' movement in France was triggered by higher fuel costs as a result of a CO_2 tax hike (Lianos 2019; Driscoll 2021), though it had broader aspect of income inequality and other social issues. There is often a mismatch between concerns on climate change and people's willingness to pay for mitigation. For example, whilst most Americans believe climate change is happening, 68% said in a survey they would oppose climate policies that added just USD10 per month to electricity bills (EPIC et al. 2019), and worry about energy costs can eclipse those about climate change elsewhere (Poortinga et al. 2018) (Chapter 13).

Global trends contrary to multilateral cooperation. State-centred politics and geopolitical/geo-economic tensions seem to have become more prominent across many countries and issues (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), making it more difficult to tackle global challenges including protecting the environment (Schreurs 2016; Parker et al. 2017; WEF 2019).

Transnational alliances. Partly countering this trend, cities, businesses and 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 and the Covenant of Mayors (Chapter 8); there are numerous other alliances and networks such as those in finance (Chapter 15) and technology (Chapter 16), amongst many others (Chapters 13 and 14).

Finally, under the Paris Agreement process, during 2020/21, many countries strengthened their Nationally Determined Contributions (NDCs). Including updates until October 2021, these would imply global GHG emissions declining by 2030 to between 1–4% below 2019 levels (unconditional NDCs), or 4–10% (for NDCs conditional on international support) (Table 4.3). This is a significant change but would still not be compatible with 1.5°C pathways, and even if delivered in full, to limit warming to 2°C (>67%), emissions would have to fall very rapidly after 2030 (Section 3.2.5).

Thus, developments since AR5 highlight the complexity of the mitigation challenge. There is no far-sighted, globally optimising decision-maker and indeed climate policymaking at all levels is subject to conflicting pressures in multiple ways. The next section overviews the drivers and constraints.

1.4 Drivers and Constraints of Climate Mitigation and System Transitions/Transformation

This section provides a brief assessment of key factors and dynamics that drive, shape and/or limit climate mitigation in (i) **economic factors**: which include sectors and services, trade and leakage, finance and investment, and technological innovation; (ii) **socio-political issues**: which include political economy, social innovation, and equity and fairness; and (iii) **institutional factors**, which comprise policy, legal frameworks and international cooperation.

The AR5 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. However, the terminology of drivers and constraints have been chosen here to reflect the fact that each of these factors can serve as an enabling condition or a constraint to ambitious climate action depending 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 (Battiston et al. 2021). Similarly, political economy factors can align in favour of ambitious climate action or act in ways that inhibit strong cooperation and low-carbon transition. The other key insight from the assessment of the system drivers and constraints undertaken below is that none of the factors or conditions by themselves is more or less important than the others. In addition to being deeply intertwined all the factors matter in different measures with each exacting more or less force depending on the prevailing social, economic, cultural and political context. Often achieving accelerated mitigation would require effort to bring several of the factors in alignment in and across multiple levels of political or governance scales.

1.4.1 Services, Sectors and Urbanisation

Human activities drive emissions primarily through the demand for a wide range of services such as food, shelter, heating/cooling, goods, travel, communication, and entertainment. This demand is fulfilled by various activities often grouped into sectors such as agriculture, industry and commerce. The literature uses a wide range of sectoral definitions to organise data and analysis (Chapter 2). Energy sectors are typically organised into primary energy producers, energy transformation processes (such as power generation and fuel refining), and major energy users such as buildings, industry and transport (Chapters 2 and 5). Other research (Chapter 8) organises data around interacting urban and rural human activities. Land-based activities can be organised into agriculture, forestry and other land-use (AFOLU), or land use, land-use change and forestry (LULUCF) (Chapter 7). Each set of sectoral definitions and analysis offers its own insights.

Sectoral perspectives help to identify and understand the drivers of emissions, opportunities for emissions mitigation, and interactions with resources, other goals and other sectors, including the co-evolution of systems across scales (Kyle et al. 2016; Moss et al. 2016; Mori et al. 2017; IPBES 2019). Interactions between sectors and agents pursuing multiple goals is a major theme pervading this assessment.

The 'nexus' between energy, water, and land – all key contributors to human well-being – also helps to provide, regulate and support ecosystem and cultural services (Bazilian et al. 2011; Ringler et al. 2013; Smajgl et al. 2016; Albrecht et al. 2018; Brouwer et al. 2018; D'Odorico et al. 2018; Van Vuuren et al. 2019), with important implications for cities in managing new systems of transformation (Thornbush et al. 2013; Wolfram et al. 2016) (Chapter 8). Other important nexuses shaping our planet's future (Fajardy et al. 2018) include agriculture, forestry, land use and ecosystem services (Chazdon 2008; Settele et al. 2016; Torralba et al. 2016; Nesshöver et al. 2017; Keesstra et al. 2018).

Historically, energy-related GHG emissions were considered a by-product of the increasing scale of human activity, driven by population size, economic activity and technology. That simple notion has evolved greatly over time to become much more complex and diverse, with increasing focus on the provision of energy services (Cullen and Allwood 2010; Bardi et al. 2019; Brockway et al. 2019; Garrett et al. 2020). The demand for agricultural products has historically driven conversion of natural lands (land-use change). AFOLU along with food processing accounts for 21–37% of total net anthropogenic GHG emissions (SRCCL SPM A3).[5]

Continued growth in population and income are expected to continue driving up demand for goods and services (Chapters 2, 3 and 5), with an important role for urbanisation which is proceeding at an unprecedented speed and scale. In the last decade, the urban population grew by 70 million people each year, or about 1.3 million people per week, with urban area expanding by about 102 km^2 per day (Chapter 8). Urban areas account for most (45–87%) of the global carbon footprint (8.1) and the strong and positive correlation between urbanisation and incomes means higher consumption from urban lifestyles will continue driving direct and indirect GHG emissions. Cities provide a conduit to many of the services such as transportation, housing, water, food, medical care and recreation, and other services and urban carbon emissions are driven not only by population and income but also by the form and structure of urban areas (Sections 8.1 and 8.3–8.6). This creates opportunities for decarbonisation through urban planning and purposeful 'experimentation' (Newman et al. 2017) (Chapter 8).

Human needs and wants evolve over time making the transition toward climate and sustainable development goals either more or less difficult. For example, changes in the composition of goods consumed, such as shifting diets toward a more vegetarian balance, can reduce land-use emissions without compromising the quality of life (Stehfest et al. 2009; Gough 2017; van Vuuren et al. 2018; van den Berg et al. 2019; Hargreaves et al. 2021; SRCCL SPM B2.3).

Human behaviour and choices, including joint achievement of wider social goals, will play an important part in enabling or hindering climate mitigation and sustainable development (Shi et al. 2016), for example, shifting passenger transportation preferences in ways that combine climate, health and sustainable development goals (Romanello et al. 2021).

1.4.2 Trade, Consumption and Leakage

Emissions associated with international trade account for 20–33 % of global emissions, as calculated using multi-regional input-output analysis (Wiedmann and Lenzen 2018). Whether international trade drives an increase or decrease in global GHG emissions depends on the emissions intensity of traded products as well as the influence of trade on relocation of production, with studies reaching diverse conclusions about the net effect of trade openness on CO_2 emissions (Section 2.4.5). Tariff reduction of low-carbon technologies could facilitate effective mitigation (de Melo and Vijil 2014; Ertugrul et al. 2016; Islam et al. 2016; WTO 2016).

The magnitude of carbon leakage (see Glossary) caused by unilateral mitigation in a fragmented climate policy world depends on trade and substitution patterns of fossil fuels and the design of policies (IPCC 2014a, Box 5.4), but its potential significance in trade-exposed energy-intensive sectors (Bauer et al. 2013; Carbone and Rivers 2017; Naegele and Zaklan 2019) can make it an important constraint on policy. See Section 13.6.6.1 in Chapter 13 for channels and evidence. Akimoto et al. (2018) argue that differences in marginal abatement

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[5] AFOLU accounted for about 13% of CO_2, 44% of CH_4 and 82% of N_2O global anthropogenic GHG emissions in 2007–2016.

costs of NDCs could cause carbon leakage in energy-intensive, trade-exposed sectors, and could weaken effective global mitigation.

Policy responses to cope with carbon leakage include border carbon adjustment (BCAs) and differentiated carbon taxes (Liu et al. 2020). Some BCA options focusing on levelling the cost of carbon paid by consumers on products could be designed in line with the WTO (Ismer et al. 2016), while others may not be (Mehling et al. 2019). All proposals could involve difficulty of tracing and verifying the carbon content of inputs (Onder 2012; Denis-Ryan et al. 2016). An international consensus and certification practice on the carbon content would help to overcome WTO compatibility (Holzer 2014). See Chapter 13 and Mehling et al. (2019) on the context of trade law and the PA.

Official inventories report territorial emissions, which do not consider the impacts embodied in imports of goods. Global supply chains undoubtedly lead to a growth in trade volumes (Federico and Tena-Junguito 2017), alternative methods have been suggested to account for emissions associated with international trade, 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 based on thermodynamics (Khajehpour et al. 2019). Consumption-based emissions (i.e., attribution of emissions related to domestic consumption and imports to final destination) are not officially reported in global emissions datasets but data has improved (Tukker and Dietzenbacher 2013; Afionis et al. 2017). This analysis has been used extensively for consumption-based accounting of emissions, and other environmental impacts (Wiedmann and Lenzen 2018; Malik et al. 2019) (Section 2.3).

Increasing international trade has resulted in a general shifting of fossil fuel-driven emissions-intensive production from developed to developing countries (Arto and Dietzenbacher 2014; Malik and Lan 2016), and between developing countries (Zhang et al. 2019). High-income developed countries thus tend to be net importers of emissions, whereas low/middle-income developing countries net exporters (Peters et al. 2011) (Figure 1.2c, d). This trend is 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. 2020b).

The Paris Agreement primarily deals with national commitments relating to domestic emissions and removals, hence emissions from international aviation and shipping are not covered. Aviation and shipping accounted for approximately 2.7% of greenhouse gas emissions in 2019 (before COVID-19); see Section 10.5.2 for discussion. In addition to CO_2 emissions, aircraft-produced contrail cirrus clouds, and emissions of black carbon and short-lived aerosols (e.g., sulphates) from shipping are especially harmful for the Arctic (Section 10.8 and Box 10.6).

1.4.3 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.

The fall in renewable energy costs alongside rapid growth in capacity (Figure 1.3; see also Figures 6.8 and 6.11 in Chapter 6) has been accompanied by varied progress in many other technology areas such as electric vehicles, fuel cells for both stationary and mobile applications (Dodds 2019), thermal energy (Chapter 6), and battery and other storage technologies (Freeman et al. 2017) (Chapters 6, 9 and 12; Figure TS.7). Nuclear contributions may be enhanced by new generations of reactors (e.g., Generation III) and small modular reactors (Knapp and Pevec 2018) (Chapter 6).

Large-scale hydrogen developments could provide a complementary energy channel with long-term storage. Like electricity, hydrogen (H_2) is an energy vector with multiple potential applications, including in industrial processes such as steel and non-metallic materials production (Chapter 11), for long-range transportation (Chapter 10), and low-temperature heating in buildings (Chapter 9). Emissions depend on how it is produced, and deploying H_2 delivery infrastructure economically is a challenge when the future scale of hydrogen demand is so uncertain (Chapter 6). H_2 from natural gas with CO_2 capture and storage (CCS) may help to kick-start the H_2 economy (Sunny et al. 2020).

CO_2-based fuels and feedstocks such as synthetic methane, methanol, diesel, jet fuel and other hydrocarbons, potentially from carbon capture and utilisation (CCU), represent drop-in solutions with limited new infrastructure needs (Artz et al. 2018; Bobeck et al. 2019; Yugo and Soler 2019) (Chapter 10). Deployment and development of CCS technologies (with large-scale storage of captured CO_2) have been much slower than projected in previous assessments (IEA 2019b; Page et al. 2019) (Chapter 11).

Potential constraints on new energy technologies may include their material requirements, notably rare earth materials for electronics or lithium for batteries (Wanger 2011; Flexer et al. 2018), stressing the importance of recycling (IPCC 2011b; Rosendahl and Rubiano 2019). Innovation is enabling greater recycling and reuse of energy-intensive materials (Shemi et al. 2018), and introducing radically new and more environmentally friendly materials, however, still not all materials can be recycled (Allwood 2014).

By sequestering carbon in biomass and soils, soil carbon management, and other terrestrial strategies could offset hard-to-reduce emissions in other sectors. However, large-scale bioenergy deployment could increase risks of desertification, land degradation, and food insecurity (IPCC 2019a), and higher water withdrawals (Hasegawa et al. 2018; Fuhrman et al. 2020), though this may be at least partially offset by innovation in agriculture, diet shifts and plant-based proteins contributing to meeting demand for food, feed, fibre and bioenergy (or bioenergy with carbon capture and storage (BECCS) with CCS) (Havlik et al. 2014; Popp et al. 2017; Köberle et al. 2020) (Chapters 5 and 7).

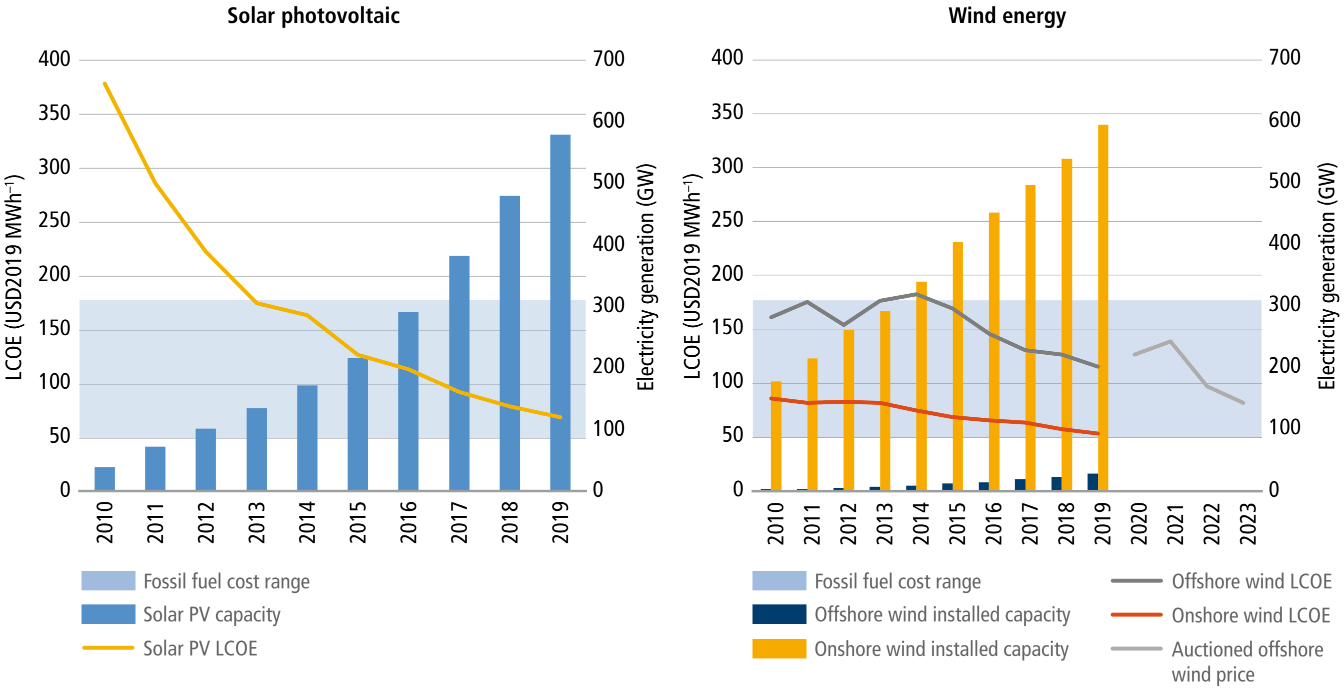

Figure 1.3 | Cost reductions and adoption in solar photovoltaic and wind energy. Fossil fuel Levelised Cost of Electricity (LCOE) is indicated by blue shading at USD50–177 MWh^{-1} (IRENA 2020b). Source: data from IRENA (2021a,b).

A broad class of more speculative technologies propose to counteract effects of climate change by removing CO_2 from the atmosphere (CDR), or by directly modifying the Earth's energy balance at a large scale (solar radiation modification or SRM). CDR technologies include ocean iron fertilisation, enhanced weathering and ocean alkalinisation (Council 2015a), along with direct air carbon capture and storage (DACCS). They could potentially draw down atmospheric CO_2 much faster than the Earth's natural carbon cycle, and reduce reliance on biomass-based removal (Köberle 2019; Realmonte et al. 2019), but some present novel risks to the environment and DACCS is currently more expensive than most other forms of mitigation (Fuss et al. 2018) (Cross-Chapter Box 8 in Chapter 12). Solar radiation modification (SRM) could potentially cool the planet rapidly at low estimated direct costs by reflecting incoming sunlight (Council 2015b), but entails uncertain side effects and thorny international equity and governance challenges (Netra et al. 2018; Florin et al. 2020; National Academies of Sciences 2021) (Chapter 14). Understanding the climate response to SRM remains subject to large uncertainties (AR6 WGI). Some literature uses the term 'geoengineering' for both CDR or SRM when applied at a planetary scale (Shepherd 2009; GESAMP 2019). In this report, CDR and SRM are discussed separately, reflecting their very different geophysical characteristics.

Large improvements in information storage, processing, and communication technologies, including artificial intelligence, will affect emissions. They can enhance energy-efficient control, reduce transaction costs for energy production and distribution, improve demand-side management (DSM) (Raza and Khosravi 2015), and reduce the need for physical transport (Smidfelt Rosqvist and Winslott Hiselius 2016) (Chapters 5, 6 and 9–11). However, data centres and related IT systems (including blockchain), are electricity-intensive and will raise demand for energy (Avgerinou et al. 2017) – cryptocurrencies may be a major global source of CO_2 if the electricity production is not decarbonised (Mora et al. 2018) – and there is also a concern that Information technologies can compound and exacerbate current inequalities (Chapters 5, 16 and Cross-Chapter Box 11 in Chapter 16). IT may affect broader patterns of work and leisure (Boppart and Krusell 2020), and the emissions intensity of how people spend their leisure time will become more important (Chapters 5 and 9). Because higher efficiency tends to reduces costs, it often involves some 'rebound' offsetting at least some of the emission savings (Sudbury and Hutchinson 2016; Belkhir and Elmeligi 2018; Cohen and Cavoli 2019).

Technology can enable both emissions reductions and/or increased emissions (Chapter 16). Governments play an important role in most major innovations, in both 'technology-push' (Mazzucato 2013) and induced by 'demand-pull' (Grubb et al. 2021a), so policy is important in determining its pace, direction and utilisation (Roberts and Geels 2019a) (Sections 1.7.1 and 1.7.3). Overall, the challenge will be to enhance the synergies and minimise the trade-offs and rebounds, including taking account of ethical and distributional dimensions (Gonella et al. 2019).

1.4.4 Finance and Investment

Finance is both an enabler and a constraint on mitigation, and since AR5, attention to the financial sector's role in mitigation has grown. This is partly in the context of the Paris Agreement finance articles and the Green Climate Fund, the pledge to mobilise USD100 billion yr^{-1} by 2020, and the Addis Abbaba Action Agenda (Section 1.3.1).

However, there is a persistent but uncertain gap in mitigation finance (Cui and Huang 2018) (Table 15.15.1), even though tracked climate finance overwhelmingly goes toward mitigation compared to adaptation (UNEP 2020) (Section 15.3; Working Group II). Green bond issuance has increased recently in parallel with efforts to reform the international financial system by supporting development of local capital markets (Section 15.6.4).

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. The risks include physical risks related to the impacts of climate change itself; transition risks related to the exposure to policy, technology and behavioural changes in line with a low-carbon transition; and liability risks from litigation for climate-related damages (Box 15.2). These 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) (Sections 6.7 and 15.6.3). Such risks continue to be underestimated by financial institutions (Section 15.6.1). The continuing expansion of fossil fuel infrastructure and insufficient transparency on how these are valued 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 (Battiston et al. 2017) (Section 15.6.3). The Financial Stability Board's Taskforce on Climate-related Financial Disclosures' (TCFD) recommendations on transparency aim to ensure that investors and companies consider climate change risks in their strategies and capital allocation (TCFD 2018). This is helping 'investors to reassess core assumptions' and may lead to 'significant' capital reallocation (Fink 2020). However, metrics and indicators of assets risk exposure are inadequate (Monasterolo 2017; Campiglio et al. 2018) and transparency alone is insufficient to drive the required asset reallocation in the absence of clear regulatory frameworks (Ameli et al. 2020; Chenet et al. 2021). A coalition of central banks have formed the Network for Greening the Financial Sector, to support and advance the transformation of the financial system (Allen et al. 2020; NGFS 2020), with some of them conducting climate-related institutional stress tests.

Governments cannot single-handedly fund the transition (Section 15.6.7), least of all in low-income developing countries with large sovereign debt and poor access to global financial markets. Long-term sources of private capital are required to close the financing gap across sectors and geographies (Section 15.6.7). Future investment needs are greatest in emerging and developing economies (Section 15.5.2) which already face higher costs of capital, hindering capacity to finance a transition (Buhr et al. 2018; Ameli et al. 2020). Requisite North–South financial flows are impeded by both geographic and technological risk premiums (Iyer et al. 2015), and the COVID-19 pandemic has further compromised the ability of developing and emerging economies to finance development activities or attract additional climate finance from developed countries (Section 15.6.3, and Cross-Chapter Box 1 in this chapter). 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 (Gray and Irwin 2003). A Green Climate Fund (GCF) report notes the paradox that USD14 trillion of negative-yielding debt in OECD countries might be expected to flow to much larger low-carbon, climate-resilient investment opportunities in developing countries, but 'this is not happening' (Hourcade et al. 2021b).

There is often a disconnect between stated national climate ambition and finance flows, and overseas direct investment (ODI) from donor countries may be at odds with national climate pledges such as NDCs. One report found funds supported by foreign state-owned enterprises into 56 recipient countries in Asia and Africa in 2014–2017 went mostly to fossil fuel-based projects not strongly aligned with low-carbon priorities of recipient countries' NDCs (Zhou et al. 2018). Similarly, Steffen and Schmidt (2019) 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 (Section 15.6). Voituriez et al. (2019) identify significant mitigation potential if financing countries simply applied their own environmental standards to their overseas investments.

1.4.5 Political Economy

The politics of interest (most especially economic interest) of key actors at sub-national, national and global levels can be important determinants of climate (in)action (O'Hara 2009; Lo 2010; Tanner and Allouche 2011; Sovacool et al. 2015; Lohmann 2017; Clapp et al. 2018; Newell and Taylor 2018; Lohmann 2019). Political economy approaches can be crudely divided into 'economic approaches to politics', and those used by other social scientists (Paterson and P-Laberge 2018). The former shows how electoral concerns lead to weak treaties (Battaglini and Harstad 2016) and when policy negotiations cause status-quo biases and the use of inefficient policy instruments (Austen-Smith et al. 2019) or delays and excessive harmonisation (Harstad 2007). The latter emphasises the central role of structures of power and production, and a commitment to economic growth and capital accumulation in relation to climate action, given the historically central role of fossil fuels to economic development and the deep embedding of fossil energy in daily life (Newell and Paterson 2010; Huber 2012; Di Muzio 2015; Malm 2015).

The economic centrality of fossil fuels 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 (Jones and Levy 2009; Newell and Paterson 2010; Geels 2014). The effects of climate policy 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), and there is a widespread cultural assumption that continued fossil fuel use is central to this (Strambo and Espinosa 2020). Decarbonisation strategies are often centred around projects to develop new sources of economic activity: carbon markets creating new commodities (Newell and Paterson 2010); investment generated in new urban infrastructure (Whitehead 2013); and/or innovations in a range of new energy technologies (Fankhauser et al. 2013; Lachapelle et al. 2017; Meckling and Nahm 2018).

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; Jones and Levy 2009; Geels 2014; Breetz et al. 2018). Incumbent industries are often more concentrated than those benefiting from climate policy and lobby more effectively to prevent losses than those who would gain (Meng and Rode 2019). Drawing upon wider networks (Brulle 2014), campaigns by oil and coal companies against climate action in the United States of America and Australia are perhaps the most well known and largely successful of these (Pearse 2017; Brulle et al. 2020; Mildenberger 2020; Stokes 2020), although similar dynamics have been demonstrated in Brazil and South Africa (Hochstetler 2020), Canada (Harrison 2018), and Norway and Germany (Fitzgerald et al. 2019), for example. In other contexts, resistance by incumbent companies is more subtle but nevertheless has weakened policy design on emissions trading systems (Rosembloom and Markard 2020), and limited the development of alternative-fuelled automobiles (Levy and Egan 2003; Wells and Nieuwenhuis 2012).

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, and conversely, why some low-emitting countries may find it easier to pursue climate action because they have fewer vested interests in high-carbon economies. These dynamics can arise from the vested interest of state-owned enterprises (SOEs) (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 (Baker 2015; Swilling et al. 2016; Heffron and McCauley 2018; Ransan-Cooper et al. 2018; Turhan et al. 2019).

1.4.6 Equity and Fairness

Equity and fairness can serve as both drivers and barriers to climate mitigation at different scales of governance. Literature regularly highlights equity and justice issues as critical components in local politics and international diplomacy regarding all SDGs, such as goals for no poverty, zero hunger, gender equality, affordable clean energy, reducing inequality, but also for climate action (SDG 13) (Marmot and Bell 2018; Spijkers 2018). Equity issues help explain why it has proved hard to reach more substantive global agreements, as it is hard to agree on a level of greenhouse gas (GHG) mitigation (or emissions) and how to distribute mitigation efforts among countries (Kverndokk 2018) for several reasons. First, an optimal trade-off between mitigation costs and damage costs of climate change depends on ethical considerations, and simulations from integrated assessment models using different ethical parameters producing different optimal mitigation paths (IPCC 2018b) (Section 3.6.1.2). 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 sustainable development (Evans and Phelan 2016; Heffron and McCauley 2018; Okereke 2018) depends on taking equity seriously in climate policies and international negotiations (Okereke and Coventry 2016; Klinsky et al. 2017; Martinez et al. 2019).

Climate change and climate policies affect countries and people differently. Low-income countries tend to be more dependent on primary industries (agriculture and fisheries, etc.) than richer countries, and their infrastructure may be less robust to tackle more severe weather conditions. Within a country, the burdens may not be equally distributed either, due to policy measures implemented and from differences in vulnerability and adaptive capacity following from e.g. income and wealth distribution, race and gender. For instance, unequal social structures can result in women being more vulnerable to the effects of climate change compared to men, especially in poor countries (Arora-Jonsson 2011; 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 costs for the emission-reduction goal of NDCs (Fujimori et al. 2016; Hof et al. 2017; Akimoto et al. 2018; Evans & Gabbatiss 2019). Equalising the burdens from climate policies may give more support for mitigation policies (Maestre-Andrés et al. 2019).

Taking equity into account in designing an international climate agreement is complicated as there is no single universally accepted equity criterion, 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 et al. 2010; Kverndokk et al. 2014).

International transfers from rich to poor countries to support mitigation and adaptation activities may help with equalising burdens, as agreed upon in the UNFCCC (1992) (Chapters 14 and 15), such that they may be motivated by strategic as well as equity reasons (Kverndokk 2018) (Section 1.4.4).

1.4.7 Social Innovation and Behaviour Change

Social and psychological factors affect both perceptions and behaviour (Weber 2015; Whitmarsh et al. 2021). Religion, values, culture, gender, identity, social status and habits strongly influence individual behaviours and choices, and therefore sustainable consumption (Sections 1.6.3.1 and 5.2). Identities can provide powerful attachments to consumption activities and objects that inhibit shifts away from them (Brekke et al. 2003; Bénabou and Tirole 2011; Stoll-Kleemann and Schmidt 2017; Ruby et al. 2020). Consumption is a habit-driven and social practice rather than simply a set of individual decisions, making shifts in consumption harder to pursue (Evans et al. 2012; Shove and Spurling 2013; Kurz et al. 2015; Warde 2017; Verplanken and Whitmarsh 2021). Finally, shifts towards low-carbon behaviour are also inhibited by social-psychological and political dynamics that cause individuals to ignore the connections from daily consumption practices to climate change impacts (Norgaard 2011; Brulle and Norgaard 2019).

As a notable example, plant-based alternatives to meat could reduce emissions from diets (Eshel et al. 2019; Willett et al. 2019). However, diets are deeply entrenched in cultures and identities, and hard to change (Fresco 2015; Mylan 2018). Changing diets also raises cross-cultural ethical issues, in addition to meat's role in providing nutrition (Plumwood 2004). 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 entrench new sustainable behaviours.

Behaviour can be influenced through a number of mechanisms besides economic policy and regulation, such as information campaigns, advertising and 'nudging'. Innovations and infrastructure also impact behaviour, as with bicycle lanes to reduce road traffic. Wider social innovations also have indirect impacts. 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; Hamilton 2011; McCrary and Royer 2011). Reducing poverty and improvements in health and reproductive choice 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; IPCC 2014a Section 4.3.5).

1.4.8 Policy Impacts

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) (Chapters 13 and 16). 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/mobility (Chapter 10), and decarbonising industrial systems (Chapter 11).

Policy has been and will be central not only because GHG emissions are almost universally under-priced in market economies (Stern and Stiglitz 2017; World Bank 2019), and because of inadequate economic incentives to innovation (Jaffe et al. 2005), but also due to various delay mechanisms (Karlsson and Gilek 2020) and multiple sources of path-dependence and lock-in to existing systems (Section 1.8.2), including: '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 WGIII p.18).

Many hundreds of policies have been introduced explicitly to mitigate GHG emissions, improve energy efficiency or land use, or to foster low-carbon industries and innovation, with demonstrable impact. The role of policy to date has been most evident in energy efficiency (Sections 5.4 and 5.6) and electricity (Chapter 6). The IPCC Special Report on Renewable Energy already found that: 'Government policies play a crucial role in accelerating the deployment of RE technologies' (IPCC 2011a, p. 24). Policy packages since then have driven rapid expansion in renewables capacity and cost reductions (e.g., through the German *Energiewende*), and emission reductions from electricity (most dramatically with the halving of CO_2 emissions from the UK power sector, driven by multiple policy instruments and regulatory changes), as detailed in Chapter 6 (Section 6.7.5).

Chapter 13 charts the international evolution of policies and many of the lessons drawn. Attributing the overall impact on emissions is complex, but an emerging literature of several hundred papers indicates impacts on multiple drivers of emissions. Collectively, policies are likely to have curtailed global emissions growth by several $GtCO_2$-eq annually already by the mid-2010s (Cross-Chapter Box 10 in Chapter 14). This suggests initial evidence that policy has driven some decoupling (Figure 1.1d) and started to 'bend the curve' of global emissions, but more specific attribution to observed trends is not as yet possible.[6]

However, some policies (e.g., subsidies to fossil fuel production or consumption) increase emissions, whilst others (e.g., investment protection) may constrain efforts at mitigation. Also, wider economic and developmental policies have important direct and indirect impacts on emissions. Policy is thus both a driver and a constraint on mitigation.

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 strategic and landscape levels (Section 1.7.3). Chapters 13, 16 and 17 appraise policies for transformation in the context of sustainable development, indicating the importance of policy as a driver 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,

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[6] Linking estimated policy impacts to trends is complex, and as yet very tentative. An important factor is that many mitigation policies involve investments in low-carbon or energy-efficient technology, the savings from which persist. As a purely illustrative example: the annual increase in global emissions during 2000–2010 averaged around 1 $GtCO_2$-eq yr^{-1}, but with large fluctuations. If policies by 2010 reduced the *annual increase* in that year by 100 $MtCO_2$-eq (0.1 $GtCO_2$-eq) below what it would otherwise have been, this is hard to discern. But if these savings sustain, and in each subsequent year, policies cut another 100 $MtCO_2$-eq off the annual increase compared to the previous year, global emissions after a decade would be around 5 $GtCO_2$-eq yr^{-1} below what they would have been without any such policies, and on average close to stabilising. However each step would be difficult to discern in the noise of annual fluctuations.

of finance (Chapters 13 and 15), and for encouraging private-sector innovation at scale (Chapter 16), for example, if it offers greater stability and mid-term predictability for carbon prices; Nash and Steurer (2019) find that seven national climate change acts in European countries all act as 'living policy processes, though to varying extents'.

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

1.4.9 Legal Framework and Institutions

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

Institutions entrench specific political decision-making processes, often empowering some interests over others, including powerful interest groups who have vested interests in maintaining the current high-carbon economic structures (Okereke and Russel 2010; Wilhite 2016; Engau et al. 2017); see also Section 1.4.6 and Chapter 13 on the sub-national and national governance challenges including coordination, mediating politics and strategy setting.

Some suggest that societal transformation towards a low-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), and associated institutions and social innovations to increase involvement of non-state actors in climate governance (Fuhr et al. 2018). However literature is divided as to how much democratisation of climate politics, with greater emphasis on equity and community participation, would advance societal transformation in the face of climate change (Stehr 2005), or may actually hinder radical climate action in some circumstances (Povitkina 2018).

Since 2016, the number of climate litigation cases has increased rapidly. The UN Environment Programme's Global Climate Litigation Report: 2020 Status Review (UNEP 2020) noted that between March 2017 and 1 July 2020, the number of cases nearly doubled with at least 1550 climate cases filed in eight countries. Several important cases such as Urgenda Foundation vs The State of the Netherlands ('Urgenda') and Juliana et al. vs United States ('Juliana') have had ripple effects, inspiring other similar cases (Lin and Kysar 2020).

Numerous international climate governance initiatives engage national and sub-national governments, NGOs and private corporations, constituting a 'regime complex' (Raustiala and Victor 2004; 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 baselines or monitoring, reporting, and verification, they are not likely to fill the 'mitigation gap' (Michaelowa and Michaelowa 2017).

1.4.10 International Cooperation

Tackling climate change is often mentioned as an important reason for strong international cooperation in the 21st century (Falkner 2016; Keohane and Victor 2016; Bodansky et al. 2017; Cramton et al. 2017b). Mitigation costs are borne by countries taking action, while the benefits of reduced climate change are not limited to them, being in economic terms 'global and non-excludable'. Hence anthropogenic climate change is typically seen as a global commons problem (Falkner 2016; Wapner and Elver 2017). Moreover, the belief that mitigation will raise energy costs and may adversely affect competitiveness creates incentives for free riding, where states avoid taking their fair share of action (Barrett 2005; Keohane and Victor 2016). International cooperation has the potential to address these challenges through collective action (Tulkens 2019) and international institutions offer the opportunity for actors to engage in meaningful communication and exchange of ideas about potential solutions (Cole 2015). International cooperation is also vital for the creation and diffusion of norms and the framework for stabilising expectations among actors (Pettenger 2016).

Some key roles of the UNFCCC have been detailed by its former heads (Kinley et al. 2021). In addition to specific agreements (most recently the PA) it has enhanced transparency through reporting and data, and generated or reinforced several important norms for global climate action including the principles of equity, common but differentiated responsibility and respective capabilities, and the precautionary principles for maintaining global cooperation among states with unevenly distributed emissions sources, climate impacts, and varying mitigation costs across countries (Keohane and Victor, 2016). In addition to formal negotiations, the annual Conference of the Parties (COPs) have increased awareness, and motivated more ambitious actions, sometimes through the formation of 'coalitions of the willing', for example. It provides a structure for measuring and monitoring action towards a global goal (Milkoreit and Haapala 2019). International cooperation (including the UNFCCC) can also promote technology development and transfer and capacity building; mobilise finance for mitigation and adaptation; and help address concerns on climate justice (Okereke and Coventry 2016; Chan et al. 2018) (Chapters 14–16).

A common criticism of international institutions is their limited (if any) powers to enforce compliance (Zahar 2017). As a global legal institution, the PA has little enforcement mechanism (Sindico 2015), but enforcement is not a necessary condition for an instrument to be legally binding (Bodansky 2016; Rajamani 2016). In reality implementation of specific commitments tends to be high once countries have ratified and a treaty or an agreement is in force (Bodansky 2016; Rajamani 2016). Often, the problem is not so much of 'power to enforce compliance or sanction non-compliance', but the level of ambition (Chapter 14).

However, whilst in most respects a driver, international cooperation has also been characterised as 'organised hypocrisy' where proclamations are not matched with corresponding action (Egnell 2010). Various reasons for inadequate progress after 30 years of climate negotiations, have been identified (Stoddard et al. 2021). International cooperation can also seem to be a barrier to ambitious action when negotiation is trapped in 'relative-gains' calculus, in which countries seek to game the regime or gain leverage over one another (Purdon 2017), or where states lower ambition to the 'least common dominator' to accommodate participation of the least ambitious states (Falkner 2016). Geden (2016) and Dubash (2020) offer more nuanced assessments.

International collaboration works best if an agreement can be made self-reinforcing with incentives for mutual gains and joint action (Barrett 2016; Keohane and Victor 2016), but the structure of the climate challenge makes this hard to achieve. The evidence from the Montreal Protocol on ozone-depleting substances and from the Kyoto Protocol on GHGs, is that legally binding targets have been *effective* in that participating Parties complied with them (Shishlov et al. 2016; Albrecht and Parker 2019), and (for Kyoto) these account for most of the countries that have sustained emission reductions for at least the past 10 to 15 years (Sections 1.3.2 and 2.2). However, such binding commitments may deter *participation* if there are no clear incentives to sustain participation and especially if other growing emitters are omitted by design, as with the Kyoto Protocol. Consequently the USA refused to ratify (and Canada withdrew), particularly on the grounds that developing countries had no targets; with participation in Kyoto's second period commitments declining further, the net result was limited global progress in emissions under Kyoto (Bodansky 2016; Okereke and Coventry 2016; Scavenius and Rayner 2018) despite full legal compliance in both commitment periods (Chapter 14).

The negotiation of the Paris Agreement was thus done in the context of serious questions about how best to structure international climate cooperation to achieve better results. This new agreement is designed to sidestep the fractious bargaining which characterised international climate cooperation (Marcu 2017). It contains a mix of hard, soft and non-obligations, the boundaries between which are blurred, but each of which plays a distinct and valuable role (Rajamani 2016). The provisions of the PA could encourage flexible responses to changing conditions, but limit assurances of ambitious national commitments and their fulfilment (Pickering et al. 2018). The extent to which this new arrangement will drive ambitious climate policy in the long run remains to be seen (Chapter 14).

Whilst the PA abandoned common accounting systems and time frames, outside of 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 multiple platforms including the Climate Change Cooperation Index (C3-I), Climate Change Performance Index (CCPI), Climate Laws, Institutions and Measures Index (CLIMI) (Bernauer and Böhmelt 2013) and Energy Transition Index (Singh et al. 2019). International cooperative initiatives between and among non-state (e.g., business, investors and civil society) and sub-national (e.g., city and state) actors have also been emerging, taking the forms of public-private partnerships, private-sector governance initiatives, NGO transnational initiatives, and sub-national transnational initiatives (Bulkeley and Schroeder 2012; Hsu et al. 2018). Literature is mostly positive about the role of these transnational initiatives in facilitating climate action across scales although criticism and caution about their accountability and effectiveness remain (Chan et al. 2016; Michaelowa and Michaelowa 2017; Roger et al. 2017; Widerberg and Pattberg 2017) (Chapter 14).

1.5 Emissions Scenarios and Illustrative Mitigation Pathways (IMPs)

Scenarios are a powerful tool for exploring an uncertain future world against the background of alternative choices and development. Scenarios can be constructed using both narrative and quantitative methods. When these two methods are 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 (Nakicenovic et al. 2000; van Vuuren et al. 2011, 2014) (see also AR6 WGI Section 1.6 for a history of scenarios within the IPCC). This WGIII assessment employs a wide range of qualitative and quantitative scenarios including quantitative scenarios developed through a wide and heterogeneous set of tools ranging from spreadsheets to complex computational models (Annex III: Scenarios and Modelling Methods provides further discussion and examples of computational models).

The concept of an **illustrative pathway (IP)** was introduced in the IPCC Special Report on Global Warming of 1.5°C (IPCC 2018b) to highlight a subset of the quantitative scenarios, drawn from a larger pool of published literature, with specific characteristics that would help represent some of the key findings emerging from the assessment in terms of different strategies, ambitions and options available to achieve the Paris goals.

Integrated assessment models (IAMs) are the primary tools for quantitatively evaluating the technological and macroeconomic implications of decarbonisation, particularly for global long-term pathways. They broadly divide into 'stylised aggregate benefit-cost models', and more complex 'detailed process' IAMs (Weyant 2017), often mirroring the benefit-cost and cost-effective approaches outlined in Section 1.7.1, with more detailed classification in, for example, Nikas et al. (2019). IAMs embody a number of structural and socio-demographic assumptions and include multiple modelling approaches, ranging from economic optimising behaviour to simulation (see Annex III). Detailed process models can include energy system models used to analyse decarbonisation and 'net zero' scenarios by international agencies (e.g., IEA 2020a).

Calculating cost-effective trajectories towards given goals typically involves detailed process IAMs. Often these calculate the dynamic portfolio of technologies consistent with a given climate target. Some track records of technology forecasting in IAMs are outlined in Section 2.5.4, and Box 16.1. Climate targets may be imposed in models in a variety of ways that include, but are not limited to, constraints on emissions or cumulated emissions (carbon budgets), and the pricing of emissions. The time-path of mitigation costs calculated through these models may be translated into 'shadow prices' that (like the social cost of carbon; SCC) offer a benchmark to assess the cost-effectiveness of investments, as used by some governments and companies (Section 1.8.2).

Scenarios in the IPCC and AR6. For AR6, WGIII received submissions of more than 2500 model-based scenarios published in the scientific literature. Such scenarios, which explore different possible evolutions of future energy and land use (with or without climate policy) and associated emissions, are made available through an interactive AR6 scenario database. The main characteristics of pathways in relation to 'net zero' emissions and remaining 'carbon budgets' are summarised in Box 3.5 in Chapter 3. The warming contribution of CO_2 is very closely related to cumulative CO_2 emissions, but the remaining 'carbon budget' for a given warming depends strongly *inter alia* on emissions of other GHGs; for targets below 2°C this may affect the corresponding 'carbon budget' by about ±220 $GtCO_2$, compared to central estimates of around 500 $GtCO_2$ (for 1.5°C) and 1350 $GtCO_2$ (for 2°C) (AR6 WGI, Table SPM.2) (Cross-Working Group Box 1 in Chapter 3).

Pathways and 'net zero'. The date at which the world needs aggregate emissions to reach net zero for Paris-consistent temperature goals depends both on progress in reducing non-CO_2 GHG emissions and near-term progress in reducing CO_2 emissions. Faster progress in the near term extends the date at which net zero must be reached, while conversely, slower near-term progress brings the date even closer to the present. Some of the modelled 1.5°C pathways with limited overshoot cut global CO_2 emissions in half until 2030, which allows for a more gradual decline thereafter, reaching net zero CO_2 after 2050; also, net zero GHGs occurs later, with remaining emissions of some non-CO_2 GHGs compensated by 'net negative' CO_2 (see Glossary and FAQ 1.3, and Cross-Chapter Box 3 in Chapter 3).

Drawing from the scenarios database, five **Illustrative Mitigation Pathways (IMPs)** were defined for this report (Figure 3.5 and Table 1.1). These are introduced here, with a more complete description and discussion provided in Section 3.2.5. These IMPs were chosen to illustrate key themes with respect to mitigation strategies across the entire WGIII assessment. The IMPs embody both a storyline, which describes in narrative form the key socio-economic characteristics of that scenario, and a quantitative illustration providing numerical values that are internally consistent and comparable across chapters of this report. Quantitative IMPs can be associated directly with specific human activities and provide a quantitative point of reference that links activities in different parts of socio-economic systems. Some parts of the report draw on these quantitative scenarios, whilst others use only the narratives. No assessment of the likelihood of each IMP has been made (as they reflect both human choice and deep uncertainty).

The IMPs are organised around two dimensions: the *level of ambition* consistent with meeting Paris goals, and the scenario features (Figure 1.4). The IMPs explore different pathways potentially consistent with meeting the long-term temperature goals of the Paris Agreement. As detailed in Section 3.2.5 and in Chapter 4, a pathway of Gradual Strengthening of current policies (**IMP-*GS***) to 2030, if followed by very fast reductions, may stay below 2°C. The **IMP-*NEG*** pathway, with somewhat deeper emission cutbacks to 2030, might enable 1.5°C to be reached but only after significant overshoot, through the subsequent extensive use of CDR in the energy and

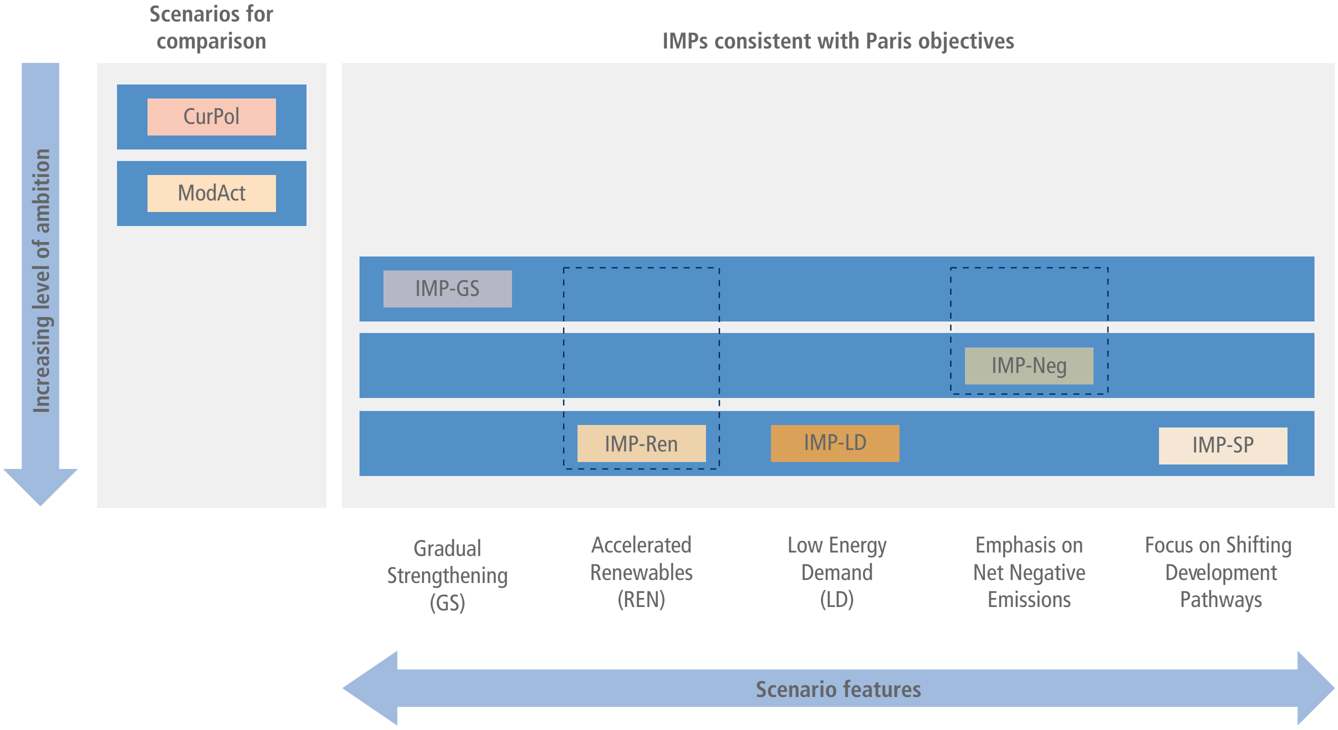

Figure 1.4 | Illustrative Mitigation Pathways (IMPs) used in AR6: illustration of key features and levels of ambition.

Table 1.1 | Illustrative Mitigation Pathways used in AR6.

Scenarios			Full name	Main policy characteristics
CurPol			Current Policies	Implementation of current climate *policies* (mostly as reported in Nationally Determined Contributions (NDCs)), neglecting stated subsequent goals and objectives (e.g., for 2030); only Gradual Strengthening after 2030; grey COVID recovery.
ModAct			Moderate Action	Implementation of current policies *and* achievement of 2030 NDCs, with further strengthening post-2030. Similarly to the situation implied by the diversity of NDCs (both policies and pledges), a fragmented policy landscape remains; mixed COVID recovery.
IMPs	**1.5°C/ <2°C**	**GS**	Gradual Strengthening	Until 2030, primarily current NDCs are implemented; after that a strong universal regime leads to coordinated and rapid decarbonisation actions.
		Neg	Net Negative Emissions	Successful international climate policy regime reduces emissions below ModAct or GS to 2030, but with a focus on the long-term temperature goal, negative emissions kick in at growing scales thereafter, so that mitigation in all sectors also includes a growing and ultimately large reliance on negative emissions, with large 'net global negative' after 2050 to meet 1.5°C after significant overshoot.
		Ren	Renewables	Successful international climate policy regime with immediate action, particularly policies and incentives (including international finance) favouring renewable energy; less emphasis on negative-emission technologies. Rapid deployment and innovation of renewables and systems; electrification of all end use.
		LD	Low Demand	Successful international climate policy regime with immediate action on the demand side; policies and financial incentives favouring reduced demand that in turn leads to early emission reductions; this reduces the decarbonisation effort on the supply side.
		SP	Shifting Pathways	Successful international climate policy regime with a focus on additional SDG policies aiming, for example, at poverty reduction and broader environmental protection. Major transformations shift development towards sustainability and reduced inequality, including deep GHG emissions reduction.

the industry sectors to achieve net negative global emissions, as discussed in Chapters 3, 6, 7, 10 and 12.

Three other IMPs illustrate different features of technology scenarios with more short-term rapid emission reductions, which could deliver outcomes compatible with the temperature range in the Paris Agreement without large overshoot. Based on the assessment in Section 5.3.3, one key mitigation strategy would be to rely on the opportunities for reducing demand (**IMP-*LD***). Chapters 6 and 7–11 show how energy systems based on accelerated deep renewable energy penetration and electrification can also provide a pathway to deep mitigation (**IMP-*REN***). Chapters 3, 4 and 17 provide insights into how shifting development pathways can lead to deep emission reductions and achieve sustainable development goals (**IMP-*SP***).

These pathways can be implemented with different levels of ambition, that can be measured through the classes (C) of temperature levels from the scenarios database, see Chapter 3 (Table 3.2). In the IMP framework, Section 3.2.5 presents and explores quantitative scenarios that can limit warming to 1.5°C (with a probability of 50% or greater, i.e., C1 for the illustrated quantification of LD, SP and REN, and C2 for NEG scenario), along with other GS pathways which keep warming below 2°C with a probability of 67% or greater (C3). In addition to these primary IMPs, the full scenario database contains sensitivity cases that explore alternative warming levels.

In addition to the IMPs two additional scenarios were selected, which illustrate the consequences of current policies and pledges. Current Policies (**CurPol**) explores the consequences of continuing along the path of implemented climate policies in 2020 and only a Gradual Strengthening after that, drawing on numerous such scenarios in the literature. Moderate Action (**ModAct**) explores the impact of implementing NDCs to 2030, but without further strengthening: both result in global mean temperature above 2°C. They provide benchmarks against which to compare the IMPs.

Table 1.1 summarises the main storyline elements of the reference scenarios and each IMP.

What the IMPs do and don't do. The IMPs are, as their name implies, a set of scenarios meant to illustrate some important themes that run through the entire WGIII assessment. They illustrate that the climate outcomes that individuals and society will face in the century ahead depend on individual and societal choices. In addition, they illustrate that there are multiple ways to successful achievement of Paris long-term temperature goals.

IMPs 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 socio-economic pathways against which efforts to implement Paris goals may be set, or to reflect variations in potential regional development pathways. They do not explore issues around income distribution or environmental justice, but assume implicitly that *where* and *how* action occurs can be separated from who pays, in ways to adequately address such issues. They are essentially pathways of technological evolution and demand shifts reflecting broad global trends in social choice. The IMPs do not directly assess issues of realisation linked to the 'drivers and constraints' summarised in our previous section, and the quantifications use, for the most part, models that are grounded mainly in the Aggregate Economics Frameworks (Section 7.1). As such they reflect primarily the geophysical, economic and technological Dimensions of Assessment, but can be assessed in relation to the full set of Feasibility criteria (Section 1.8.1).

Together the IMPs provide illustrations of potential future developments that can be shaped by human choices, including:

Where are current policies and pledges leading? What is needed to reach specific temperature goals under varying assumptions? What are the consequences of different strategies to meet climate targets (i.e., demand-side strategy, a renewable energy strategy or a strategy with a role for net negative emissions)? What are the consequences of delay? What are the implications for other SDGs of various climate mitigation pathways?

1.6 Achieving Mitigation in the Context of Sustainable Development

This chapter now sets out approaches to understanding the mitigation challenge, working from its broad location in the context of wider aspirations for sustainable development, then identifying specific analytic approaches, before summarising the corresponding main dimensions used for the assessment of options and pathways in much of the report.

1.6.1 The Climate Change and Development Connection

Climate change mitigation is one of many goals that societies pursue in the context of sustainable development, as evidenced by the wide range of the Sustainable Development Goals (SDGs). Climate change and sustainable development, as well as development more broadly, are interwoven along multiple and complex lines of relationship (Okereke et al. 2009; Fankhauser and McDermott 2016; Okereke and Massaquoi 2017; Gomez-Echeverri 2018a), as highlighted in several previous IPCC reports (IPCC 2007, 2011a, 2014a, 2018b, 2019a). With its significant negative impact on natural systems, food security and infrastructure, loss of lives and territories, species extinction, conflict health, among several other risks, climate change poses a serious threat to development and wellbeing in both rich and poor countries (IPCC 2007, 2011a, 2014a, 2018b, 2019b). Without serious efforts at mitigation and adaptation, climate change could push millions further into poverty and limit the opportunities for economic development (Chapters 4 and 17). It follows that ambitious climate mitigation is necessary to secure a safe climate within which development and well-being can be pursued and sustained.

At the same time, rapid and large-scale economic development (which has in the past driven climate change through land-use change and dependence on fossil fuels), is widely seen as needed to improve global well-being and lift millions especially in low- and middle-income countries out of poverty (Chen et al. 2017; Mugambiwa and Tirivangasi 2017; Lu et al. 2019; Baarsch et al. 2020) (Figure 1.6). This strand of literature emphasises the importance of economic growth including for tackling climate change itself, pointing to the relationship between economic development and climate resilience as well as the role of industry-powered technologies such as electric vehicles in reducing GHG levels and promoting well-being (Heinrichs et al. 2014; Kasztelan 2017). Yet, others argue that the character of social and economic development produced by the nature of capitalist society (Pelling and Manuel-Navarrete 2011; Koch 2012; Malm 2016) is ultimately unsustainable.

There are at least two major implications of the very close link between climate change and development as outlined above. The first is that the choice of development paths made by countries and regions have significant consequences for GHG emissions and efforts to combat climate change (Chapters 2, 3, 4, 5 and 14). The second is that climate mitigation at local, national and global levels 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) (Chapters 4, 6 and 10).

As a key staple of IPCC reports and the global climate policy landscape (IPCC 2007, 2014b; van Vuuren et al. 2017; Gidden et al. 2019; Quilcaille et al. 2019) (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 (Section 3.6). The close links are also recognised in the PA (Section 1.3.1).

The impact of climate change in limiting well-being 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 2015; Tosam and Mbih 2015; Mugambiwa and Tirivangasi 2017). The wide variation in the contribution to, and impact of climate change within and across countries makes equity, inequality, justice, and poverty eradication, inescapable aspects of the relationship between sustainable development and climate change (Okereke and Coventry 2016; Klinsky et al. 2017; Reckien et al. 2017; Bos and Gupta 2019; Kayal et al. 2019; Diffenbaugh and Burke 2019; Baarsch et al. 2020). This underpins the conclusion, as commonly expressed, that climate action needs to be pursued in the context of sustainable development, equity and poverty eradication (Smit et al. 2001; Tschakert and Olsson 2005; IPCC 2014a, 2018b; Klinsky and Winkler 2014).

1.6.2 Concepts and Frameworks for Integrating Climate Mitigation and Development

At one level, sustainable development can be seen as a meta framework for integrating climate action with other global sustainability goals (Casadio Tarabusi and Guarini 2013; Antal and Van Den Bergh 2016). Fundamentally, the concept of sustainable development underscores the interlinkages and interdependence of human and natural systems and the need to balance economic, social, and environmental (including climate pollution) aspects in development planning and processes (Nunan 2017; Gomez-Echeverri 2018b; Zhenmin and Espinosa 2019).

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, how to measure well-being, which goals to set, and the means through which such goals might be pursued (Arrow et al. 2011; Dasgupta et al. 2015; Michelsen et al. 2016; Okereke and Massaquoi 2017; UNEP 2018b; Haberl et al. 2019; Shang et al. 2019; Sugiawan et al. 2019).

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 of the literature recognises that despite its limitations, sustainable development with its emphasis on integrating social, economic and environmental goals, provides a more comprehensive approach to the pursuit of planetary health and human well-being. Sustainable development is then not a static objective but a dynamic framework for measuring human progress (Costanza et al. 2016; Fotis and Polemis 2018), 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; Bickersteth et al. 2017) and more recently climate-resilient development (CRD) (Fankhauser and McDermott 2016; Henly-Shepard et al. 2018; IPCC 2018b) have all emerged as ideas, tools and frameworks, intended to bring together the goals of climate mitigation and the SDGs, as well as development more broadly. Figure 1.5 suggests that the prospects for realising a climate-resilient and equitable world are enhanced by a process of transformation and development trajectories that seek to limit global warming while also achieving the SDGs. The SDGs represent medium-term goals, and long-term sustainability requires continued effort to keep the world along a climate-resilient development path. A key feature of development or transformation pathways that achieve a climate-resilient world is that they maximise the synergies and minimise the trade-offs between climate mitigation and other sustainable development goals (Klausbruckner et al. 2016; Thornton and Comberti 2017; Wüstemann et al. 2017; Dagnachew et al. 2018; Fuso Nerini et al. 2018; Mainali et al. 2018). Crucially, the nature of trade-offs and timing of related decisions will vary across countries depending on circumstances including the level of development, capability and access to resources (Cross-Chapter Box 5, Shifting Development Paths to Increase Sustainability, in Chapter 4).

Other concepts such as 'Doughnut Economics' (Raworth 2018), ecological modernisation, and mainstreaming are also used to convey ideals of development pathways that take sustainability, climate mitigation, and environmental limits seriously (Dale et al. 2015a). Mainstreaming focuses on incorporating climate change into national development activities, such as the building of infrastructure (Wamsler and Pauleit 2016; Runhaar et al. 2018). The 'green economy' and green growth – growth without undermining ecological systems, partly by gaining economic value from cleaner technologies and systems and is inclusive and equitable in its outcomes – 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; Capasso et al. 2019; Song et al. 2020; Hao et al. 2021). However, critics argue that green economy ultimately emphasises economic growth to the detriment of other important aspects of human welfare such as social

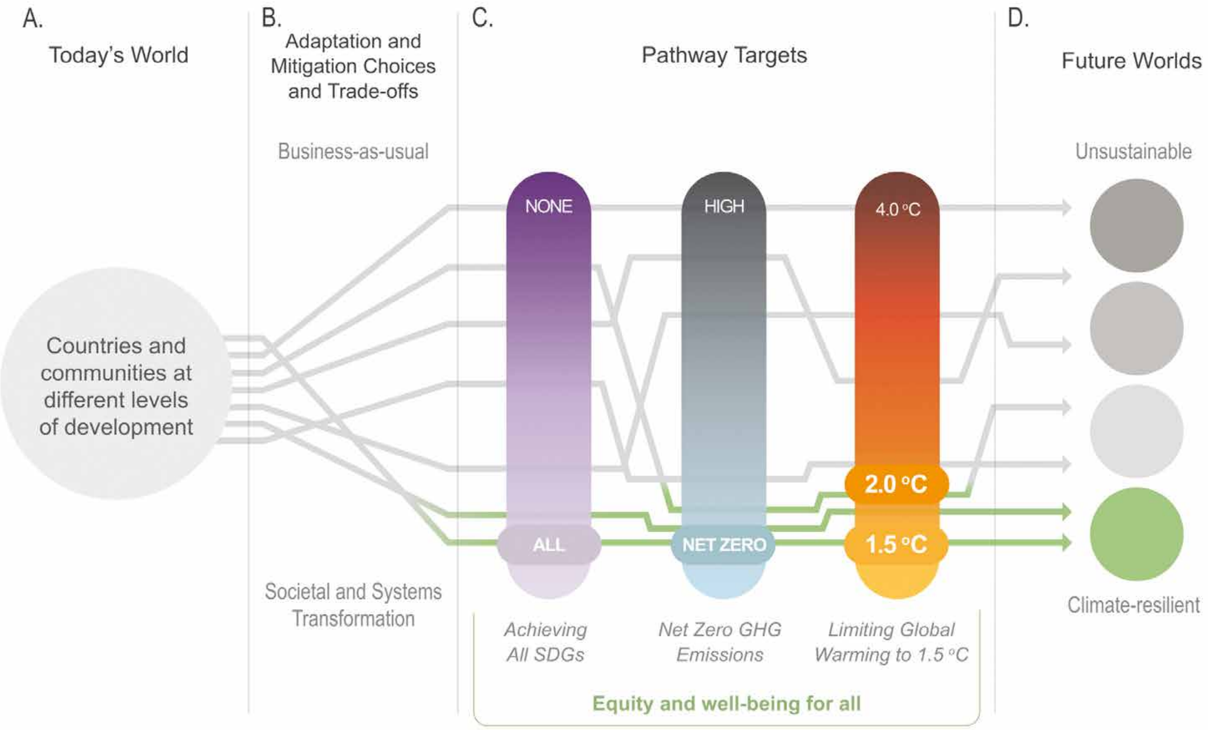

Figure 1.5 | A climate-resilient and equitable world requires limiting global warming while achieving the Sustainable Development Goals (SDGs). Source: IPCC (2018b).

justice (Death 2014; Adelman 2015; Kamuti 2015), and challenge the central idea that it is possible to decouple economic activity and growth (measured as GDP increment) from increasing use of biophysical resources (raw materials, energy) (Jackson and Victor 2019; Parrique et al. 2019; Haberl et al. 2020; Hickel and Kallis 2020; Vadén et al. 2020).

Literature on degrowth, post growth, and post development questions the sustainability and imperative of more growth especially in already industrialised countries and argues that prosperity and the 'Good Life' are not immutably tied to economic growth (Asara et al. 2015; Escobar 2015; Latouche 2018; Kallis 2019) (Section 5.2.1). The concept of Just Transition also stresses the need to integrate justice concerns so as to not impose hardship on already marginalised populations within and between countries (Evans and Phelan 2016; Goddard and Farrelly 2018; Heffron and McCauley 2018; Smith, Jackie and Patterson 2018; McCauley and Heffron 2018) (Section 1.7.2). The key insight is that pursuing climate goals in the context of sustainable development requires holistic thinking including on how to measure well-being, serious consideration of the notion of ecological limits, at least some level of decoupling and certainly choices and decision-making approaches that exploit and maximise the synergy and minimise the trade-off between climate mitigation and other sustainable development goals. It also requires consideration of equity and justice within and between countries. However, ideas of a synergistic relationship between development and climate mitigation can sometimes offer limited practical guidelines for reconciling the tensions that are often present in practical policymaking (Ferguson et al. 2014; Dale et al. 2015b; Kasztelan 2017; Kotzé 2018).

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

Climate action can be conceptualised as both a stand-alone and cross-cutting issue in the 2030 SDGs (Makomere and Liti Mbeva 2018), given that several of the other goals such as ending poverty (SDG 1), zero hunger (SDG 2), good health and well-being (SDG 3), and affordable and clean energy (SDG 7), among many others, are related to climate change (Figure 3.39).

In addition to galvanising global collective action, the SDGs provide concrete themes, targets and indicators for measuring human progress to sustainability (Kanie and Biermann 2017). The SDGs also provide a basis for exploring the synergies and trade-offs between sustainable development and climate change mitigation (Pradhan et al. 2017; Fuso Nerini et al. 2018; Mainali et al. 2018; Makomere and Liti Mbeva 2018). Progress to date (Sachs et al. 2016) shows fulfilling SDGs is a challenge for all groups of countries – developed and developing – even though the challenge differs between countries and regions (Pradhan et al. 2017).

Historically, the industrialisation associated with economic development has involved a strong relationship with GHG emissions (Section 5.2.1). Figure 1.6 shows per-capita GHG emissions on the vertical axis and Historical Index of Human Development (HIHD) levels (Prados de la Escosura 2015) on the horizontal axis.[7] The grey line shows historic global average GHG emissions per capita and levels of human development over time, from 1870 to 2014. The current positions of different regions are shown by bubbles, with sizes representing total GHG emissions. Figure 1.6 also shows the estimated position of the SDGs zone for the year 2030, and a 'sustainable development corridor' as countries reach towards higher HDI and lower emissions. To fulfil the SDGs, including SDG 13 (climate action), the historic relationship needs to change.

The top of the SDG zone is situated around the global per-capita GHG emissions level of 5 tCO_2-eq required for the world to be path towards fulfilling the Paris Agreement.[8] The horizontal position of the SDG zone is estimated based on the HIHD levels (Prados de la Escosura 2015) of countries that have been shown to either have achieved, or have some challenges, when it comes to SDG 3, SDG 4 and SDG 8 (Sachs et al. 2016), as these SDGs are related to the constituent parts of the HIHD. Beyond 2030, the sustainable development corridor allows for increasing levels of human development while lowering per-capita GHG emissions.

Figure 1.6 shows that at present, regions with HIHD levels of around 0.5 all have emissions at or above about 5 tCO_2-eq per capita (even more so on a consumption footprint basis; see Figure 1.1c,d), but there are wide variations within this. Indeed, there are regions with HIHD levels above 0.8 which have GHG per-capita emissions lower than several with HIHD levels of around 0.5. The mitigation challenge involves countries at many different stages of development seeking paths towards higher welfare with low emissions.

From Figure 1.6, there are two distinct dimensions to sustainable development pathways for fulfilling the SDGs. In terms of per-capita GHG emissions (the vertical), some regions have such low levels that they could increase and still be below the global average required in 2030 for the world to be on path to fulfil the Paris Agreement. Meanwhile, other regions with high per-capita GHG emissions would require a rapid transformation in technologies and practices. It is against this background that Dubash (2019) emphasises placing the need for urgent action on climate change in the context of domestic political priorities and the institutions within which national frameworks are crystallised.

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[7] The Historical Index of Human Development (HIHD) emulates the widely used Human Development Index (HDI) as they both summarise in indexes the key human development dimensions consisting of a healthy life, knowledge and a decent standard of living. HDI is based on: life expectancy, expected years of schooling of children, the mean years of schooling of the adult population, and gross national income (GNI) per capita adjusted for purchasing power; the HIHD is based on: life expectancy at birth, adult literacy rates, educational enrolment rates, and GDP per capita, and is used in Figure 1.6 because it is available for a longer time series (Prados de la Escosura 2015).

[8] Based on global population projections of between 8 and 8.5 billion people in 2030, and GHG emissions levels from the C1, C2 and C3 categories of scenarios in Table 3.2 and Box 3.7.

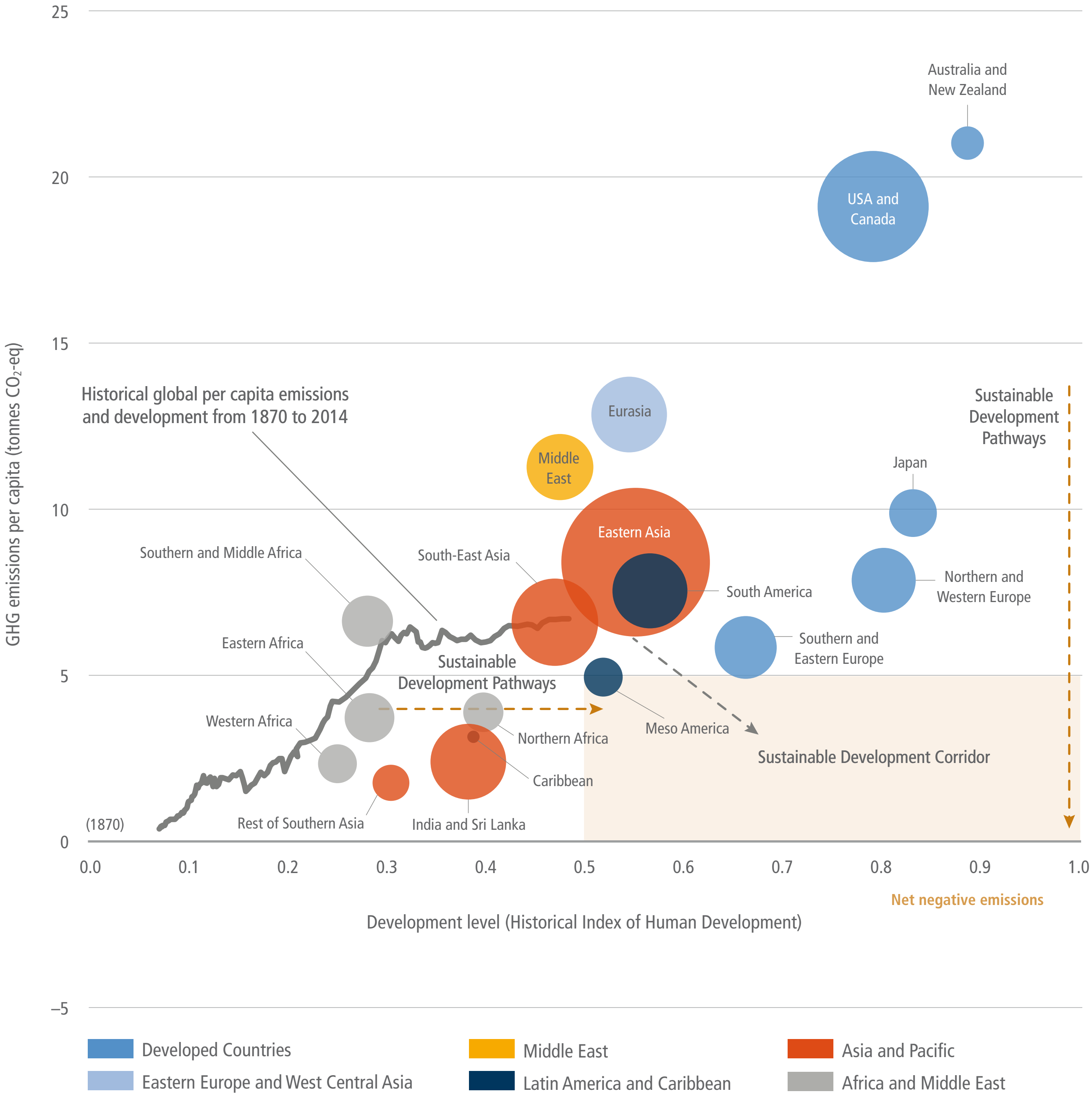

Figure 1.6 | Sustainable development pathways towards fulfilling the Sustainable Development Goals (SDGs). The graph shows global average per-capita GHG emissions (vertical axis) and relative 'Historic Index of Human Development' (HIHD) levels (horizontal) have increased globally since the industrial revolution (grey line). The bubbles on the graph show regional per-capita GHG emissions and human development levels in the year 2015, illustrating large disparities. Pathways towards fulfilling the Paris Agreement (and SDG 13) involve global average per-capita GHG emissions below about 5 tCO_2-eq by 2030. Likewise, to fulfil SDGs 3, 4 and 8, HIHD levels (see footnote 7) need to be at least 0.5 or greater. This suggests a 'sustainable development zone' for year 2030 (in pale brown); the in-figure text also suggests a 'sustainable development corridor', where countries limit per-capita GHG emissions while improving levels of human development over time. The emphasis of pathways into the sustainable development zone differ (dashed brown arrows), but in each case transformations are needed in how human development is attained while limiting GHG emissions.

Concerns over equity in the context of growing global inequality and very tight remaining global carbon budgets have motivated an emphasis on equitable access to sustainable development (Peters et al. 2015; Kartha et al. 2018b; Matthews et al. 2019; van den Berg et al. 2019). This literature emphasises the need for less developed countries to have sufficient room for development while addressing climate change (Winkler et al. 2013; Pan et al. 2014; Gajevic Sayegh 2017; Robinson and Shine 2018; Warlenius 2018). Meanwhile, many countries reliant on fossil fuels, related technologies and economic activities, are eager to ensure tax revenues are maintained, workers and industries have income and justice is embedded in the economic transformations required to limit GHG emissions (Cronin et al. 2021).

Correlation between CO_2 emission intensity, or absolute emission and gross domestic product growth, is not rigid, unambiguous and deterministic (Ojekunle et al. 2015), but the extent to which SDGs and economic growth expectations can be fulfilled while decoupling GHG emissions remains a concern (Haberl et al. 2020; Hickel and Kallis 2020). Below some thresholds of absolute poverty, more consumption is necessary for development to lead to well-being (Section 5.2.1.1), which may not be the case at higher levels of consumption (Lamb and Steinberger 2017; Steinberger et al. 2020) (Section 1.7.2).

In conclusion, 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 (Najam 2005; Okereke and Massaquoi 2017; Makomere and Liti Mbeva 2018; Dooley et al. 2021). It also requires a focus on equity considerations to avoid climate-induced harm, as well as unfairness that can result from urgent actions to cut emissions (Pan et al. 2014; Robiou du Pont et al. 2017; Kartha et al. 2018a). This is ever more important as the diminishing carbon budget has intensified debates on which countries should have the greatest claim to the 'remaining space' for emissions (Raupach et al. 2014) or production (McGlade and Ekins 2015), amplified by persistent concerns over the insufficiency of support for means of implementation, to support ambitious mitigation efforts (Pickering et al. 2015; Weikmans and Roberts 2019).

1.7 Four Analytic Frameworks for Understanding Mitigation Response Strategies

Climate change is unprecedented in its scope (sectors, actors and countries), depth (major transformations) and time scales (over generations). As such, it creates unique challenges for analysis. It has been called 'the greatest market failure in history' (Stern 2007); the 'perfect moral storm' (Gardiner 2006) and a 'super wicked problem' (Lazarus 2009; Levin et al. 2012) – one which appears difficult to solve through the traditional tools and assumptions of social organisation and analysis.

To complement the extensive literature on risks and decision-making under uncertainty reviewed in AR6 WGII (notably, Chapter 19), this section summarises insights and developments in key analytic frameworks and tools particularly relevant to understanding specific mitigation strategies, policies and other actions, including explaining the observed if limited progress to date. Organised partly as reflected in the quotes above, these include *aggregated* (principally, economic) frameworks to evaluate system-level choices; *ethical* perspectives on values and equity including stages of development and distributional concerns; and *transition* frameworks which focus on the processes and actors involved in major technological and social transitions. These need to be complemented by a fourth set of approaches which shine more light on *psychological/behavioural and political* factors. All these frameworks are relevant, and together they point to the multiple perspectives and actions required if the positive drivers of emission reduction summarised in Section 4 are to outweigh the barriers and overcome the constraints.

1.7.1 Aggregated Approaches: Economic Efficiency and Global Dynamics of Mitigation

Some of the most established and influential approaches to understanding the *aggregate* causes and consequences of climate change and mitigation across societies, draw upon economic theories and modelling to generate global emission pathways in the absence of climate policies and to study alternative mitigation pathways (described in detail in Section 3.2.5, and Appendix 3). The underlying economic concepts aggregate wealth or other measures of welfare based on utilitarian ethical foundations, and in most applications, a number of additional assumptions detailed in AR5 (Chapters 2 and 3).

1.7.1.1 Cost-benefit Analysis and Cost-effectiveness Analysis

Such global aggregate economic studies coalesce around two main questions. One, as pioneered by Nordhaus (1992, 2008) attempts to monetise overall climate damages and mitigation costs so as to strike a 'cost-benefit optimum' pathway. More detailed and empirically-grounded 'cost-effectiveness analysis' explores pathways that would minimise mitigation costs (Ekholm 2014; IPCC 2014a Section 2.5; Weyant 2017) for given targets (e.g., as agreed in international negotiations, see Section 3.2 in Chapter 3). Both approaches recognise that resources are limited and climate change competes with other priorities in government policymaking, and are generally examined with some form of Integrated Assessment Model (IAM) (Section 1.5 and Appendix III). Depending on the regional disaggregation of the modelling tools used and on the scope of the analyses, these studies may or may not address distributional aspects within and across nations associated with climate policies (Bauer et al. 2020).

For at least 10 to 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 to 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' (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. 2019); valuations should reflect that cutting emissions reduces not only average expected damages, but also the risk of catastrophic events (IWG 2021).

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; Stern 2007; Dasgupta 2008). Its importance is underlined in analytical Integrated Assessment Models (IAMs) (Golosov et al. 2014; van den Bijgaart et al. 2016; van der Ploeg and Rezai 2019) (Annex III). Economic literature suggests applying risk-free, public, and long-term interest rates when evaluating overall climate strategy (Weitzman 2001; Dasgupta 2008; Arrow et al. 2013; Groom and Hepburn 2017). Expert elicitations indicate values around 2% (majority) to 3% (Drupp et al. 2018). This is lower than in many of the studies reviewed in earlier IPCC assessments, and many IAM studies since, and by increasing the weight accorded to the future would increase current 'optimal effort'. The US 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). Individual projects may require specific risk adjustments.

Distribution of impacts. The economic damages from climate change at the nationally aggregated and sub-national level are very diverse (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 policymaking (Keohane and Oppenheimer 2016). Economics acknowledges there is no single, objectively defined 'social welfare function' (IPCC 1995, 2014a). This applies also to the distribution of responses: both underline the relevance of equity (next section) and global negotiations to determine national and collective objectives.

Obvious limitations arise from these multiple difficulties in assessing an objective, globally acceptable single estimate of climate change damages (e.g., Arrow et al. 2013; Pindyck 2013; Auffhammer 2018; Stern et al. 2021), with some arguing that agreement on a specific value can never be expected (Rosen and Guenther 2015; Pezzey 2018). A new generation of cost-benefits analysis, based on projections of actual observed damages, results in stronger mitigation efforts as optimal (Glanemann et al. 2020; Hänsel et al. 2020). 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 (Cross-Working Group Box 1 in Chapter 3).

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) and Held (2019) also 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, to improve the assessment of net costs (Drouet et al. 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). One review considered that 'the best estimate' of the optimal (near-term) level 'still ranges from a few tens to a few hundreds of dollars per ton of carbon' (Tol 2018), with various recent studies in the hundreds, taking account of risks (Taconet et al. 2019), learning (Ekholm 2018) and distribution (Ricke et al. 2018). In addition to the importance of uncertainty/risk, aggregation, and realistic damage functions as noted, on which some progress has been made, some reviews additionally critique how IAMs represent abatement costs in terms of energy efficiency and innovation (e.g., Farmer et al. 2015; Rosen and Guenther 2015; Keen 2021) (Sections 1.7.3 and 1.7.4). IAMs may better reflect associated 'rebound' at system level (Saunders et al. 2021), and 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 per tCO_2-eq across 16 studies (Karlsson et al. 2020) – complement global with additional local benefits (Table 1.2).

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 1000 $GtCO_2$, reducing the discount rate from 5% to 2% would more than double current efforts, limit 'overshoot', greatly reduce a late rush to negative emissions, and improve intergenerational justice by more evenly distributing policy costs across the 21st century.

1.7.1.2 Dynamic Efficiency and Uncertainty

Care is required to clarify what is optimised (Dietz and Venmans 2019). 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 carbon dioxide removal (CDR). 'Cost-effective' optimisations generate less initial effort than *equivalent* cost-benefit models (Dietz and Venmans 2019; Gollier 2021) as they do not incorporate benefits of reducing impacts earlier.

'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). Chapter 3 (Section 3.5) discusses interactions between near-, medium- and long-term actions in global pathways, particularly vis-à-vis inertia. Also, 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 include endogenous technical change (as reviewed in Yang et al. 2018 and Grubb et al. 2021b) (Annex III).

These dynamic and uncertainty effects typically justify greater upfront effort (Kalkuhl et al. 2012; Bertram et al. 2015), including accelerated international diffusion (Schultes et al. 2018), and strengthen optimal initial effort in cost-benefit models (Baldwin et al. 2020; Grubb et al. 2021b). Approaches to risk premia common in finance would similarly amplify the initial mitigation effort, declining as uncertainties reduce (Daniel et al. 2019).

1.7.1.3 Disequilibrium, Complex Systems and Evolutionary Approaches

Other approaches to aggregate evaluation draw on various branches of intrinsically non-equilibrium theories (e.g., Chang 2014). These including long-standing theories from the 1930s (e.g., Schumpeter 1934; Keynes 1936) to understand situations of structurally underemployed resources, potential financial instabilities (Minsky 1986), and related economic approaches which emphasise time dimensions (e.g., recent reviews in Legrand and Hagemann 2017; Stern 2018). More recently developing have been formal economic theories of endogenous growth building on, for example, Romer (1986), and developments of Schumpeterian creative destruction (Aghion et al. 2021) and evolutionary economic theories which abandon any notion of full or stable resource utilisation even as a reference concept (Nelson and Winter 1982; Freeman and Perez 1988; Carlsson and Stankiewicz 1991; Freeman and Louçã 2001; Perez 2001).

The latter especially are technically grounded in complex system theories (e.g., Arthur 1989, 1999; Beinhocker 2007; Hidalgo and Hausmann 2009). These take inherently dynamic views of economies as continually evolving systems with continuously unfolding and path-dependent properties, and emphasise uncertainty in contrast to any predictable or default optimality. Such approaches have been variously applied in policy evaluation (Walton 2014; Moore et al. 2018), and specifically for global decarbonisation (e.g., Barker and Crawford-Brown 2014) using global simulation models. Because these have no natural reference 'least lost' trajectory, they illustrate varied and divergent pathways and tend to emphasise the diversity of possibilities and relevant policies, particularly linked to innovation and potentially 'sensitive intervention points' (Farmer et al. 2019) (Section 1.7.3). They also 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, Section 15.6.3 and Box 15.7).

1.7.2 Ethical Approaches

Gardiner's (2011) book on climate change as 'The Perfect Moral Storm' identified 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, amplified by the intrinsic inequity of wealthy big emitters impacting particularly poorer victims. He argues that these are exacerbated by a third, *theoretical* failure to acknowledge a central need for 'moral sensitivity, compassion, transnational and transgenerational care, and other forms of ethical concern to rise to the surface' to help guide effective climate action. As noted in Section 1.4.6, however, equity and ethics are both a driver of and constraint on mitigation.

1.7.2.1 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 2014a Chapter 3). Most of this work is offered as a counterpoint or critique to mainstream literature's focus on the safeguarding 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 alternative values that promote deep decarbonisation, environmental conservation and protection across all levels of society is then viewed as foundational component of climate-resilient and sustainable development and for achieving human rights, and a safe climate world (Evensen 2015; Jolly et al. 2015; Popescu 2016; Tàbara et al. 2019). The UN Human Rights Office of the High Commissioner has highlighted the potentially crucial role of human rights in relation to climate change (UNHCR 2018). While acknowledging the role of policy, technology, and finance, the 'managerialist' approaches, that emphasise 'technical governance' and fail to challenge the deeper values that underpin society, may not secure the deep change required to avert dangerous climate change and other environmental challenges (Hartzell-Nichols 2014; Steinberger et al. 2020).

Social justice perspectives emphasise the distribution of responsibilities, rights, and mutual obligations between nations in navigating societal transformations (Gawel and Kuhlicke 2017; Leach et al. 2018; Patterson et al. 2018). Current approaches to climate action may fail to match what is required by science because they tend to circumvent constraints on human behaviour, especially constraints on economic interest and activity. Related literature explores 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 emphasis on trust and solidarity as foundations for global cooperation on climate change (Jolly et al. 2015). A key obstacle is that the economic interests of states tend to be stronger than the drivers for urgent climate action (Bain 2017).

Short-term interests of stakeholders are acknowledged to impede the reflection and deliberation needed for climate mitigation and adaptation planning (Hackmann 2016; Sussman et al. 2016; Schlosberg et al. 2017; Herrick 2018). Situationally appropriate mitigation and adaptation policies at both national and international level may require more ethical self-reflection (Herrick 2018), including self-transcendent values such as universalism and benevolence, and moderation which are positively related to pro-environmental behaviours (Jonsson and Nilsson 2014; Katz-Gerro et al. 2015; Braito et al. 2017; Howell and Allen 2017).

Another strong theme in the literature concerns recognition of interdependence including the intimate relationship between humans and the non-human world (Hannis 2016; Gupta and Racherla 2018; Howell and Allen 2017), with such ecological interdependence offered as an organising principle for enduring transformation to sustainability. 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; Shackleton et al. 2017; Himes-Cornell et al. 2018). There has been increasing attention on ways to design climate policy frameworks to help reconcile ecological virtue (with its emphasis on the collective) with 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 tendencies to 'free ride', and to achieve behavioural changes often associated with tackling climate change (Section 5.2.1).

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).

1.7.2.2 Equity and Representation: International Public Choice Across Time and Space

Equity perspectives highlight three asymmetries relevant for climate change (Okereke and Coventry 2016; Okereke 2017) (Section 1.4.6). *Asymmetry in contribution* highlights different contributions to climate change both in historical and current terms, and applies both within and between states as well as between generations (Caney 2016; Heyward and Roser 2016). *Asymmetry in impacts* highlights 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 (IPCC 2014a; Shi et al. 2016). *Asymmetry in capacity* highlights differences of power between groups and nations to participate in climate decision and governance, including the capacity to implement mitigation and adaptation measures.

If attention is not paid to 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 involves a central place for consideration of justice, both within and between countries (Chapters 4 and 14). Arguments that the injustices following from climate change are symptomatic of a more fundamental structural injustice in social relations, are taken to imply a need to address the deeper inequities within societies (Routledge et al. 2018).

Climate change and climate policies affect countries and people differently, with the poor likely to be more affected (Section 1.6.1). Ideas of Just Transitions (outlined in Section 1.8.2.) often have a national focus in the literature, but also imply that mitigation should not increase the asymmetries between rich and poor countries, implying a desire for transitions which seek to reduce (or at least avoid adverse) distributional affects. Thus, it comes into play in the timing of zero emissions (Chapters 3 and 14). International climate finance in which rich countries finance mitigation and adaptation in poor countries is also essential for reducing the asymmetries between rich and poor countries (Section 1.6.3 and Chapter 15).

Equity across generations – the distribution between the present and future generations – also matters. One aspect is discounting (Section 1.7.1). Another approach has been to study the burdens on each generation following from the transition to low-carbon economies (IPCC 2014a Chapter 3) (Cross-Working Group Box 3 in Chapter 12). Suggestions include shifting more investments into 'natural capital', so that future generations will inherit less physical capital but a better environment, or financing mitigation efforts today using governmental debt redeemed by future generations (Heijdra et al. 2006; Broome 2012; Karp and Rezai 2014; Hoel et al. 2019).

1.7.3 Transition and Transformation Processes

This report uses the term *transition* as the process, and *transformation* as the overall change or outcome, of large-scale shifts in technological, economic and social systems, called socio-technical systems in the innovation literature. 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 1.7 (lower panel). These dynamics arise from interactions between innovation (in technologies, companies and other organisations), markets, infrastructure and institutions, at multiple levels (Geels et al. 2017; Kramer 2018). Consequently, interdisciplinary perspectives are needed (Turnheim et al. 2015; Geels et al. 2016; Hof et al. 2020). Beyond aggregated economic perspectives on dynamics (Section 1.7.1.2), these emphasise the multiple actors and processes involved.

Technological Innovation Systems (TIS) frameworks (Section 16.4) focus on processes and policies of early innovation and 'emergence', which combine experimentation and commercialisation, involving *Strategic Niche Management* (Rip and Kemp 1998; Geels and Raven 2006). Literatures on the wider processes of transition highlight different stages (e.g., Cross-Chapter Box 12 in Chapter 16) and scales across three main levels, most generally termed *micro, meso and macro* (Rotmans et al. 2001).

The widely-used *Multi-Level Perspective* or MLP (Geels 2002) identifies the meso level as the established 'socio-technical (ST) regime', a set of interrelated sub-systems which define rules and regulatory structures around existing technologies and practices. The micro level is an ecosystem of varied niche alternatives, and overlaying the ST regime is a macro 'landscape' level. Transitions often start with niche alternatives (Grin et al. 2010; Köhler et al. 2019), which may break through to wider diffusion (second stage in Figure 1.8), especially if external landscape developments 'create pressures on the regime that lead to cracks, tensions and windows of opportunity' (Rotmans et al. 2001; Geels 2010); an example is climate change putting sustained pressure on current regimes of energy production and consumption (Kuzemko et al. 2016). There are continual interactions between landscape, regime and niches, with varied implications for *Transition Management* (Rotmans et al. 2001; Loorbach 2010).

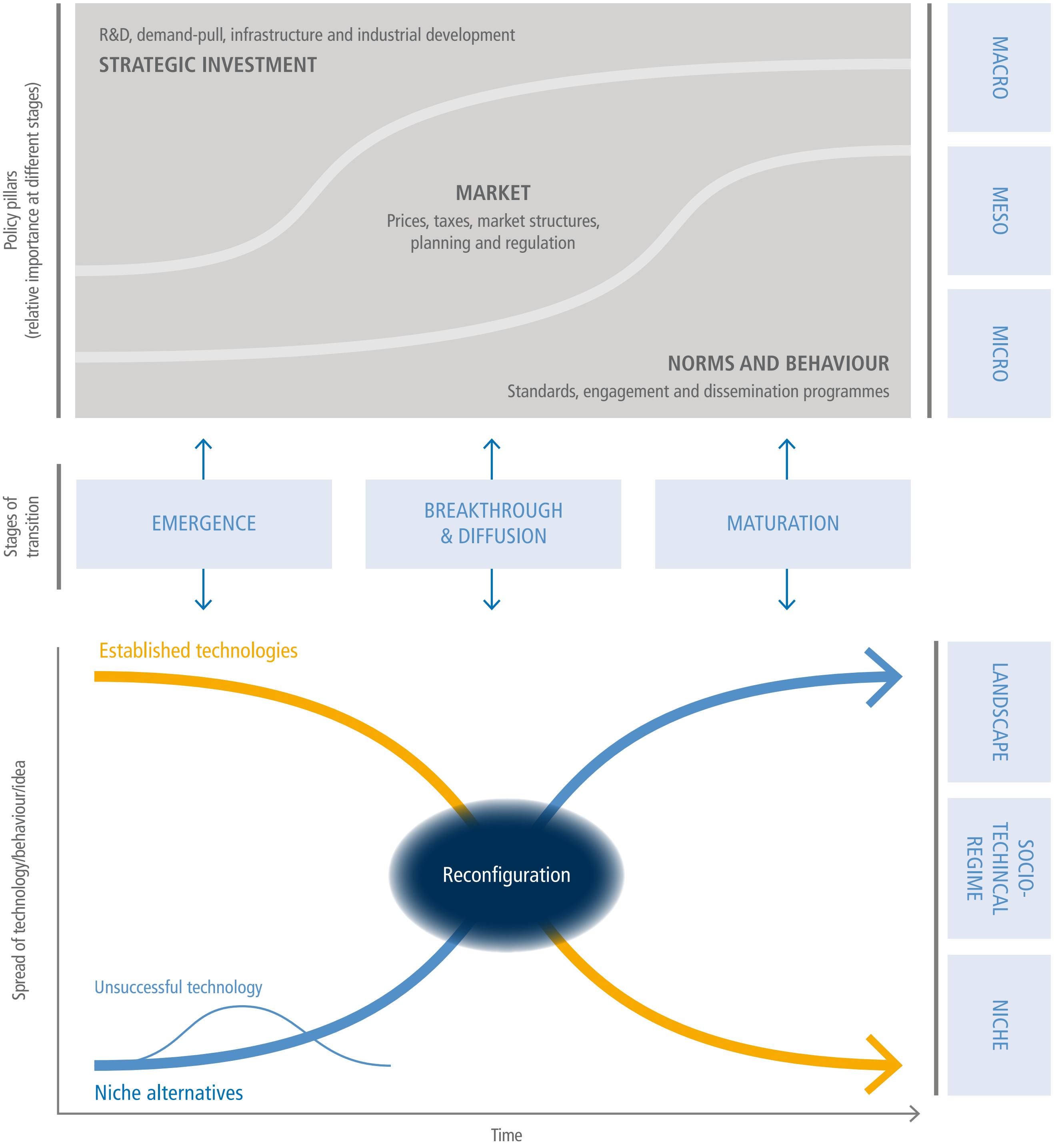

Figure 1.7 | Transition dynamics: levels, policies and processes. Note: the lower panel illustrates growth of innovative technologies or practices, which if successful emerge from niches into an S-shape dynamic of exponential growth. The diffusion stage often involves new infrastructure and reconfiguration of existing market and regulatory structures (known in the literature as the 'socio-technical regime'). During the phase of more widespread diffusion, growth levels off to linear, then slows as the industry and market matures. The processes displace incumbent technologies/practices which decline, initially slowly but then at an accelerating pace. Many related literatures identify three main levels with different characteristics, most generally termed micro, meso and macro. Transitions can be accelerated by policies appropriately targeted, which may be similarly grouped and sequenced (upper panel) in terms of three corresponding pillars of policy (Section 1.7.3): generally all are relevant, but their relative importance differs according to the stage of the transition.

In contrast to standard economic metrics of marginal or smooth change (e.g., elasticities), transition theories emphasise interdisciplinary approaches and the non-linear dynamics, social, economic and environmental aspects of transitions to sustainability (Cherp et al. 2018; Köhler et al. 2018). This may explain persistent tendencies to underestimate the exponential pace of change now being observed in renewable electricity (Chapters 2 and 6) and emerging in mobility (Chapter 10).

Recent decades have seen parallel broadening of economic perspectives and theories. Building also on the New Institutional Economics literatures, Building on the New Institutional Economics literature (Williamson 2000), Grubb et al. (2014, 2015) classify these into three 'domains of economic decision-making' associated with different branches of economic theory, respectively (i) *behavioural and organisational*; (ii) *neoclassical and welfare*; and (iii) *evolutionary and institutional*. Like MLP, these are related to different social and temporal scales, as applied also in studying the 'adaptive finance' in UK electricity transition (Hall et al. 2017). There are significant differences but these approaches all point to understanding the characteristics of different actors, notably, individuals/local actors; larger corporate organisations (public or private); and (mainly) public authorities, each with different decision-making characteristics.

Sustainability may require purposeful actions at the different levels to foster the growth of sustainable technologies and practices, including support for niche alternatives (Grin et al. 2010). The middle level (established 'socio-technical regime') tends to resist major change, reforms generally involve pressures from the other two levels. Thus, transitions can be accelerated by policies appropriately targeting relevant actors at the different levels (Köhler et al. 2019), the foundations for 'three pillars of policy' (Grubb et al. 2014), which logically evolve in the course of transition (Figure 2.6a). Incumbent industries have to adapt if they are to thrive within the growth of new systems. Policy may need to balance 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), and help manage declining industries (Koasidis et al. 2020).

There is usually a social dimension to such transitions. Key elements 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, including industry, and agriculture which then doubled its productivity over 15 years (Roberts and Geels 2019b). In practice, climate change may involve a combination of (reactive) transformational adaptation, and (proactive) societal transformation (Feola 2015), the latter seen as reorientation (including values and norms) in a sustainable direction (Section 5.4), including, for example, 'democratisation' in energy systems (Sorman et al. 2020). Business change management principles could be relevant to support positive social change (Stephan et al. 2016). Overall, effective transitions rest on appropriate enabling conditions, which can also link socio-technical transitions to broader development pathways (Cross-Chapter Box 12 in Chapter 16).

Transition theories tend to come from very different disciplines and approaches compared to either economics or other social sciences, with less quantification, notwithstanding evolutionary and complex system models (Section 1.7.1.3). However, a few distinct types of quantitative models of 'socio-technical energy transition' (Li et al. 2015) have emerged. For policy evaluation, transitions can be viewed as processes in which dynamic efficiency (Section 1.7.2) dominates over static allocative efficiency, with potential 'positive intervention points' (Farmer et al. 2019). Given inherent uncertainties, there are obvious risks (e.g., Alic and Sarewitz 2016). All this may make an evaluation framework of *risks and opportunities* more appropriate than traditional cost-benefit (Mercure et al. 2021), and (drawing on lessons from renewables and electric vehicles) create foundations for sector-based international 'positive sum cooperation' in climate mitigation (Sharpe and Lenton 2021).

1.7.4 Approaches From Psychology and Politics of Changing Course

The continued increase in global emissions to 2019, despite three decades of scientific warnings of ever-greater clarity and urgency, motivates growing attention in the literature to the psychological 'faults of our rationality' (Bryck and Ellis 2016), and the political nature of climate mitigation.

1.7.4.1 Psychological and Behavioural Dimensions

The AR5 emphasised that decision processes often include both deliberate ('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 the status quo and aversion to perceived risks and ambiguity (Kahneman and Tversky 1979). 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 can take the form of 'uncomfortable knowledge', neglected and so becoming 'unknown knowns' (Sarewitz 2020). These decision processes, and the perceptions that shape them, have been studied through different lenses from psychology (Weber 2016) to sociology (Guilbeault et al. 2018), and media studies (Boykoff 2011). Karlsson and Gilek (2020) identify science denialism and 'decision thresholds' as key mechanisms of delay.

Experimental economics (Allcott 2011) also helps 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, including procrastination and inattention, as 'we often resist actions with clear long-term benefits if they are unpleasant in the short run' (Allcott and Mullainathan 2010). Incorporating behavioural and social dynamics in models is required particularly to better represent the demand side (Nikas et al. 2020), for example, Safarzyńska (2018) demonstrates 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 can help predict the effects of behavioural interventions (Levitt and List 2009; McRae and Meeks 2016; Gillan 2017). Chapter 5 explores both positive and negative dimensions of behaivour in more depth, including the development of norms and interactions with the wider social context, with emphasis upon the services associated with human well-being, rather than the economic activities per se.

1.7.4.2 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 (Section 1.4.5). Institutional perspectives probe networks of opposition (Brulle 2019) and emphasise that their ability to block – 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 economic development, contributing to carbon lock-in (Seto et al. 2016) and inertia (Rosenschöld et al. 2014).

The influence of interest groups on policymaking varies across countries. Comparative political economy approaches tend to find that countries where interests are closely coordinated by governments ('coordinated market economies') have been able to generate transformative change more than those with a more arms-length, even combative relationship between interest groups and governments ('liberal market economies') (Lachapelle and Paterson 2013; Ćetković and Buzogány 2016; Zou et al. 2016; Meckling 2018). 'Developmental states' often have the capacity for strong intervention but any low-carbon interventions may be overwhelmed by other pressures and very rapid economic growth (Wood et al. 2020a).

Institutional features affecting climate policy 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 multi-level coordination, and semi-autonomous climate agencies), are more able to develop the strategic approaches to climate governance needed to foster transformative change (Dubash 2021).

Access of non-governmental organisations (NGOs) to policy processes enables new ideas to be adopted, but too close an NGO-government relation may stifle innovation and transformative action (Dryzek et al. 2003). NGO campaigns on fracking (Neville et al. 2019) or divestment (Mangat et al. 2018) have raised attention to ideas such as 'stranded assets' in policy arenas (Green 2018; Piggot 2018; Newell et al. 2020; Paterson 2021). Attempts to depoliticise climate change may narrow the space for democratic participation and contestation, thus impacting policy responses (Swyngedouw 2010, 2011; Kenis and Lievens 2014). 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 (Section 4.4, Chapter 13 and Cross-Chapter Box 12).

Balancing the forces outlined in Section 4.6 in Chapter 4 typically involves building coalitions of actors who benefit economically from climate policy (Levin et al. 2012). Policy stability is critical to enabling long-term investments in decarbonisation (Rietig and Laing 2017; Rosenbloom et al. 2018). Policy design can encourage coalitions to form that sustain momentum by supporting further policy development to accelerate decarbonisation (Roberts et al. 2018), for example, by generating concentrated benefits to coalition members (Bernstein and Hoffmann 2018; Meckling 2019; Millar et al. 2020), as with renewable feed-in tariffs (FiTs) in Germany (Michaelowa 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. However, policy design can also provoke coalitions to oppose climate policy, as in the FiT programme in Ontario (Stokes 2013; Raymond 2020) or the yellow vest protests against carbon taxation in France (Berry and Laurent 2019). The Just Transitions frame can thus also be understood in terms of coalition-building, as well as ethics, as the pursuit of low-carbon transitions which spread the economic benefits broadly, through 'green jobs', and the redistributive policies embedded in them both nationally and globally (Healy and Barry 2017; Winkler 2020). Appropriate policy design will be different at different stages of the transition process (Meckling et al. 2017; Breetz et al. 2018).

Integration. Politics is ultimately the way in which societies make decisions – which in turn, reflect diverse forces and assumed frameworks. Effective policy requires understandings which combine economic efficiency, ethics and equity, the dynamics and processes of large-scale transitions, and the role of psychology and politics. No one framework is adequate to such a broad-ranging goal, nor are single tools. Chapter 13 (Figure 13.6) presents a 'framing' table for policy instruments depending on the extent to which they focus on mitigation per se or wider socio-economic development, and whether they aim to shift marginal incentives or drive larger transitions. Holistic analysis needs to bridge modelling, qualitative transition theories illuminated by case studies, and practice-based action research (Geels et al. 2016).

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. Climate policy may help to motivate policies with beneficial synergies (such as

Table 1.2 | Potential for net co-benefits arising from synergies and trade-offs, opportunities and risks.

	Positives	Negatives
Broadly known (e.g., air pollution, distributional).	Synergies	Trade-offs
Deep uncertainties (e.g., radical innovations).	Opportunities	Risks
	Select options with maximum synergies, and foster and exploit opportunities.	Ameliorate trade-offs (e.g., revenue redistribution), and minimise or allocate risks appropriately.
	Net co-benefits from appropriate mitigation choices	

the consumer cost savings from energy efficiency, better forest management, transitions to cleaner vehicles) and opportunities (such as stimulating innovation), by focusing on options for which the positives outweigh the negatives, or can be made to be, through smart policy (e.g., Karlsson et al. 2020). More broadly, climate concerns may help to attract international investment, and help overcoming bureaucratic or political obstacles to better policy, and support synergies between mitigation, adaptation, and other SDGs, a foundation for shifting development pathways towards sustainability (Chapter 17 and Section 1.6.1).

1.8 Feasibility and Multi-dimensional Assessment of Mitigation

1.8.1 Building on the SR1.5 Assessment Framework: Feasibility and Enabling Conditions

While previous ARs dealt with the definition of alternative mitigation pathways mostly exploring the technological potentials, the latest research focused on what kind of mitigation pathways are feasible in a broader sense, underlining the multi-dimensional nature of the mitigation challenge. Building on frameworks introduced by Majone (1975) and Gilabert and Lawford-Smith (2012), SR1.5 introduced multi-dimensional approaches to analysing 'feasibility' and 'enabling conditions', which AR6 develops and applies broadly in relation to six 'dimensions of feasibility assessment' (Figure 1.8). Two reflect the physical environment:

- *Geophysical*, not only the global risks from climate change but also, for technology assessment, the global availability of critical resources.
- *Environmental and ecological*, including local environmental constraints and co-benefits of different technologies and pathways.

The other four dimensions correspond broadly to the four analytic frameworks outlined in Section 1.7:

- *Economic*, particularly aggregate economic and financial indicators, and SDGs reflecting different stages and goals of economic development.
- *Socio-cultural*, including particularly ethical and justice dimensions, and social and cultural norms.
- *Technological,* including innovation needs and transitional dynamics associated with new and emergent technologies and associated systems.
- *Institutional and political,* including political acceptability, legal and administrative feasibility, and the capacity and governance requirements at different levels to deliver sustained mitigation in the wider context of sustainable development.

The 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 the best use of new technologies, risks of future stranded assets, greater local pollution, and multiple other environmental threats.

The dimensions as listed provide a basis for this assessment both in the sectoral chapters (6–11), providing a common framework for cross-sectoral assessment detailed further in Chapter 12, and in the evaluation of global pathways (Section 3.2). More specific indicators under each of these dimensions offer consistency in assessing the challenges, choices, and enabling requirements facing different aspects of mitigating climate change.

Figure 1.8 also illustrates variants on these dimensions appropriate for evaluating domestic and international policies (Chapters 13 and 14). The SR1.5 (Section 4.4) also introduced a framework of 'Enabling Conditions for systemic change', which as illustrated also has key dimensions in common with those of our feasibility assessment. In AR6 these enabling conditions are applied particularly in the context of shifting development pathways (Chapter 4.4).

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 could also clearly involve several dimensions, for example, concerning the politics of international trade, finance and resource distribution (economic dimension); international versus nationalistic identity (socio-cultural); and multilateral governance (institutional).

In this report, chapters with a strong demand-side dimension also suggest a simple policy hierarchy, reflecting that avoiding wastage – demands superfluous to human needs and wants – can carry benefits across multiple indicators. Consequently, Chapters 5 and 10 organise key actions in a hierarchy of **Avoid** (unnecessary demand) – **Shift** (to less resource-intensive modes) – **Improve** (technologies for existing modes), with a closely-related policy hierarchy in Chapter 9 (buildings).

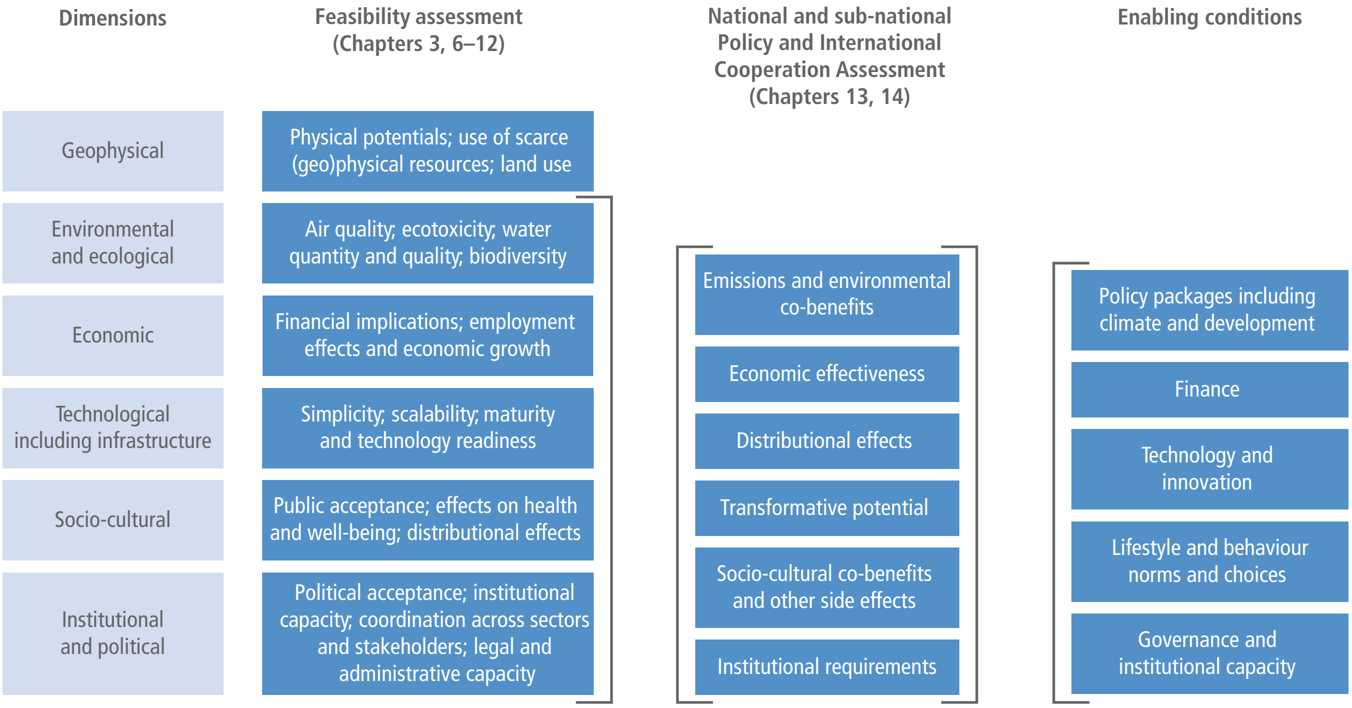

Figure 1.8 | Feasibility and related dimensions of assessment.

1.8.2 Illustrations of Multi-dimensional Assessment: Lock-in, Policies and 'Just Transition'

The rest of this section illustrates briefly how such multi-dimensional assessment, utilising the associated analytic frameworks, can shed light on a few key issues which arise across many chapters of this assessment.

Carbon Lock-in. The continued rise of global emissions reflects in part the strongly *path-dependent* nature of socio-economic systems, which implies a historic tendency to 'carbon lock-in' (Unruh 2000). An interdisciplinary review (Seto et al. 2016) identifies a dozen main components organised into four types, across the relevant dimensions of assessment as summarised in Table 1.3.

Along with the long lifetime of various physical assets detailed in AR5, AR6 underlines the exceptional degree of path-dependence in urban systems (Chapter 8) and associated buildings (Chapter 9) and transport (Chapter 10) sectors, but it is a feature across almost all the major emitting sectors. The (typically expected) operating lifetimes of existing carbon-emitting assets would involve anticipated emissions (often but inaccurately called 'committed' emissions in the literature), substantially exceeding the remaining carbon budgets associated with 1.5°C pathways (Chapter 2.7). Ongoing GHG-intensive investments, including those from basic industrialisation in poorer countries, are adding to this.

The fact that investors anticipate a level of fossil fuel use that is not compatible with severe climate constraints creates a clear risk of '*stranded assets'* facing these investors (Box 6.2), and others who depend on them, which itself raises issues of equity. A multi-dimensional/multi-framework assessment helps to explain why such investments have continued, even in rich countries, and the consequent risks, and the complexity of shifting such investments in all countries. It may also inform approaches that could exploit path-dependence in clean energy systems, if there is sufficient investment in building up the low-GHG industries, infrastructures and networks required.

Carbon pricing. Appraisal of policy instruments also requires such multi-dimensional assessment. Stern's (2007) reference to climate change as 'the greatest market failure in history' highlights that damages inflicted by climate change are not properly costed in most 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, and/or to meet agreed goals. Aggregate economic frameworks generally indicate carbon pricing (on principles which extend to other gases) as the most cost-effective way to reduce emissions, notwithstanding various market failures which complicate this logic.[9] 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. In practice the extent and level of carbon pricing implemented to date is far lower than this or

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[9] Beyond GHG externalities, Stern (2015) lists such market failures as: inadequate R&D; failures in risk/capital markets; network effects creating coordination failures; wider information failures; and co-benefits.

Table 1.3 | Carbon lock-in – types and key characteristics. Source: adapted from Seto et al. (2016).

Lock-in type	Key characteristics
Economic	– Large investments with long lead times and sunk costs, made on the basis of anticipated use of resources, capital, and equipment to pay back the investment and generate profits. – Initial choices account for private but not social costs and benefits.
Socio-cultural, equity and behaviour	– Lock-in through social structure (e.g., norms and social processes). – Lock-in through individual decision-making (e.g., psychological processes). – Single, calculated choices become a long string of non-calculated and self-reinforcing habits. – Interrupting habits is difficult but possible (e.g., family size, thermostat setting) to change. – Individuals and communities become dependent on the fossil fuel economy, meaning that change may have adverse distributional impacts.
Technology and infrastructure	– Learning-by-doing and scale effects, including the cumulative nature of innovation, reinforces established technologies. – Interaction of technologies and networks (physical, organisational, financial) on which they depend. – Random, unintentional events including network and learning-effect final outcomes (e.g., lock-in to the QWERTY keyboard).
Institutional and political	– Powerful economic, social, and political actors seek to reinforce the status quo that favours their interests. – Laws and Institutions, including regulatory structures, are designed to stabilise and lock-in a desired trajectory, and also to provide long-term predictability (socio-technical regimes in transition theories). – Beneficial and intended outcomes for some actors. – Not random chance but intentional choice (e.g., support for renewable electricity in Germany) can develop political consistencies that reinforce a direction of travel.

than most economic analyses now recommend (Section 3.6.1), and nowhere is carbon pricing the only instrument deployed.

A socio-cultural and equity perspective emphasises that the faith in and role of markets varies widely between countries – many energy systems do not in fact operate on a basis of competitive markets – and that because market-based carbon pricing involves large revenue transfers, it must also contend with major distributional effects and political viability (Prinn et al. 2017; Klenert et al. 2018), both domestic (Chapter 13) and international (Chapter 14). A major review (Maestre-Andrés et al. 2019) finds persistent distributional concerns (rich incumbents have also been vocal in using arguments about impacts on the poor (Rennkamp 2019)), but suggests these may be addressed by combining redistribution of revenues with support for low-carbon innovation. Measures could include redistributing the tax revenue to favour of low-income groups or differentiated carbon taxes (Metcalf 2009; Klenert and Mattauch 2016; Stiglitz 2019), including 'dual track' approaches (van den Bergh et al. 2020). To an extent though, all these depend on levels of trust, and institutional capacity.

Technological and transitions perspectives in turn find carbon-pricing incentives may only stimulate incremental improvements, but other instruments may be much more effective for driving deeper innovation and transitions (Chapters 14, 15 and 16), whilst psychological and behavioural studies emphasise many factors beyond only pricing (Sections 5.4.1 and 5.4.2). In practice, a wide range of policy instruments are used (Chapter 13).

Finally, in economic theory, negotiations on a common carbon price (or other common policies) may have large benefits (less subject to 'free riding') compared to a focus on negotiating national targets (Cramton et al. 2017a). The fact that this has never even been seriously considered (outside some efforts in the EU) may reflect the exceptional sovereignty sensitivities around taxation and cultural differences around the role of markets. However, 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 (Hourcade et al. 2021a).

Thus, practical assessment of carbon pricing inherently needs multi-dimensional analysis. The realities of political economy and lobbying have to date severely limited the implementation of carbon pricing (Mildenberger 2020), leading some social scientists to ask '*Can* we price carbon?' (Rabe 2018). Slowly growing adoption (World Bank 2019) suggests 'yes', but only through complex evolution of efforts: a study of 66 implemented carbon-pricing policies show important effects of regional clustering, international processes, and seizing political windows of opportunity (Skovgaard et al. 2019).

Just Transitions. Finally, whilst 'transition' frameworks may explain potential dynamics that could transform systems, a multi-dimensional/multi-framework assessment underlines the motivation for Just Transitions (Sections 1.6.2.3 and 4.5). This can be defined as a transition from a high-carbon to a low-carbon economy which is considered sufficiently equitable for the affected individuals, workers, communities, sectors, regions and countries (Jasanoff 2018; Newell and Mulvaney 2013). As noted, sufficient equity is not only an ethical issue but an enabler of deeper ambition for accelerated mitigation (Klinsky and Winkler 2018; Urpelainen and Van de Graaf 2018; Hoegh-Guldberg et al. 2019). 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

(Sovacool et al. 2019; Green and Gambhir 2020) (Section 4.5), as well as reference to the concept in the PA and its emphasis in the Talanoa Dialogue and Silesia Declaration (Section 1.2.2).

Whilst the broad concepts of Just Transitions have roots going back decades, its specific realisation in relation to climate change is of course complex: Section 4.5 identifies at least eight distinct elements proposed in the literature, even before considering the international dimensions.

1.9 Governing Climate Change

Previous sections have highlighted the multiple factors that drive and constrain climate action, the complex interconnection between climate mitigation and other societal objectives, and the diversity of analytical frames for interpreting these connections. Despite the complexities, there are signs of progress including increased societal awareness, change in social attitudes, policy commitments by a broad range of actors and sustained emission reductions in some jurisdictions. Nevertheless, emission trends at the global level remains incompatible with the goals agreed in the Paris Agreement. Fundamentally, the challenge of how best to urgently scale up and speed up the climate-mitigation effort at all scales – from local to global – to the pace needed to address the climate challenge is that of governance understood as 'modes and mechanisms to steer society' (Jordan et al. 2015). The concept of governance encompasses the ability to plan and create the organisations needed to achieve a desired goal (Güney 2017) and the process of interaction among actors involved in a common problem for making and implementing decisions (Kooiman 2003; Hufty 2012).

Climate change governance has been projected as conscious transformation at unprecedented scale and speed involving a contest of ideas and experimentation across scales of authority and jurisdiction (Hildén et al. 2017; Kivimaa et al. 2017; Laakso et al. 2017; Gordon 2018; van der Heijden 2018). Yet, there remains a sense that achieving the urgent transition to a low-carbon, climate-resilient and sustainable world requires significant innovation in governance (Hoffmann 2011; Stevenson and Dryzek 2013; Aykut 2016).

Starting from an initial focus on multilateral agreements, climate change governance has long evolved into a complex polycentric structure that spans from the global to national and sub-national levels, with 'multiple parallel initiatives involving a range of actors at different levels of governance' (Okereke et al. 2009) and relying on both formal and informal networks and policy channels (Bulkeley et al. 2014; Jordan et al. 2015). At the international level, implementation of the Paris Agreement and the UNFCCC more broadly is proceeding in parallel with other activities in an 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 levels of governance (Chan et al. 2018).

Multi-level governance has been used to highlight the notion that the processes involved in making and implementing decisions on climate change are 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 (IPCC 2014a; Bäckstrand et al. 2017; Jordan et al. 2018) (Chapter 13, and Sections 13.3.1 and 13.5.2). Increased multi-level participation of sub-national actors, along with a diversity of other transnational and non-state actors has helped to facilitate increased awareness, experimentation, innovation, learning and achieving benefits at multiple scales. Multi-level participation in governance systems can help to build coalitions to support climate change mitigation policies (Roberts et al. 2018) and fragmentation has the potential to take cooperative and even synergistic forms (Biermann et al. 2009).

However, there is no guarantee that multi-level governance can successfully deal with complex human-ecological systems (York et al. 2005; Biermann et al. 2017; Di Gregorio et al. 2019). Multi-level governance can contribute to an extremely polarised discussion and policy blockage rather than enabling policy innovation (Fisher and Leifeld 2019). A fragmented governance landscape may lead to coordination and legitimacy gaps undermining the regime (Nasiritousi and Bäckstrand 2019). The realities of the 'drivers and constraints' detailed in Section 4, the 'glocal' nature of climate change, the divided authority in world politics, diverse preferences of public and private entities across the spectrum, and pervasive suspicions of free riding, imply the challenge as how to incrementally deepen cooperation in a polycentric global system, rather than seeking a single, integrated governance (Keohane and Victor 2016).

Crucially, climate governance takes place in the context of embedded power relations, operating in global, national and local contexts. Effective rules and institutions to govern climate change are more likely to emerge where and when power structures and interests favour action. However widespread and enduring cooperation can only be expected when the benefits outweigh the cost of cooperation and when the interests of key actors are sufficiently aligned (Barrett 1994; Finus and Rübbelke 2008; Victor 2011; Mainali et al. 2018; Tulkens 2019). Investigating the distribution and role of hard and soft power resources, capacities and power relations within and across different jurisdictional levels is therefore important to uncover hindrances to effective climate governance (Marquardt 2017). Institutions at international and national levels are also critical as they have the ability to mediate the power and interest of actors, and sustain cooperation based on equity and fair rules and outcomes. Governance, in fact, 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. It is also useful for engaging the wider public and international networks in imagining low-carbon societies (e.g., Levy and Spicer 2013; Milkoreit 2017; Nikoleris et al. 2017; Wapner and Elver 2017; Bengtsson Sonesson et al. 2019; Fatemi et al. 2020). Experimentation also represents an important source of governance 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 et al. 2018; Lo and Castán Broto 2019).

1.10 Conclusions

Global conditions have changed substantially since the IPCC's Fifth Assessment Report 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 of protest and activism – 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' CO_2 and/or GHG emission goals and decarbonisation or low-carbon growth strategies, but the current NDCs to 2030 collectively would barely reduce global emissions below present levels (Section 1.3.3). 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.

The assessment of the key drivers for, and barriers against mitigation undertaken in this chapter underscore the complexity and multi-dimensional nature of climate mitigation. Historically, much of the academic analysis of mitigating climate change, particularly global approaches, has focused on modelling costs and pathways, and discussion about 'optimal' policy instruments. Developments since AR5 have continued to highlight the role of a wide range of factors intersecting the political, economic, social and institutional domains. Yet despite such complexities, there are signs of progress emerging from years of policy effort in terms of technology, social attitudes, and emission reductions in some countries, with tentative signs of impact on the trajectory of global emissions. The challenge remains how best to urgently scale up and speed up the climate mitigation effort at all scales – from local to global – to achieve the level of mitigation needed to address the problem as indicated by climate science. A related challenge is how to ensure that mitigation effort and any associated benefits of action are distributed fairly within and between countries and aligned to the overarching objective of global sustainable development. Lastly, globally effective and efficient mitigation will require international cooperation especially in the realms of finance and technology.

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 the relationship with 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 connect the scattered elements of progress to date, and hence accelerate progress towards agreed goals and multiple dimensions of climate change mitigation in the context of sustainable development.

1.11 Knowledge Gaps

Despite huge expansion in the literature (Callaghan et al. 2020), knowledge gaps remain. Modeling still struggles to bring together detailed physical and economic climate impacts and mitigation, with limited representation of financial and distributional dynamics. There are few interdisciplinary tools which apply theories of transition and transformation to questions of economic and social impacts, compounded by remaining uncertainties concerning the role of new technological sets, international instruments, policy and political evaluation.

One scan of future research needs suggests three priority areas (Roberts et al. 2020): (i) human welfare-focused development (e.g., reducing inequality); (ii) how the historic position of states within international power relations conditions their ability to respond to climate change; (iii) transition dynamics and the flexibility of institutions to drive towards low-carbon development pathways. There remain gaps in understanding how international dynamics and agreements filter down to affect constituencies and local implementation. Literature on the potential for supply-side agreements, 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 (IPBES 2019). Climate policies could increase the pressure on land and oceans (IPCC 2019c,b), with insufficient attention to relationships between biodiversity and climate agreements and associated policies. IPBES aims to coordinate with the IPCC more directly, but literature will be required to support these reports.

Compounding these gaps is the fact that socially oriented, agriculture-related options, where human and non-human systems intersect most obviously, remain under-researched (e.g., Balasubramanya and Stifel 2020). Efforts to engage with policies here, especially framed around ecosystem services, have often neglected their 'practical fitness' in favour of focusing on their 'institutional fitness', which needs to be addressed in future research (Stevenson et al. 2021).

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 city planning, public transport, EV-charging networks, and CCU/CCS. 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 implementation, and mitigation goals – informed by the PA and the UNFCCC Global Stocktake – require much further research.

1.12 Roadmap to the Report

This Sixth Assessment Report covers mitigation in five main parts (Figure 1.9), 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 to 5 cover the big picture trends, drivers and projections at national and global levels. Chapter 2 analyses emission trends and drivers to date. Chapter 3 presents long-term global scenarios, including the projected economic and other characteristics of mitigation through to the balancing of sources and sinks through the second half of this century, and the implications for global temperature change and risks. Chapter 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. Chapter 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 to 12 examine sectoral contributions and possibilities for mitigation. Chapter 6 summarises characteristics and trends in the energy sector, specifically supply, including the remarkable changes in the cost of some key technologies since AR5. Chapter 7 examines the roles of AFOLU, drawing upon and updating the recent Special Report, including the potential tensions between the multiple uses of land. Chapter 8 presents a holistic view of the trends and pressures of urban systems, as both a challenge and an opportunity for mitigation. Chapters 9 and 10 then examine two sectors which entwine with, but go well beyond, urban systems: buildings (Chapter 9) including construction materials and zero-carbon buildings; and transport (Chapter 10), including shipping and aviation and a wider look at mobility as a general service. Chapter 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, Chapter 12 takes a cross-sectoral perspective and explores cross-cutting issues like the interactions of biomass energy, food and land, and carbon dioxide removal.

Four chapters then review thematic issues in implementation and governance of mitigation. Chapter 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 (Chapter 5), along with governance approaches and capacity-building, and the role and relationships of sub-national actors. Chapter 14 then considers the roles and status of international cooperation, including the UNFCCC agreements and international institutions, sectoral agreements and multiple forms of international partnerships, and the ethics and governance challenges of solar radiation modification. Chapter 15 explores investment and finance, 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 (Chapter 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, Chapter 17 considers accelerating the transition in the context of sustainable development, including practical pathways for joint responses to climate change and sustainable development challenges. This includes major regional perspectives, mitigation-adaptation interlinkages, and enabling conditions including the roles of technology, finance and cooperation for sustainable development.

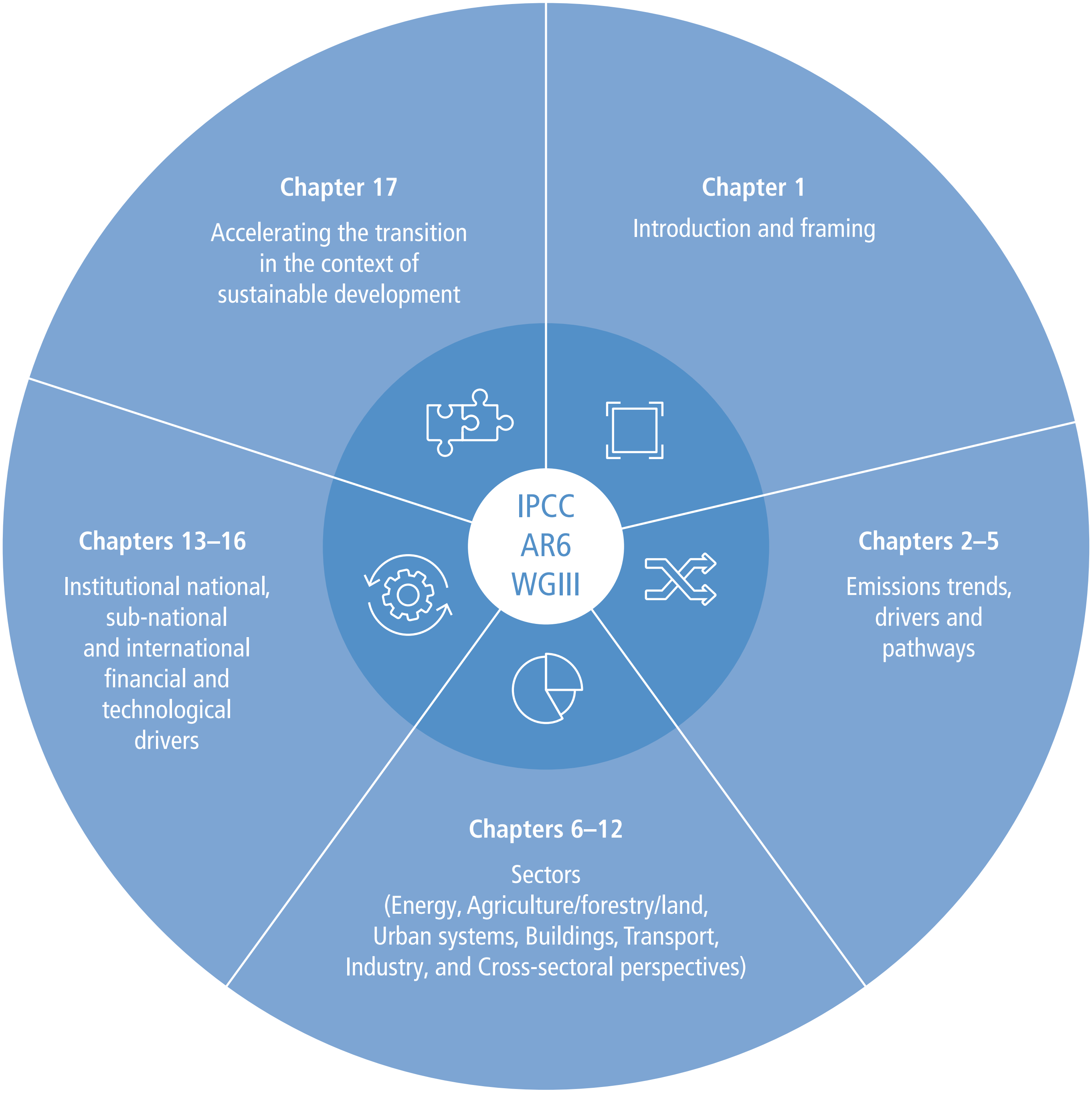

Figure 1.9 | The structure of the AR6 mitigation report.

Frequently Asked Questions (FAQs)

FAQ 1.1 | What is climate change mitigation?

Climate change mitigation refers to actions or activities that limit emissions of greenhouse gases (GHGs) from entering the atmosphere and/or reduce their levels in the atmosphere. Mitigation includes reducing the GHGs emitted from energy production and use (e.g., that reduces use of fossil fuels), and land use, and methods to mitigate warming, for example, by carbon sinks which remove emissions from the atmosphere through land-use or other (including artificial) mechanisms (Sections 12.3 and 14.4.5; see AR6 WGI for physical science, and WGIII Chapter 7 for AFOLU mitigation).

The ultimate goal of mitigation is to preserve a biosphere which can sustain human civilisation and the complex of ecosystem services which surround and support it. This means reducing anthropogenic GHG emissions towards net zero to limit the warming, with global goals agreed in the Paris Agreement. Effective mitigation strategies require an understanding of mechanisms that underpin release of emissions, and the technical, policy and societal options for influencing these.

FAQ 1.2 | Which greenhouse gases (GHGs) are relevant to which sectors?

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, but some have extremely long atmospheric lifetimes extending to tens of thousands of years, such as F-gases (Chapter 2).

Different combinations of gases are emitted from different activities. 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 (approximately 64% of emissions, Figure SPM.2). Fossil fuels are also a major source of methane (CH_4), the second biggest contributor to global warming. 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 industrial processes (mainly CO_2, N_2O and F-gases), and municipal waste and wastewater (mainly CH_4) (Chapter 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, whilst some other short-lived pollutants temporarily cool the surface (IPCC AR6 WGI Section 6.5.4.3).

FAQ 1.3 | What is the difference between 'net zero emissions' and 'carbon neutrality'?

Annex I (Glossary) states that 'carbon neutrality and net zero CO_2 emissions are overlapping concepts' which 'can be applied at the global or sub-global scales (e.g., regional, national and sub-national)'. At the global scale the terms are equivalent. At sub-global scales, net zero CO_2 typically applies to emissions under direct control or territorial responsibility of the entity reporting them (e.g., a country, district or sector); while carbon neutrality is also applied to firms, commodities and activities (e.g., a service or an event) and generally includes emissions and removals beyond the entity's direct control or territorial responsibility, termed 'Scope 3' or 'value chain emissions' (Bhatia et al. 2011).

This means the emissions and removals that should be included are wider for 'neutrality' than for net zero goals, but also that offset mechanisms could be employed to help achieve neutrality through abatement beyond what is possible under the direct control of the entity. Rules and environmental integrity criteria are intended to ensure additionality and avoid double counting of offsets consistent with 'neutrality' claims (see 'carbon neutrality' and 'offset' in Glossary, for detail and a list of criteria).

While the term 'carbon' neutrality in this report is defined as referring specifically to CO_2 neutrality, use of this term in practice can be ambiguous, as some users apply it to neutrality of all GHG emissions. GHG neutrality means an entity's gross emissions of all GHG must be balanced by the removal of an equivalent amount of CO_2 from the atmosphere. This requires the selection of a suitable metric that aggregates emissions from non-CO_2 gases, such as the commonly used GWP100 metric (for a discussion of GHG metrics, see AR6 WGI Box 1.3 and Cross-Chapter Box 2 in Chapter 2 of this report).

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