Chapter 1: Introduction and Framing

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Executive summary

Recent years have seen rising public awareness of the multiple threats posed by climate change to present and future generations across the world. The Paris Agreement, adopted in 2015 against many odds, agreed three overall aims: (i) to keep temperature rise "Well below 2°C above pre-industrial levels and to pursue efforts … towards 1.5"; (ii) to increase the ability of countries to deal with the impacts of climate change; and (iii) to make global financial flows consistent with a low GHG emissions and climate-resilient pathway. It committed its Parties to strengthen the global response towards these goals, in the context of sustainable development and efforts to eradicate poverty. Earlier in the same year, (2015) the UN had endorsed a universal agenda – 'Transforming our World: the 2030 Agenda for Sustainable Development', with 17 non-legally-binding Sustainable Development Goals (SDGs) including on climate change, and 169 targets to support people, prosperity, partnerships and the planet.

However, despite efforts to tackle climate change at multiple scales, global greenhouse gas (GHG) emissions have continued to rise. After a period of exceptionally rapid growth as charted in AR5, energy-related CO_2 emissions plateaued between 2014 and 2016 while the global economy continued to expand, but increased again subsequently albeit more slowly. At present, the national goals declared under the Paris Agreement are not sufficient to meet its agreed aims. The declared contributions by Parties suggest global GHG emissions of 52-58 $GtCO_2eq\ yr^{-1}$ in 2030 (IPCC 2018a), which would be incompatible with 1.5°C or well-below 2°C, as even 2°C would require wholly unprecedented global emission reductions post-2030.

Along with better understanding of the science of climate change (AR6 WGI), and of vulnerabilities, impacts and adaptation (AR6 WGII), the landscape of climate mitigation has evolved substantially since the evidence assessed by AR5. Analytically, along with continued development of concepts, models and technologies, there have been numerous insights from both successes and failures of mitigation policy.

Evidence point to great diversity in national trends. Some developed countries have brought down GHG emissions substantially in the past few years, and aggregate emissions from developed countries has declined, whilst still much higher than poorer countries per-capita. Some developing countries have already embarked on much lower GHG development pathways. However, for all nations, the gap between commitment and the action remains wide. This context of a growing gap between the agreed Aims, and overall actual action and commitments, suggests a need to accelerate action with unprecedented scale of transition in all key sectors to avert the disastrous consequences of climate change.

A major constraint on rapid low carbon transition is that climate change cannot be tackled in isolation. It may be the most daunting global problem of the era, but it is currently far from the dominant priority in most countries. Greenhouse Gas emissions are implicated in the pursuit of wider needs, aspirations and demands for economic growth and wellbeing. With its emphasis on integrating social, economic and environmental goals, sustainable development provides a comprehensive framework for the pursuit of climate mitigation and human wellbeing. However, countries differ enormously in where they are in their development path – a condition which affects their capability, goals, priority and approach to the pursuit of sustainability. The wide variation in the contribution to, and capability to respond to climate change calls for the need for attention to equity, justice, and faireness within and between countries in conceptualizing the relationship between sustainable development and climate change as well as for specificity in analyzing the drivers and forces that constraint action across time and scale.

Trends to date illustrate the often-contradictory forces at play. The demand for most services continues to soar with economic progress even as it increases social demands for environmental quality and sustainability. There is a gap between climate ambition and people's willingness to bear additional costs.

Trade can enhance economic efficiency and facilitate the transfer of clean technologies (though it can also constrain local initiatives and amplify environmental damage when this is not priced), but major trade disputes are growing and there is little progress on incorporating environmental norms in the trade system. Interest in the role of financial systems - and the systemic risks that climate change poses – is rising sharply, but much finance continues to flow into carbon-intensive investments, often supported by governments, continuing to increase the capital assets at risk.

With increasing populism, nationalism, authoritarianism and growing protectionism , multilateral cooperation appears to be under greater pressure than at any time since the Second World War. However, this is challenged in particular by important social and technological trends. The rapid rise of youth and other social movements on environment and sustainability is changing both political dynamics, and in some cases, consumer preferences (eg. regarding meat). There are growing levels of transnational cooperation not only between such movements, but between cities, financial and other business networks.

To assess potential pathways, the SR1.5 introduced six broad dimensions of ‘feasibility’: geophysical; environmental-ecological; technological; economic; socio-cultural; and institutional which provide a framework for assessing the *challenges and choices* now facing humanity in relation to climate change and sustainable development, and the potential enabling factors that could minimize trade-offs and enhance synergies.

With existing technologies and practices, some difficult tradeoffs may be unavoidable. This points to an emphasis on *transitions*, including innovation in technologies, institutions, and development pathways. With the suitable governance systems, all the sectors analysed in this report (energy, land use, urban development, buildings, transport, and industry) have some potential to be transformed in ways that could support innovative and sustainable pathways, for countries at all stages of economic development.

Striking progress in key technologies facilitates both low carbon and broader sustainable development across most of the sectors involved. Renewable energy has become competitive with fossil fuels in growing numbers of countries and regions and costs continue to fall. Electric vehicles, and communications, IT and other general-purpose technologies, open possibilities for widespread low-carbon transformation in multiple sectors that were hardly visible in the literature assessed in AR5. Transitions are under way in many countries, sometimes impeded more by incumbent interests and governance structures than by the fundamental economics.

The costs of transition are uncertain and could vary widely depending on how ordered and planned the transitions are, as well as on their speed, timing, and the nature and scale of international coordination. Cost assessments vary depending on the metrics and models used (Chapter 6, AR5 WG III) [*statement on trends in cost assessment to be added for the SOD*]. However they suggest eliminating greenhouse gas emissions whilst still providing the services which society demands to be possible, though achieving this may involve broader social transformations, to both drive and benefit from such transitions.

All this shows the need for diverse analytic frameworks. With such wide uncertainty and rapid transformations, there is no obvious ‘business as usual’. Scenarios, as internally consistent tools for probing possible futures both quantitatively and qualitatively, can form a bedrock for assessments: this report sets out five ‘Illustrative pathways’. Assessing these and associated options would then benefit from using at least three analytic frameworks.

Economic frameworks need to extend beyond simple cost-benefit analysis, to encompass the centrality of risk, options, cost-effective delivery of multiple objectives, to help identify and avoid lock-in, to embody innovation, and to reflect the possibilities for behavioural and social change.

Ethical frameworks illuminate the critical role of ethics, values, attitudes, and behaviours as foundational frames to understand and assess climate action, sustainable development and societal transformation. Climate policies that are considered unfair may be hard to implement, both in the national and international arenas. Entrenching values that promote deep decarbonisation, environmental conservation and protection across all levels of society is viewed as foundational component of climate resilient and sustainable development.

Explicit frameworks of *transition analysis* identify interacting processes at three broad levels, which also align with different levels of economic behavior and associated theories: a common component is that major transitions usually need to overcome political resistance in the middle ("meso") level of economic rules and regulations (the socio-technical regimes governing specific sectoral markets), as well as macro-level infrastructure and innovation systems. These in turn interact with social transformations, so as to ensure '*just transitions*'.

To help address the complexities of this "Super-wicked" problem and the limits to what countries can achieve on their own, new forms of governance are needed.

The next stages of climate mitigation consequently require broadened assessment frameworks. This AR6 brings to bear frameworks for assessing trade-offs and synergies of climate mitigation in the context of sustainable development, including equity concerns, and evaluation of the multi-level dynamics involved in accelerating just transitions across a growing number of sectors.

1.1 Introduction

Previous IPCC Assessment Reports have underlined that climate change involves a range of risks, which increase with the degree of temperature change. These Reports have consistently highlighted the need for concerted global effort to reduce greenhouse gas (GHG) emissions to guarantee a safe climate system needed to support global sustainable development and wellbeing. The Fifth Assessment Report (AR5) highlighted the continued rise of GHG emissions and concentrations, though with growing climate mitigation policies around the world. The persisting gap between current trajectory and potential emission pathways needed to put the world on the path of achieving the temperature aim set by the Paris Agreement, which clarified the implications of the UNFCCC commitment to 'avoid dangerous anthropogenic interference', clearly underlines the urgency of the mitigation challenge, including that of reaching net zero emissions.

Since the release of the AR5, the IPCC has also published three Special Reports all of which emphasize the rising threat of climate change and the need for more ambitious mitigation efforts at all scales. These include the 'Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty' (hereafter SR1.5, 2018) (IPCC 2018a); the 'Special Report on Climate Change and Land' (IPCC 2019a); and the 'Special Report on the Ocean and Cryosphere in a Changing Climate' (SROCCC) (IPCC 2019b).

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

As mapped out in this report, overall since AR5 (IPCC 2014a), the global aggregate trend of emissions has continued upwards, but more slowly. However, national trends are diverse. A few countries have substantially cut emissions – both on their territory, and including their 'consumption footprint' - alongside sustained economic growth (Chapter 2). Per-capita GHG emissions between countries even at similar stages of economic development (GDP per capita) vary by a factor of three, and by more than two on consumption basis (ie. taking account of trade) *(Chapter 2)*. Innovation and industrial development of key technologies in several relevant sectors have transformed prospects for cheap mitigation (Chapters 6-12), along with emerging options – technical and behavioural (Chapters 5, 9 - 11) for providing services with lower energy demand. New actors, including numerous non-state transnational alliances and the finance sector, have emerged as important players (Chs 13 - 16).

Analytically, along with continued development of concepts, models and technologies, there have been numerous insights from both successes and failures of mitigation policy. This can inform both policy design and the political realization of more ambition. However, policies and investments as assessed in this report are still clearly inadequate to put us in line with the long term targets agreed in Paris (Chapter 4).

Diagram to be included in Second Order Draft, showing Illustrative Emission Pathways and corresponding temperature implications.

Figure 1.1

Recent literature assessed by WGs I & II of this AR6 implies a renewed and heightened need for urgent climate action in order to avoid widespread negative impacts to social, environmental and economic systems. The science is clear that the climate is changing due to human activity, but meeting the 1.5ºC target allows for additional emissions of only between a few years (Millar et al. 2017) to a couple of decades (Leach et al. 2018) at current emissions levels of about 40 Gt CO_2 per year before the target is reached. The greater the inertia (including political) in emission trends and the obstacles to mitigation, the more that GHGs will continue to accumulate, increasing the scale of costs and risks also associated with having to subsequently remove GHGs from the atmosphere, particularly to achieve the lower ends of the Paris Agreement targets (Hilaire et al. 2019). Climate change will in turn impact emissions by affecting resources used for energy production and terrestrial carbon sinks (WGI).

Overall, these factors and the associated literatures point to more dynamic consideration of intertwined challenges concerning the transformation of key GHG emitting systems: to minimise the trade-offs, and maximise the synergies, of delivering deep decarbonization whilst enhancing sustainable development. This Assessment Report, consequently, draws upon a rapidly expanding body of literature covering theory, modeling and practical experience, so as to inform ambitious and globalizing efforts to deliver the aims of the Paris Agreement.

1.2 Developments since AR5 (2014)

1.2.1 Previous ARs and SRs Key findings

Successive IPCC Assessments have increasingly emphasised the importance of climate mitigation and the need to consider the broader context of multiple societal goals, particularly the broader challenges of sustainable development. Key insights from AR5 and the subsequent three special reports (IPCC 2014a, 2018a, 2019a,b) are summarized below.

In AR5 projections of so-called business as usual (BAU) emission pathways obviously did not take into account efforts as submitted within the Paris Agreement, which are covered in Chapter 4 of this report. AR5 projected that on current trends, AFOLU would be the only sector to reduce emissions (p.17 SPM WGIII AR5) (IPCC 2014b). Direct CO_2 emissions from energy sector could double or even triple by 2050 (p.20 SPM WGIII AR5) due to global population and economic growth, resulting in global mean surface temperature increases in 2100 from 3.7°C to 4.8°C compared to pre-industrial levels *(SOD to report any changes from WGI).*

A key message from recent reports is the urgency to mitigate GHG emissions if we want to avoid rapid and potentially irreversible changes in natural and human systems (IPCC 2018a, 2019c,b). Successive IPCC reports have drawn upon increasing sophistication of modelling tools to project forward emissions that would happen in the absence of serious decarbonisation action, as well as the emission pathways that meet long term temperature targets and the strategies they entail. Emission pathways that limit global warming to 2-1.5°C (with respect to "pre-industrial temperatures" as approximated by average 1850-1900) have extensively been studied in the IPCC SR1.5 (IPCC 2018a). Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (high confidence) (IPCC 2018a). To be consistent with a 2°C target, global emissions would have to peak by 2030-2035 and for 1.5°, by about 2025 (IPCC SR1.5 p.X) (IPCC 2018a). As capital and plants responsible for GHG emissions are long lived, the timing of the shift in investments and strategies will be crucial (p.18 SPM WGIII AR5) (IPCC 2018b). Across all ‘Paris-consistent’ pathways, net global emissions decline below zero, as early as in 2040 and as late as in 2080, depending on the assumptions about the relative contributions of ‘negative emissions’ with carbon dioxide removal technologies (e.g. Bioenergy with Carbon Capture and Storage (BECCS) and removals in the Agriculture, Forestry and Other Land Use (AFOLU)), and the extent of possible ‘overshoot’.

The emission contributions as submitted under the Paris Agreement suggest global GHG emissions between 52 and 58 $GtCO_2eq\ yr^{-1}$ in 2030 (IPCC 2018a). This would not limit global warming to 1.5°C, even if followed by very challenging emissions reductions after 2030. To meet even 2°C, ambition would have to rapidly ramp up after 2030. At present, the national goals declared under the Paris Agreement are thus not sufficient to meet the stated objective of the Agreement.

These less ambitious near-term emission trends thus imply subsequently ‘negative emissions’ at large scale (with attendant costs and uncertainties) in the future; and/or Solar Radiation Management, both involving other environmental and governance challenges as discussed in SR1.5 (for negative emissions) and this report, Chapter 12.

The economic costs of this transition are uncertain and could vary widely depending on how ordered and planned the transition is, as well as on its speed and timing. In addition, cost assessments vary depending on the metrics and models used (Chapter 6, AR5 WG III). Modelled direct mitigation costs of pathways limiting global warming to 1.5°C, with no or limited overshoot, span a wide range (for instance, the estimated carbon price for a Below-1.5°C pathway range from 135–6050 $\$_{2010}/tCO_2eq$ in 2030, 245–14300 $\$_{2010}/tCO_2eq$ in 2050, 420–19300 $\$_{2010}/tCO_2eq$ in 2070 and 690–30100 $\$_{2010}/tCO_2eq$ in 2100), but are typically 3-4 times higher than in pathways limiting global warming to below 2°C (high confidence), before taking account of co-benefits and avoided climate impacts (IPCC 2018b).

Climate mitigation and adaptation should not be an end in themselves but a means 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: there are both synergies and trade-offs. For example, there are clear potential positive synergies between stringent climate policy and improvements in air quality leading to better health [AR5 Fig SPM.6], but there would be trade-offs if policy raises net energy bills in ways not adequately compensated. The Special report on Climate change and Land also emphasizes 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. It is crucial however to devise these responses by keeping into the pictures all potential trade-offs and synergies.

Previous ARs have presented detailed understanding of the contribution of various sectors and activities to global GHG emissions. When indirect emissions and emissions from electricity, heat and other energy conversions are included, the four main consumption (/end-use) drivers are AFOLU, buildings, transport and industry, each accounting for over 20 percent of total GHG emissions. These – together with the energy and urban systems which feed and shape these end-use sectors – define the sectoral chapters in this AR6 report.

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

The atmosphere is a global public good. This implies that international cooperation on climate change alongside local, national, regional and global policies will be crucial to solve the problem.

AR5 noted that greater cooperation would ensue if policies were perceived as fair and equitable by all countries along the entire spectrum of economic development – implying a need for equitable sharing of the effort. A key takeaway from AR5 is that climate policy involves value judgement and ethics. (AR5 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.")

AR5 also underlined that climate policy inherently involves risk and uncertainty (in nature, economy, society and individuals). Economic analysis provides a rich suite of tools - cost-benefit analysis, cost-effectiveness analysis, multi-criteria analysis and expected utility theory all of which have pros and cons – to help manage these, which we consider much more briefly in section 5 of this chapter.

The most recent Assessments (AR5 and SR1.5) (IPCC 2014a, 2018a) have begun to consider the role of individual behavioural choices and cultural norms in driving energy and food patterns. Notably, SR1.5 (section 4.4.3) outlined emerging evidence on the potential for changes in behaviour and culture to contribute to decarbonisation (and lower the cost); for the first time, AR6 devotes a whole chapter (5) to consider these and other drivers of energy demand, food choices and social aspects.

1.2.2 Recent developments in the multilateral context and the 2015 agreements

Since 2015, there are notable multilateral efforts in the form of multilateral agreements enacted. They are: the Paris Agreement which aims for enhancing implementation of the 1992 UNFCCC, along with UN agreements on Disaster Risk Management (Sendai) and Finance for Development (Addis Ababa), culminating with the Sustainable Development Goals (SDGs).

The Paris Agreement. The Paris Agreement (**PA**) committed Parties to 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UNFCCC 2015). Hailed as 'the most successful climate change conference ever' for eight specific steps forward (Kinley 2017), it aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty. 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).

The PA contains numerous provisions on climate mitigation for the post-2020 period (i.e. beyond the second period of the 1997 Kyoto Protocol), including for Nationally Determined Contributions (**NDCs**: PA Art.3), aiming to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century", commonly known as "**net zero**" - along with numerous other provisions outlined in Chapter 14 (Rajamani 2016).

The PA is predicated on encouraging progressively ambitious climate action from all countries on the basis of voluntary Nationally Determined Contributions (Rajamani 2016; Clémençon 2016), unlike the Kyoto Protocol's legally binding obligations on developed countries only. The logic is to allow countries to set their own level of ambitions for climate change mitigation in their NDCs, but within a collaborative and legally binding process to foster ambition towards the agreed goals (Falkner 2016a; Bodansky 2016). The Paris Agreement, hailed as a entered into force in November 2016 and as of April 2019 it has 185 Parties (out of 197 Parties to the UNFCCC).

A key feature of the PA is the provision for global stocktake in which Parties have to take collective stock on the progress of achieving the purpose of the PA and its long-term goals in the light of equity and available best science (UNFCCC 2015 Art.14; Falkner (2016a)). The first global stocktake is scheduled for 2023, with subsequent iterations every five years thereafter. The outcome of these reviews is meant to inform Parties to update and enhance the pledges in their NDCs (PA Art.14 para 3). In the spirit of sustainable development and poverty eradication, developed country parties are to assist developing country parties with financial resources (PA Art.9). The Green Climate Fund (GCF) was given an important role in serving the Agreement and delivering the UNFCCC Objective, and supporting the goal of keeping climate change well below 2 degrees Celsius. GCF rapidly gathered pledges worth USD 10.3 billion, from developed and developing countries, regions, and one city (Paris) (Antimiani et al. 2017; Bowman and Minas 2019).

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

Finance. The PA's Article 2.1c – its Third 'Aim' – is "Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development." This reflects a broadened focus, beyond the costs of climate impacts/adaptation and mitigation, to recognizing that both imply a structural shift of and, potentially, additional scale of, investment, that needs to engage the wider financial system (Chapter 15, 15.1 and 15.2.4). The IPCC 1.5C report estimated that 1.5°C pathways would require *increased investment* of 0.5-1% of global GDP between now and 2050, which is up to 2.5% of global savings / investment over the period. For low- and middle-income countries, SDG-compatible infrastructure investments in the most relevant sectors are estimated to be around 4-5% of their GDP, and 'infrastructure investment paths compatible with full decarbonization in the second half of the century need not cost more than more-polluting alternatives' (World Bank 2019a).

The parallel 2015 UN Addis Ababa Conference on Finance for Development, and its resulting Action Agenda, aims to 'address the challenge of financing … to end poverty and hunger, and to achieve sustainable development in its three dimensions through promoting inclusive economic growth, protecting the environment, and promoting social inclusion.' The Conference recognises the significant potential of regional co-operation and provides a forum for discussing the solutions pathways to common challenges faced by developing countries (Chapter 15, 15.6.4).

Alongside this, private and blended climate finance is increasing but is still short of projected requirements consistent with Paris Agreement targets (Chapter 15, 15.3.3.1). 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 (Chapter 15, 15.6.3). To date, the most significant governance development is the Financial Stability Board's TCFD (Task Force on Climate Disclosure) recommendations which were welcomed by over 500 financial institutions and companies as signatories albeit with patchy implementation (Chapter 15, 15.6.3). Although this reflects concern about the risks posed by climate change to the stability of the global financial system (and *vice-versa)*, this is also accompanied by growing consensus that transparency alone cannot mitigate these risks (Ameli et al. 2019) (Chapter 15, 15.6.3).

Talanoa Dialogue and Just Transition Launched at COP23, the ‘Talanoa Dialogue Synthesis Report’ (UNFCCC 2018a) formed the basic political phases of the Talanoa Dialogue during COP24 (Mead 2018), which emphasized the need to implement holistic approaches across multiple economic sectors for efficient climate change mitigation. At COP24 also, the Just Transition Silesia Declaration, focusing on the need to consider social aspects in designing policies for climate change mitigation was signed by 56 heads of state (UNFCCC 2018b; COP24 2018). This underlined the importance of aiming for a ‘Just Transition’ in terms of reducing emissions, at the same time preserving livelihoods and managing economic risks for countries that rely heavily on emissions-intensive [resources and] technologies for domestic growth (Markkanen and Anger-Kraavi 2019). There is a need for a transition from the economy-driven approach taken by policy-makers to a more coherent and integrated approach for realizing the vision of the Paris Agreement (Mundaca et al. 2019). Initiatives launched for meeting the goals of the Paris Agreement include the Non-State Actor Zone for Climate Action (NAZCA) portal, which was launched during the UN Climate Change Conference in Lima, Peru, in December 2014 for initiating city-based actions for mitigating climate change (Mead 2015).

1.2.3 Context and recent developments in economy, emissions, and climate / sustainability gaps

Beyond the UN and related processes, the world since 2015 has seen sharply contrasting trends in many dimensions.

Aggregate emission trends. After a period of exceptionally rapid growth as charted in AR5, global energy-related CO_2 emissions plateaued between 2014 and 2016 while the global economy continued to expand but increased again in 2017 and 2018 with annual increase of 1.5% and 1.7% respectively. This temporary decoupling reflected interplay of strong energy efficiency improvements and low-carbon technology deployment, reducing coal demand in the former period (IEA 2019), but higher energy productivity and lower-carbon options did not expand fast enough subsequently to offset the pressures for growth at global level (UNEP 2018a; IEA 2019).

Figure 1.2 shows the distribution of global CO_2 emissions by income. The areas of each block are proportional to emissions. The world remains unequal by any measure: changes (described more fully in Chapter 2) reflect modest emission reductions in most industrialized countries (but with per-capita emissions still far above most of the developing world); the rise of east Asia in particular; and continued rapid population growth mainly in south Asia and Africa.

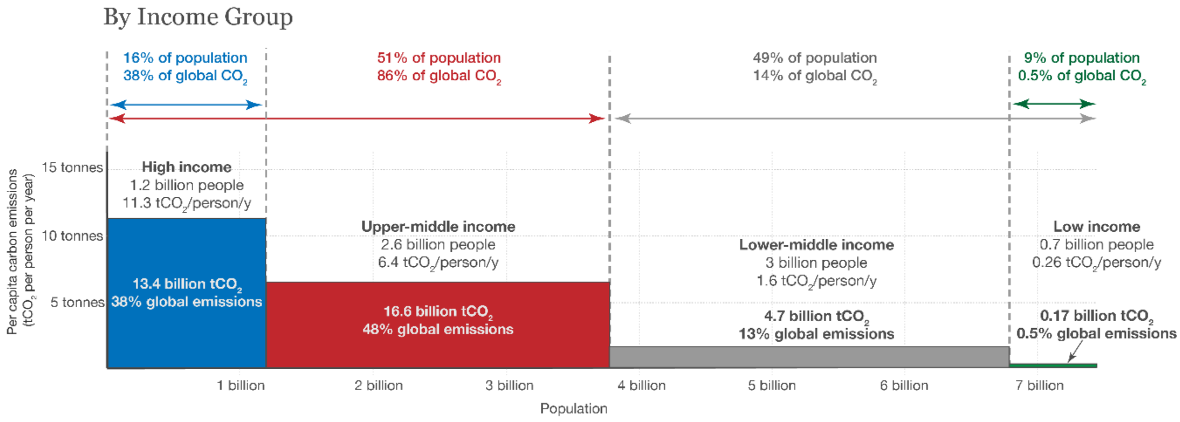

Figure 1.2 Global CO_2 emissions by income and region

Source: Our World in Data (2019)

Climate impacts. Rising global temperatures and extreme events have helped to maintain the political profile of climate change in many regions. These included record high temperatures in the summer in the Australia, Middle East and North Africa, an increase in forest fires in North America and Australia, and large temperature increases, which affects regions as diverse as Australia and the tundra and ice sheet in the Arctic *(All Impact statements to be reviewed and confirmed with AR6 WG I and II reports).*

Macroeconomic uncertainties. Following strong growth in 2017 and early 2018, the global economy and its outlook has been tempered by many factors. Disorderly financial market developments could disrupt activity in some economies and lead to contagion effects (World Bank 2019b). Trade disputes, most notably between US and China, could escalate or become more widespread, denting economic activity in these regions and elsewhere (IMF 2019a; Freund et al. 2018; Reznikova and Ivashchenko 2018).

Distribution and climate impacts. 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, reflecting high income inequality (World Bank 2019b; Laborde Debucquet and Martin 2017). Diffenbaugh and Burke (2019) show that global warming already has increased global economic inequality. Even if between-country inequality has decreased over a 50-year period, global warming has slowed the decrease (ibid), because while mild warming can be positive or uncertain for cool countries, it has more adverse impacts on growth in warm countries including most of the low-income countries (*ibid*).

Global trends contrary to multilateral cooperation. The rise of state-centered politics and geopolitical/geo-economic tensions are emerging across many countries and issues, not only on climate cooperation (WEF 2019). Multilateral cooperation is threatened by trends such as rising populism, nationalism, authoritarianism and growing protectionism (Abrahamsen et al. 2019). These trends make it more difficult to tackle global challenges including protecting the environment (WEF 2019). Despite great efforts to secure the Paris Agreement (Schreurs 2016; Parker et al. 2017), in November 2019 the United States initiated withdrawal, likely to hamper global climate cooperation in the future (Urpelainen and Van de Graaf 2018; Zhang et al. 2017).

Civil society pressures for stronger action ... Recently, youth movements in several countries show young people's awareness about climate change, evidenced by the school strikes for the climate that started in Sweden, but became a global phenomenon in 2018-19 (Hagedorn et al. 2019). Senior figures across many religions, most prominently in the papal encyclical *Laudato Si': On Care for our Common Home* (Francis 2015) have also raised strong voices about our duties to protect future generations and the natural world, and warned about the inequities of climate change. There has been a resurgence of grass root movements and activism. These movements, reflecting wider trends in the use of internet and social media in organizing large-scale international protests (Fisher et al. 2019), may play a major role in building political pressure for accelerating climate change mitigation. (*Due to the timing of these events, peer reviewed studies on these will be considerd in the Second Order draft*).

… but also strong resistance. On the other hand, the 'yellow vest' movement rallied against fuel taxes levied by the French government aimed at reducing CO_2 emissions from vehicles, illustrates that such policies may face political resistance (Lianos 2019) particularly in relation to income inequality and other social issues. To be successful, climate policies will need to be part of a larger social policy package consistent with a just transition" (Urpelainen and Van de Graaf 2018). There is a mismatch between concerns on climate change and people's willingness to pay for higher costs that may result from mitigation policies. While a survey shows that 71% of Americans believe climate change is happening, 68% would be opposed if monthly charges increased to 10$ a month, which is in stark contrast with global carbon prices compatible with 430-480 ppm CO2 eq (IPCC 2014c; EPIC 2019). See also further discusson on citizen engagement in Chapter 13.

Transnational alliances. Cities, businesses, a wide range of other non-state actors also have emerged with important international networks to foster mitigation. City-based examples include the Cities Alliance in addressing climate change, Carbon Neutral Cities Alliance, and the Covenant of Mayors (Chapter 8); there are numerous other alliances and networks such as those in finance (Chapter 15), technology (Chapter 16), amongst many others (Chapters 13, 14).

Technology. Recent years have seen large improvements in technologies relevant to greenhouse gas emissions. Most striking, the cost of solar PV has fallen by a factor of 5-10 in the decade since the IPCC *Special Report on Renewable Energy* (2011a), which largely formed the basis for the AR5 assessments, whilst the SR1.5 reported major cost reductions. This AR6 report finds solar and wind energy now to be increasingly competitive with fossil fuels in many conditions (Chapters 6, 9, 12). The share of renewable energy in power production has expanded much faster than anticipated (Hoekstra et al. 2017). Globally, solar PV capacity grew at an average 40%/yr from 15GW in 2008 to 500GW in 2018, with costs tumbling as noted below, when wind reached almost 600GW (REN21 2019); wind and solar combined in 2018 generated 7.5% of power globally, rising to 15% in Europe (ENERDATA 2019).

Battery technology has improved, helping electrification of many sectors through storing electricity from renewable power production and for the use of electricity in transportation (Chapters 6, 12). Battery electric vehicles have started to displace internal combustion engine cars, and most of the car manufacturers have started on decarbonization programs (Chapter 10). Alongside this, the shale revolution has opened up new cheap fossil fuel resources, not yet matched by the progress in CCS (Section 4).

In conclusion, developments since AR5 have underlined that climate mitigation technology, trade, shifting geopolitics, divergent political debates over sovereignty and globalization, inequities within and between countries, the concerns of the rising generation, multilevel and transnational actions and even religion, are all part of the context. In section 1.4 we outline the impact of these forces on climate change mitigation. The unifying goal, however, is to achieve technological and socioeconomic transformations that can deliver ambitious climate change mitigation and sustainable development in the context of a rapidly changing world.

1.3 Sustainable Development and Climate Change Mitigation

Climate change and sustainable development are interwoven along multiple and complex lines of relationship (Fankhauser 2016; Gomez-Echeverri 2018; Okereke and Massaquoi 2017; Okereke et al. 2009). The close connection between sustainable development and climate change is highlighted in several previous IPCC reports (IPCC 2007a, 2011a, 2014a, 2018a, 2019b). With its significant impact on food security, health, infrastructure, biodiversity among others, climate change poses a serious threat to development and wellbeing (IPCC 2007a, 2011a, 2014a, 2018a, 2019b). It follows that ambitious climate mitigation is necessary to secure a safe climate limit within which development and wellbeing can be pursued and sustained. However, a different approach emphasizes that rapid and largescale economic development, the sort of which, at least historically, have resulted in climate change, is needed to improve global well being (Baarsch et al. 2020; Lu et al. 2019; Mugambiwa and Tirivangasi 2017; Chen et al. 2017; Iuga 2016). Yet, others stress that climate change is caused by industrial development and more specfically the character of social and economic development produced by the nature of capitalist society (Pelling and Manuel-Navarrete 2011; Koch 2012; Malm 2016), which they therefore view as ultimately unsustainable.

An obvious implication of the very close interaction between climate change and development as outlined above is that climate mitigation at local, national and global level cannot be effectively achieved by a narrow focus on ‘climate-specific’ sectors, actors and policies; but rather through a much broader attention to the mix of development choices and the resulting development paths and trajectories (O’Neill et al. 2014). As a key staple of IPCC reports and global climate policy landscape (Gidden et al. 2019; Quilcaille et al. 2019; van Vuuren et al. 2017; IPCC 2014b, 2007b) (see also Chapter 2), integrated assessment models and global scenarios (such as the “Shared Socio-Economic Pathways” – SPPs) highlight the interaction between development paths, climate change and emission stabilization (see section 1.5.1 for in depth discussion on scenarios).

Equity and justice are important in conceptualizing the relationship between sustainable development and climate change because of the wide variation in the contribution to, and impact of climate change within and across countries (Reckien et al. 2017; Diffenbaugh and Burke 2019; Okereke and Coventry 2016; Baarsch et al. 2020; Bos and Gupta 2019; Klinsky et al. 2017). Specifically, the impact of climate change in limiting development is most acutely felt by the world’s poorest, 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).

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

1.3.1 Relevant Concepts and their limitations

At one level, the concept of sustainable development can in fact be seen as an attempt to resolve the climate/environment-development tension with the fundamental aspiration and assumption being that economic growth and climate change with its environmental impacts can be decoupled (Antal and Van Den Bergh 2016; Casadio Tarabusi and Guarini 2013). Fundamentally, sustainable development implies a close integration and the balancing of economic, social, and environmental (including climate aspects) and into development process and planning. However, despite the appeal of the concept, tensions remain over the interpretation and practical application of the concept with acute disagreements regarding what the balancing entails in real life, which goals to set, and the means through which such goals might be pursued (Michelsen et al. 2016; Okereke and Massaquoi 2017; Shang et al. 2019). For example, while the literature on de-growth, post growth and post development continues to question the sustainability and imperative of more growth (Escobar 2015; Asara et al. 2015; Kallis 2017; Latouche 2018), others have, on the contrary, continued to emphasise the importance of economic growth in tackling climate change, pointing to the relationship between development and climate resilience as well as the role of industry-powered technologies such as electric vehicles, and even negative emission technologies in reducing emissions and promoting wellbeing (Heinrichs et al. 2014; Kasztelan 2017).

Moreover, countries differ enormously in where they are in their development path – a condition which affects their capability, goals, priority and approach to the pursuit of sustainability (Shi et al. 2016; Ramos-Mejía et al. 2018; Okereke et al. 2019). The processes and politics involved in setting and negotiating these goals and approaches across sectors, and countries are a significant part of what the subsequent chapters in this report cover. Most climate and sustainble development literature recognises that despite its limitations, sustainable development, with its emphasis on integrating social, economic and environmental goals, provides a comprehensive framework for the pursuit of human progress and wellbeing. This is more so the case when Sustainable Development is recognised not as a static objective but as a dynamic framework for measuring human progress (Costanza et al. 2016; Fotis and Polemis 2018). Sustainable development is therefore relevant for all countries even if different groups of nations experience the challenge of sustainability in different ways.

Much like Sustainable Development, concepts like low-carbon development (Mulugetta and Urban 2010; Yuan et al. 2011; Wang et al. 2017; Tian et al. 2019) , climate-compatible development (CCD) (Mitchell and Maxwell 2010; Tompkins et al. 2013; Stringer et al. 2014) and more recently climate-resilient development (CRD) (Fankhauser and McDermott 2015; Henly-Shepard et al. 2018) have all emerged as ideas intended to bring together the goals of climate mitigation and development especially in the developing countries. In more industrialised countries terms such as ecological modernization, eco-modernism, the Green New Deal and social transformations are often used (see e.g. Dale et. al (2015). The green economy has gained popularity in both developed and developing countries as an approach for harnessing economic growth to address environmental issues (Bina 2013; Georgeson et al. 2017). Under a green economy, countries would enhance economic growth while ensuring that it does not undermine ecological systems. Critics have however argued that green economy ultimately emphasizes economic growth to the detriment of other important aspects of human welfare such as social justice (Adelman 2015; Death 2014; Kamuti 2015). Furthermore, some have observed that while terms like the green economy and climate resilient development offer conceptual tools for imagining a synergistic relationship between development and climate mitigation, they generally offer limited practical guidelines for reconciling the tensions that are often present in policy making (Dale et al. 2015; Ferguson et al. 2015; Kasztelan, 2017 Kotzé 2018).

Increasingly, the central thought that underpins most literature on how to operationalise the link between sustainable development and climate mitigation is the concept of synergies and trade-offs (Dagnachew et al. 2018; Fuso Nerini et al. 2018; Thornton and Comberti 2017; Wüstemann et al. 2017; Klausbruckner et al. 2016; Mainali et al. 2018). Climate mitigation can have many co-benefits to other development aspirations. For example, energy efficiency and renewable energy programs can have positive effect in clean air and health, job creation, community cohesion and addressing inequality. At the same time, narrow climate focused policies can undermine sustainable development aspirations such as when large land-based mitigation takes the land that can be used for food production or when regressive carbon tax policies exacerbates poverty and inequality. For its own part, development pathways that are sustainable can contribute to climate mitigation with examples including sustainable urban planning, organic agriculture, green building, sustainable consumption, green production, etc. The key insight is that pursuing climate stabilization in the context of sustainable development requires decisions and choices that exploit and maximize the synergy and minimises the trade-off between climate mitigation and sustainable development.

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

1.3.2 Climate Mitigation, Equity and Sustainable Development Goals (SDGS)

The stated objective of the UNFCCC is to ‘achieve the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system and enable economic development to proceed in a sustainable manner' (UNFCCC 1992, Art 2). Similarly, Article 2 of the Paris Agreement states that the aim is to 'strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty' (UNFCCC 2015). This same philosophy is clearly expressed in the adoption of climate change as one of the foci in the 17 Sustainable Develop Goals agreed by the world leaders in 2015 (Ürge-Vorsatz et al. 2018).

A major utility of the SDGs, apart from galvanizing global collective action, is that they provide concrete themes as well as short to medium term metrics and targets for measuring human progress to sustainability (Kanie and Biermann 2017). The SDGs also help to sharpen the links and provide a concrete basis for exploring the synergies and trade-offs between sustainable development and climate mitigation as well as between different sustainable development goals (Mainali et al. 2018; Fuso Nerini et al. 2018; Prajal et al. 2017). Even though climate change is explicitly addressed under SDG 13 (Climate Action), it is part of targets and indicators of some of the other 16 SDGs. Climate action has therefore been conceptualised as both a stand-alone and cross-cutting issue in the 2030 Development Agenda (Makomere and Mbeva 2018).

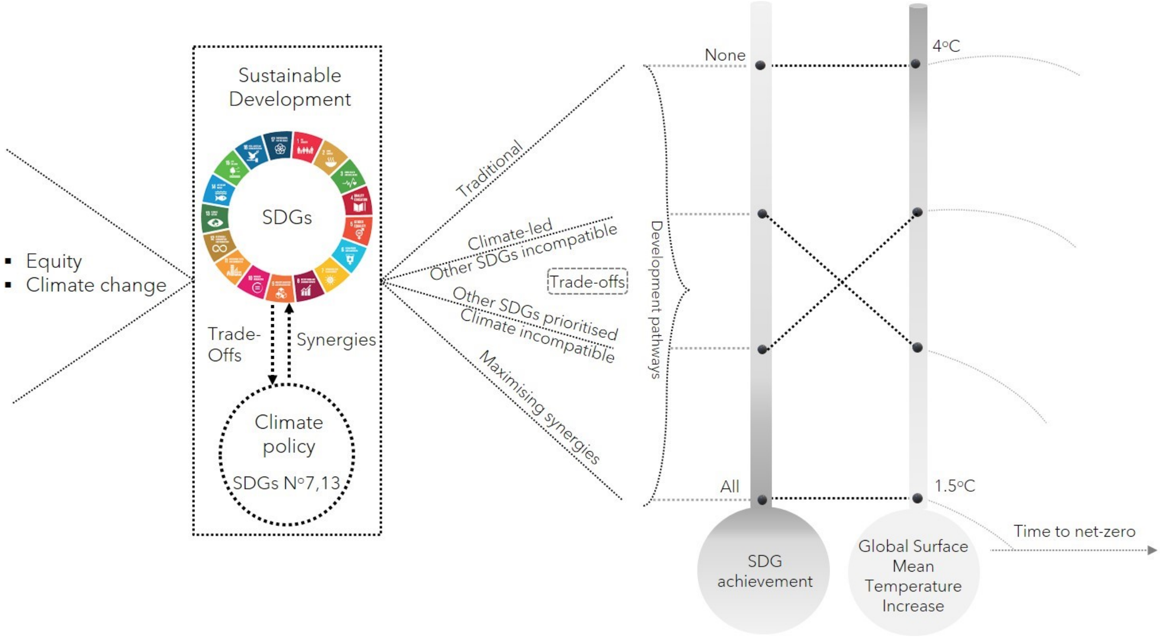

Figure 1.3 Links between climate mitigation, sustainable development, and equity (Source: Chapter Authors)

As indicated in Figure 1.3 above, development pathways that narrowly focus on climate mitigation or economic growth will not lead to the attainment of the SDGs and climate stabilization objectives. Rather the best chances of achieving both the SDGs and long term climate goals lie in the development paths that maximises the synergy between climate mitigation and broader sustainable development.

The need to think through the conceptual and practical relationship between climate change action and sustainable development remains very pressing especially in the context of Paris and the SDGs. First, while the Paris Agreement and the SDGs share the common goal of building a climate-safe future that is more sustainable, resilient and prosperous for humanity (Hellin and Fisher 2019) the timelines the integration between both agreement in terms of policy tools and timelines are limited. Second, the architecture of the Paris Agreement on Climate Change is based on an approach where countries submit NDCs and strengthen them over time (Hale 2016; Voigt and Ferreira 2016). This pledge-review-ratchet mechanism is meant to enhance overall mitigation actions to limit the change in global average surface temperature to 2 degrees Celsius, and the aspirational target of 1.5 degrees Celsius. However, while this approach may have the virtue of allowing many countries to participate in the agreement, it is not obvious that this mechanism is adequate to achieve the Paris goal. Dubash (2019) emphasises the importance of placing the need for urgent action on climate change in context of the Paris Agreement framework, with its emphasis on sustainable development as well as the importance of approaches that reinforce domestic political priorities and considerations. It is also important to pay attention to the institutions within which national frameworks are crystallised.

Concerns over equity have led to the suggestion that the emphasis should be on equitable access to sustainable development. This literature emphasises the equity dimension and recognised the need for less developed countries to have sufficient room for development while addressing climate change (Pan et al. 2014; Winkler et al. 2013).

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

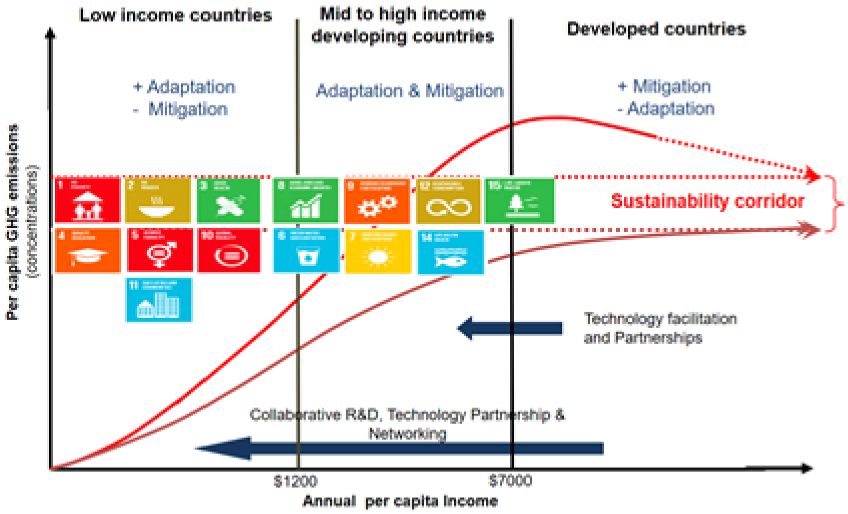

Figure 1.4 Sustainable Development is Relevant for all Countries even if Challenges Differ

While Figure 1.4 envisions a “global sustainability corridor” where the global development path is compatible with net zero emission or 1.5 stabilization, the Figure shows that bringing all countries into such a sustainable corridor would require different countries to focus on different SDGs as priorities, at least in the medium term – the key determinant being the current development status and socio-economic conditions of countries. For example, the main concern of the Least Developed Countries (LDCs) might be economic development and how to cope with climate variability (adaptation), while developed countries which typically have more financial and technological capabilities could focus on climate mitigation and reducing over consumption. The countries falling in between those two categories can address both adaptation and mitigation actions at different degrees of combination and emphasis of different sectors depending on national circumstances.

While economic growth at least up to a level of broad industrialization has been historically linked to greenhouse gas emissions growth, the correlation between CO_2 emission intensity, or absolute emission and gross domestic product growth, is not rigid, unambiguous and deterministic (Ojekunle et al. 2015).

It cannot be taken that pollution achieving a certain measure of economic growth inevitably demands a given amount of GHG emissions. As recent history has shown, investments in technology and the social innovation can result in countries attaining the sustainability corridor at a lower per capita GHG emissions. Figure 1.4 also communicates the point that the SDGs can be clustered into social, environmental, economic, dimensions and that the key priorities for the poorer countries may be lying more in the social cluster even if these countries are equally passionate about talking climate action. The developed countries may prioritise the environmental cluster of SDGs even if they are also concerned with addressing inequality and other social issues. It is also important to notice that the social cluster elements are closely interlinked as it is difficult to make the distinction between poverty, hunger, malnutrition, health, etc.

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

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

1.4 Drivers, Systems and Constraints

1.4.1 Drivers, sectors and services

Anthropogenic greenhouse gas emissions are an unintended by-product of transforming resources to serve human needs and desires, as shaped by human culture and institutions and the physical world in which we live.

Figure 1.5Figure 1.5 organises key drivers into five large aggregates, starting with the fundamental human preferences in the context of human institutions and culture; these are not necessarily independent of each other, or uniquely defined, but provide a set of broad aggregate forces that shape the scale of emissions:

- The desire for goods and services to enhance the quality of life are the ultimate source of economic activity and by-product emissions. Shifts in preferences can either increase or decrease emissions. For example, simply shifting diet toward a more vegetarian balance can reduce land-use change emissions (IPCC 2019c).
- The scale of economic activity is one important determinant of emissions. In general, wealthier economies produce more emissions per capita, but that pattern is not uniform (Chapter 2).
- The composition of goods and services and the technology with which they are produced, are equally important. Technology is not merely machines, but the entire set of ways in which humans transform resources—physical, intellectual, social and otherwise—into preferred states. Much of this Assessment describes how changes in the way humans deliver the goods and services they desire, that is technology, can provide these and meet sustainability goals, without concurrent net greenhouse gas emissions.
- Resource endowments play an important role. The challenge of mitigation would largely disappear if fossil fuels were small, or where zero carbon resources are cheap and plentiful.
- Policies, institutions and culture also shape emissions. Existing energy institutions have been largely shaped around fossil fuels, and mitigation policies and measures appear inadequate to meet Nationally Determined Contribution (NDC) goals as currently expressed (UNFCCC), let alone the far more ambitious Paris goals (UNEP 2018a) (UN Gap report).

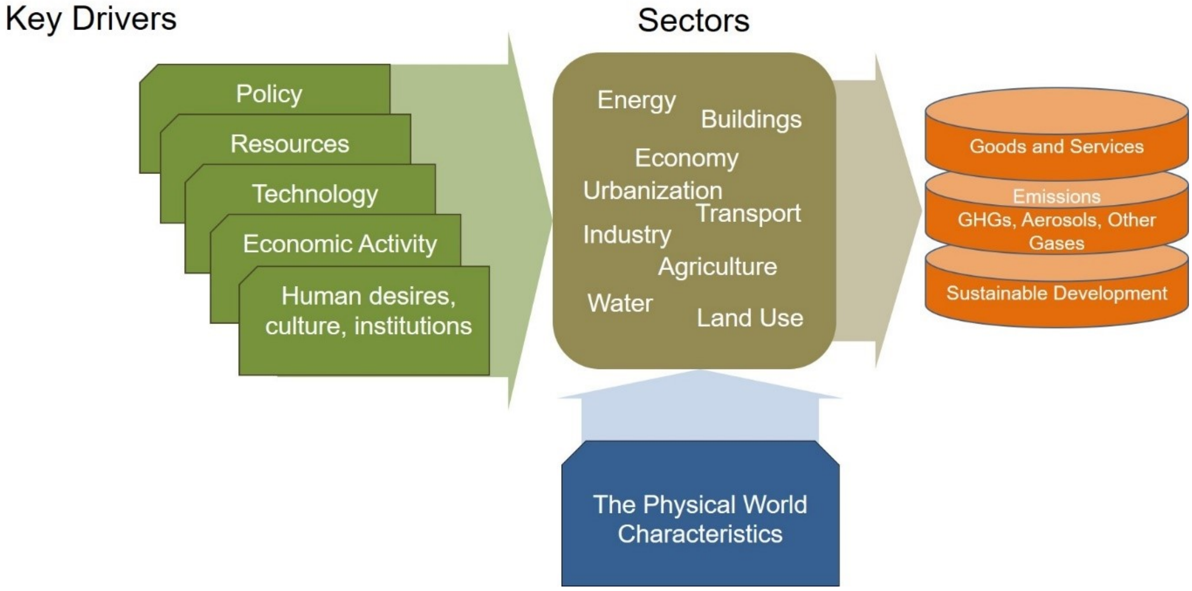

Figure 1.5 Key drivers, sectors and types of outputs

Achieving the Paris goals entails transformating many factors that shape emissions, from preferences and lifestyles (human desires), to technologies used to satisfy human desires, and the resources that humans utilize in combination with technologies. Policies and measures including regulatory, fiscal, informational, can play a key role, but must be supported by an underlying desire of humans to make a change (Diringer et al. 2019).

Human societies value a wide range of services ranging from nutrition to shelter to mobility and so forth. The means by which services have been provided has varied substantially over time. Meeting sustainable goals, including addressing climate change, means providing the goods, services, and overall quality of life desired by human populations while protecting the Earth systems that enable sustainable development. Systems do not evolve independently. They interact. They interact across sectors, across scales, and across time. Human systems interact with physical systems. There has been considerable interest to better understand various co-evolution scales (IHESD 2018; IM3 2016; PCHES 2016; Moss et al. 2016; USGCRP 2016; U.S. Department of Energy 2014). The co-evolution of energy, water, land and economy is sometimes referred to as the "nexus" (U.S. Department of Energy 2014; Bazilian et al. 2011; Ringler et al. 2013; Smajgl et al. 2016; Albrecht et al. 2018; D'Odorico et al. 2018). Land-energy-water (LEW) and climate-land-energy-water (CLEW) are just one of many nexuses. A key perspective to note is that the fundamental paradigm of nexus is to assess trade-offs and unravel synergies between the various interlinked energy, water, food, land and climate dimensions (Brouwer et al. 2018). This is particularly important in the context of provision of services, such as energy, agriculture and land use and ecosystem services, as well as the role of cities in providing new systems of transformation.

City transformation services. Cities throughout history have been the place where people come together and create new solutions to problems because of agglomeration economies, workplace diversity and opportunities for creative solutions based on face-to-face contact (Glaeser; Hall 1998). This is even more evident today as cities are growing so rapidly and the importance of knowledge economy jobs has shaped the type of employment being provided (Florida 2010; Newman and Kenworthy 2015). Cities can be seen as part of the climate problem or as part of the solution when their systems of innovation and transformation are turned into decarbonizing old power and transport systems, creating renewable energy and regenerating the atmosphere through carbon dioxide removal technologies (Newman et al. 2017). Such services can be developed through policy processes at city level as well as national level (IPCC 2018c).

Energy services: Energy is an example of a pure intermediate good. It is not consumed for its own sake, but rather for the services that it provides. Energy exists in various forms: exhaustible resource (fossil fuels, oil, gas, coal, peat uranium) and renewable resources (hydro, wind, solar, biological, tidal, geothermal, dung). The size of the global energy system has grown from roughly 11 EJ/year in 1850, primarily in the form of traditional fuels (e.g. wood, straw, dung) (Grubler et al. 2014; Zou et al. 2016), to more than 600 EJ/year in 2017, dominated by modern energy forms (BP 2019). There are 8 different classes of services in whose provision energy is used including transport of people and freight, provision of sustenance, materials, space conditioning, lighting, communications, cooking, water-heating and other (See Cullen and Allwood, 2010, Figure 2). Conversion losses in the transformation of primary energy forms to energy services are on the order of two-thirds (Grubler et al., 2014), leaving much room for improvement. There has been a long term trend to increasing the share of end-use energy that is in the form of electricity rather than fuels (Edmonds et al. 2006). From a demand and service perspective, it is primarily about the services that provide satisfaction for human well-being. This perspective is different from simply considering energy and material inputs (see Chapter 5). The balance lies in identifying mitigation options, along with efficient provision of services for ensuring well-being.

Agriculture and land use: Humans have had a major impact on land cover (Foley et al. 2005; Newbold et al. 2016), by transforming the landscape to produce goods and services such as food, fiber, forest products, urban settlements and extracted resources. There is a strong interaction between ecosystem services and human land use. Climate change will stress both intensively managed and less managed ecosystems. Temperature changes will tend to shift ecosystems toward higher latitudes, and can impact the health of species living in those ecosystems (Thomson et al. 2015). Increased CO_2 will affect both commercial and natural ecosystems in as yet uncertain ways. Emissions mitigation will also affect the way humans use land and the services the land provides. Storing carbon in expanded forests could increase ecosystem services, but it could also lead to monocultures. The use of bioenergy, which is a potential means by which negative emissions can be created to meet deep decarbonization goals, could result in expanded intensively managed landscapes, higher food prices, and water stress (Chapter 7; IPCC 2019b).

Ecosystem services: Ecosystem services are categorized as provisioning services (e.g. food, fresh water), regulating services (e.g. pollination), cultural services (e.g. aesthetic values) or supporting services (e.g. photosynthesis, nutrient cycling) (IPBES 2018; Millennium Ecosystem Assessment 2005). More specifically, pollination and nutrient cycling are processes that are required to have healthy functioning to achieve services such as food and fresh water (Wallace 2007). Earth's processes are under threat from anthropogenic factors such as pollution and rising emissions. Pollinators, for example, have been shown to improve crop yields by 75% (Vanbergen 2013). However, they are drastically declining due to land-use change and application of pesticides (Settele et al. 2016). Nature-based solutions (e.g. agro-forestry, land restoration) can offer ways of enhancing ecosystem services for sustainable development (Keesstra et al. 2018; Nesshöver et al. 2017; Torralba et al. 2016; IPCC 2019a).

Climate-land-energy-water nexus is of utmost importance to sustainable development. Water plays a central role in the nexus. It is intertwined with energy production, transformation and use. It is critical to human life both directly, and indirectly through agriculture and other land-based human activities. It is also critical to the health of ecosystems and through the provision of ecosystem services that sustain human welfare. As human populations have grown in size and income demands for agricultural products have grown as has water scarcity. This has resulted in increasing reliance in some regions on ground water in excess of recharge rates as well as the import of goods and services that represent an import of "virtual water" (Allen and Breshears 1998). Effective mitigation strategies require an integrated approach that considers the trade-offs and synergies between various dimensions of nexus (Chapter 7; IPCC 2019b).

1.4.2 Trade, consumption and leakage

The overall impact of trade opening on GHG emissions depends on the magnitude of scale effect (a change in emissions due to a higher level of economic activity), consumption effect (a change in emissions due to a change in the relative share of different goods in production) and technique effect (a change in emissions due to a change in production method). Scale and technique effects tend to work in opposite directions and consumption effect depends on comparative advantage of countries (Grossman and Helpman 1992; WTO 2018). An empirical analysis of top 10 non-OECD emitters indicates that trade opening over 1971-2011 has increased CO_2 emissions in 4 countries (Ertugrul et al. 2016). Other analysis shows that 1% tariff cut by G20 countries would increase the embodied CO_2 emissions for most of the manufacturing and mining sectors as well as those embodied in imports (Islam et al. 2016).

Trade could accelerate diffusion of low carbon technologies and tariff reduction of environment goods and services that have an environmentally beneficial outcome facilitates effective mitigation (de Melo and Vijil 2014).

Policy makers and business sectors are concerned about carbon leakages, a shift of CO2 emissions from a region with emission constraints to an unregulated area, caused by unilateral climate policies. There is no evidence that EU-Emissions Trading Scheme has caused carbon leakage *via* a change in relative competitiveness in an open global economy, during 2007-2011, but this is largely due to low emission cost and provision of large amount of free emissions allowances to counteract the leakage risk ("free allocation") (Naegele and Zaklan 2019). A multi-model scenario analysis indicates that the magnitude of carbon leakage caused by early and unilateral mitigation policies in a fragmented climate policy world depends on trade and substitution patterns of fossil fuels and the design of policies (Bauer et al. 2013). Other analysis indicates that differences in marginal abatement cost of NDCs could cause carbon leakages in energy intensive sectors and weaken effective global mitigation (Akimoto et al. 2018). Carbone and Rivers (2017) estimates that unilateral climate policy could cause 10-30% leakage in the sectors which are highly energy intensive and exposed to global competition.

While there are a number of policy responses to cope with carbon leakage including border tax adjustment (BTA), they have limitations. Some options could potentially be incompatible with WTO, particularly those not focused on simply leveling the cost of carbon paid by consumers. Others could involve difficulty of tracing the carbon content of inputs (Onder 2012; Denis-Ryan et al. 2016).

Supply chains that connect production and consumption activities are increasingly becoming global (Hubacek et al. 2016), leading to a growth in trade volumes (Federico and Tena-Junguito 2017) Emissions embodied in international trade account for about 20-33 % of global emissions (Wiedmann and Lenzen 2018a). Historically, and till now, official reporting of emissions is undertaken from a production-based or territorial perspective (i.e. emissions resulting from the production of goods for domestic consumption and exports get attributed to the place where emissions occur). Whereas, consumption-based emissions (i.e. attribution of emissions related to domestic consumption and imports – final destination) are not officially reported in global emissions datasets (see Chapter 2 for a discussion of the two accounting perspectives). Understanding consumption-based emissions at multiple levels, such as at a national, regional, city and household level (see Chapter 2), is crucial for gaining insights into the trends in emissions, and for uncovering the socio-demographic drivers of emissions.

From a consumption perspective: high-income developed countries typically tend to be net importers of emissions, whereas low/middle income developing countries net-exporters (Peters et al. 2011).This trend is now shifting, with a growth in trade between non-OECD countries (Meng et al. 2018; Zhang et al. 2019), and a decline in imports to OECD countries (Wood et al. 2019). An increase in international trade has resulted in a general shifting of emissions-intensive production from developed to developing countries (Malik and Lan 2016; Arto and Dietzenbacher 2014), and between developing countries (Zhang et al. 2019). This trend, called outsourcing/carbon leakage, has been documented to be a driver for an increase in emissions. Carbon leakage can also occur due to differences in mitigation policies between nations (see Section 13.2.6).

Compilation of consumption-based GHG inventories has been suggested as a way of monitoring carbon leakage (Peters and Hertwich 2008). To this end, entire global supply chains must be considered (Peters et al. 2011), using well-established techniques encompassing information about trade between different sectors of nations. Multi-regional input-output tables (Tukker and Dietzenbacher 2013), for example, contain information about domestic and international trade, hence have been used extensively for consumption-based accounting of emissions at multiple levels (Wiedmann and Lenzen 2018a; Malik et al. 2019). Not only is it important to assess the displacement between production and consumption sites for design of effective mitigations strategies for CO_2 emissions, but also for addressing the role of this separation in fueling a range of other environmental and social impacts, such as inequality (Wiedmann and Lenzen 2018b). A comparison of production- and consumption-based accounting is provided in Chapter 2.

The concept of 'Climate Clubs' has been suggested as a possible collaborative strategy for reducing emissions, with some proposals focused on border taxes for non-participants (Nordhaus 2015) whilst others explore clubs based on the potential benefits of free trade, risk reduction and technology cooperation amongs members (eg. Obergassel et al (2019); Hermwille (2019)). whilst others explore clubs based on the potential benefits of free trade, risk reduction and technology cooperation amongs members (eg. Obergassel et al 2019; Hermwille 2019).

International aviation and shipping emit approximately 1.6% and 2.6% of global CO_2 respectively (though GHG impact of former is increased by indirect effects). Both depend on liquid fuels and are growing rapidly at 3-5% per year (UNFCCC 2016), with long-lived capital stock risking lock-in. They are not explicitly covered by the Paris Agreement, as they were under the Kyoto Protocol (Scott et al. 2016); Fleming and de Lepinay, 2019; IMO, 2014), though aviation within the European Economic Area (EEA) is covered by the EU-ETS, and the respective specialized UN agencies (ICAO and IMO) have become more actively involved in mitigation initiatives. Some alternative biofuels have been certified for 'drop-in' usage for aviation for blends up to 50%, though with some concerns over availability, life-cycle emissions and refining capacity (Staples et al. 2018). It has been reported that tourism (with air travel included) is responsible for about 8% of global emissions (Lenzen et al. 2018).

Oceans, viewed more broadly, may however offer substantial mitigation potential, with ocean renewables being the biggest of five potential areas of contribution to 'closing the emissions gap' (Hoegh-Guldberg et al. 2019; IPCC 2019b).

1.4.3 Technology

The rapid developments in technology even over the past decade (section 2 above) enhance potential for transformative changes, in particular to help deliver climate goals simultaneously with other SDGs. History demonstrates that technologies often can be put to both good and bad uses, depending their governance and public choices; the challenge will be to enhance the synergies and minimize the trade-offs.

Information Technology. There have been explosive improvements in information storage, processing and communication over the last few years which transform possibilities (Chapter16). In energy systems this can enhance energy-efficient control (e.g., in heating, industry), distributed energy, such as small-scale PV, demand-side management including 'smart' appliances which may flex their demand according to the short-term price changes, and real-time management of power flows to accommodate variable sources – a 'smart' electricity system (Chapters 5, 6, 9-11) (Raza and Khosravi 2015). More generally, IT systems can reduce transaction cost for energy production and distribution, and communications technologies could reduce the need for physical transport, though with uncertain overall impact (Rosqvist and Hiselius 2016). IT may itself reduce the GHG intensity of economic growth, if information and entertainment are valued activities with low energy needs; some suggest, towards a "weightless economy" (Quah 1999), "characterized by intangible products and services" (Coyle 1997).

In policy, IT may facilitate tracing embedded emissions from source to final product (e.g., to enhance consumer choice on carbon footprint of foods, materials etc. (Reference Sought from chapter 16).

There are however concerns about threats to privacy, and high dependence on IT may involve security risks (in extreme, cyber warfare) (Meinert et al. 2018; Gaudenzi and Siciliano 2018). Also, some IT technologies, including blockchain, are electricity-intensive: one study estimates that Bitcoin transactions alone caused almost 70MtCO_2 emissions in 2017 and that continued growth at projected rates could make crypotcurrencies a major global source of CO_2 if the electricity production is not decarbonized (Mora et al. 2018).

Clean technologies including batteries

Aside from IT, major cost reductions in renewables and especially solar PV (Figure 1.6 and Figure 1, from Chapter 6 ZOD), open up large new zero carbon energy resources and may transform prospects for clean development (Chapter 6). Rapid improvements in battery and other storage technologies (eg. (Crabtree et al. 2015) may both help manage variability (Chapters 6, 9) and facilitate electric transport; both renewables and electric vehicles are growing exponentially (Chapters 6, 10), with emerging linkage of electricity and transport systems (Chapter 12) (White and Zhang 2011; Freeman et al. 2017). Rapid advances in fuel cells for both stationary and mobile applications (Dodds 2019) may open up additional routes to linkage of clean electricity, transport and heating systems (Chapters 6, 9, 12).

Note that all energy production and conversion systems involve materials use (and hence, some emissions in their construction as discussed in Chapter 7 of the AR5 (see figure 7.7). Whilst innovation can enhance possibilities for meeting climate and SDG goals simultaneously, new technologies may raise other concerns, such as the supply of rare earth materials for electronics or lithium for batteries (Wanger 2011; Flexer et al. 2018). Thus, recycling of materials may be an important issue for the future of battery technologies (Rosendahl and Rubiano 2019; IPCC 2011b).

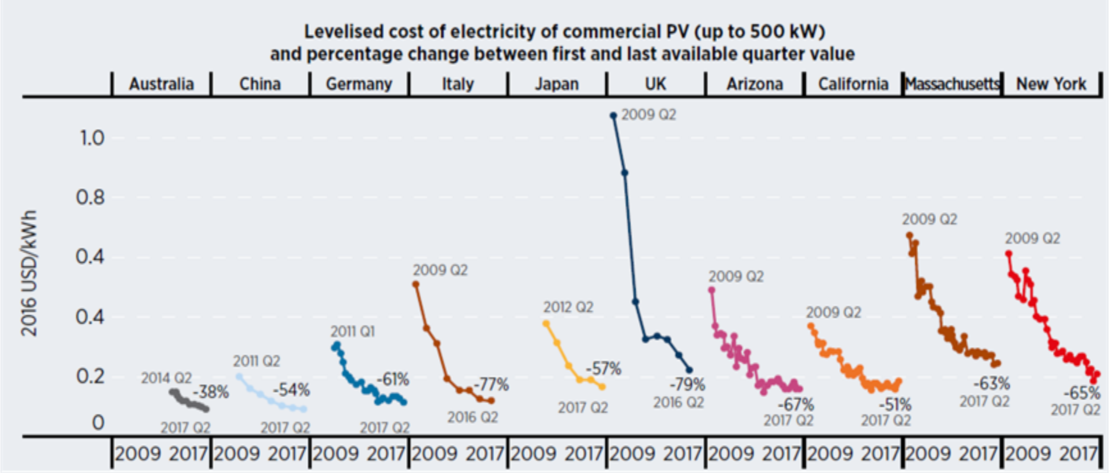

Figure 1.6 PV Levelised energy cost reductions in different regions

Source: IRENA (2018) and this report Chapter 6 (to be reconfirmed for SOD)

Generation III light nuclear fission reactors with improved fuel technology, superior thermal efficiency, significantly enhanced safety systems (including passive nuclear safety), and standardized designs for reduced maintenance and capital costs could be ready for large scale deployment in the years 2025-2065 contributing as an economical base load long before nuclear fusion could make an essential contribution (Knapp and Pevec 2018). On the other hand, if potential financial and regulatory risks are not properly managed for nuclear power projects, it can lead to high project and operation costs, and, fail to fulfil their objectives (Manan et al. 2015).

Development of CCS technologies has however been much slower than projected in previous Assessments. Eighteen full scale commercial facilities were operating in 2018 (Global CCS Institute 2018), the capacity (about 30 $MtCO_2$ yr^{-1}) compared to projections of volumes needed, e.g. for the IEA's Sustainable Development Scenario, with 350 $MtCO_2$ yr^{-1} by 2030 and 1500 $MtCO_2$ yr^{-1} by 2050 (International Energy Agency (IEA) 2018). Innovations notably with hydrogen may offer alternatives for some industrial processes like steel production, but CCS is however still a favored option for others like cement (Energy Transitions Commission 2019).

One sector that has seen little in the way of innovation for decades is agriculture. However, a recent spur in both technological and knowledge innovation show potential for meeting demand for food, feed, fiber and bioenergy while keeping within planetary boundaries. For technological innovation, recent developments in information technology enable introduction of precision agriculture that could increase productivity (yields), resilience, profitability and lower the carbon intensity of agricultural production. Knowledge innovation involves the application of management techniques that enhance environmental performance such as no-till agriculture, crop-livestock-forestry integrated systems (iCLF) and agroforestry (Chapter 7, Section 4.8) are all examples of what is broadly referred to as climate-smart agriculture. Deployed in conjunction, technological and knowledge innovation in agriculture production can potentially increase productivity and reduce environmental impacts. These are only some examples of activities that enhance or protect soil carbon, which can also include biochar and recuperation of degraded lands, especially pastureland (Chapter 7). Innovation in spatial data and monitoring system can also help reducing deforestation rates (Seymour and Harris 2019).

Plant-based meat innovation could also help drastically reduce meat consumption (Eshel et al. 2019).

Innovation is also enabling greater recycling and re-use of energy-intensive materials (e.g. Milford et al. (2013)) and introducing radically new materials, which might displace more carbon-intensive products and/or further improve the economics of some clean energy technologies (eg. large wind turbine blades.

Social dimensions

Public attitudes also affect the choice and progress of technologies, as witnessed through the impact of public objections to nuclear, biomass, CCS and sometimes wind (Chapters 5 and 6). Information Technologies will have broader impacts on the patterns of work and leisure; they may accelerate trends to fewer or relocated working hours which – coupled with rising affluence – means that the emissions intensity of how people spend their leisure time will become (even) more important (Chapter 5), and change the shares and intensities of residential and non-residential energy demands (Chapter 9).

Incentives, policy and ownership

Innovation in low carbon technologies comes partly from direct public and private investments in research and development, but also through many learning effects and scale economies as new products and technologies are developed and deployed (Chapter 16).

Private sector incentives to low carbon innovation in energy and commodities are limited by many factors. The full benefits of innovation often extend way beyond the original innovators (eg. 'spillovers' to other companies and countries). There may be limited high-value markets if relevant innovations are still mostly selling the same product ('electrons, molecules and food'). These low incentives for private innovation suggest a stronger role for governments in fostering industrial developments through niches (level 1), market structures (level 2) and strategic incentives beyond just R&D (level 3), which in combination may support transformation of entire sectors (Roberts and Geels 2019; Grubb 2014).

In fact, governments have an important role in most major innovations, leading Mazzucato (2013) to refer to the 'entrepreneurial state' and its role in shaping the direction in which technological systems evolve through 'mission oriented' industrial strategies which seek to accelerate innovation in technologies and systems that bring public benefits.

Innovations tend to be driven from a few global centres; other regions may fear technology dependence, whether on multinational companies or other governments. This is a generic issue rather than climate-specific; initiatives such as Mission Innovation and the UNCTC and its networks (section 1.2), combined with funding from the Green Climate Fund, may help to alleviate such concerns but also show the tensions inherent in creating incentives to both develop and diffuse technologies for global good.

Overall, the central conclusion is a positive one, though with important caveats. Innovation has already vastly broadened the range of possibilities for decarbonization and low carbon, climate resilient development. Public policy, at multiple levels, is however inescapable in shaping which opportunities, and to what extent, develop at a global scale.

1.4.4 Finance and investment

Attention to climate finance has risen considerably since AR5 and recent developments include demands for transparency on climate-related financial risks as well as a growing literature on knowledge and capacity gaps surrounding the amount, allocation and mechanisms of climate financial flows globally (Chapter 15, 15.3.3; 15.4.1; 15.6.3). The importance of the financial sector in the global fight against climate change is increasingly recognised (Bodnar et al. 2018; Weber et al. 2018), but so is the fact that it can only do so much, and that political leadership is central to enabling a conducive financial environment to unlock required investment flows (Ameli et al. 2019). In addition, a lively debate is ongoing over the role of central banks and monetary policy in scaling up climate-related finance and managing an orderly transition to a low-carbon economy (Krogstrup and Oman 2019). Growing impacts of extreme weather events related to a changing climate are already affecting global supply chains and economic activity, especially in vulnerable developing countries, increasing exposure to physical risks of climate change, exacerbating the challenge of financing mitigation action (Chapter 15, 15.5). Conversely, economic inertia may expose certain actors to a rapid and unorderly transition to a low-carbon economy (transition risks). Despite growing literature on physical and transition risks, significant knowledge gaps and inertia remain which need to be addressed to ensure implementation of robust risk management to maintain financial and economic stability, manage climate impacts and support an orderly transition to a low-carbon future (Warren 2019). Unlocking the flow of capital means the financial sector will have to address barriers that prevent socially optimal investments that include short-termism, information gaps, ineffective carbon pricing, regional biases, and (perceived) opportunity and transaction costs among others (Chapter 15, 15.4.1).

Major shifts in investment patterns are required to realize the targets of the Paris Agreement (Chapter 15, 15.2.2), particularly the target enshrined in Article 2c for Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development" (UNFCCC 2015). A sparse literature indicates investments could be higher, much higher, or lower than a policy baseline (McCollum et al. 2018; Rogelj et al. 2018; Grubler et al. 2018). Investments in energy infrastructure in 2016 totalled about 1.8 $trillion ($\$_{2010}$: 2.2% of global GDP) (IEA 2017). Projections from six IAMs result in investment ranges of 1.6–2.7 $trillion/yr by mid-century for policy baselines and of 1.6-3.8 $trillion/yr on average in 2016-2050 period (Rogelj et al. 2018; McCollum et al. 2018). However, asset portfolios have exposure to significant physical (climate) and transition (policy) risks, with limited reporting of these by financial actors and companies (Dietz et al. 2016; Battiston et al. 2017; Monasterolo et al. 2017; Schulten et al. 2019; UNEP-FI 2018, 2019).

Carbon-intensive activities may see reduced investments in a transition to a low-carbon economy. For example, in deep-decarbonisation scenarios, investments into fossil power generation technologies (including those with CCS) decrease to less than 50 bn USD per year, from 127 in 2018, while investments into non-biomass renewables increase more than three-fold to over USD 1 trillion per year in 2030 (IEA 2019). The bulk of power sector investment is projected to happen in medium- and low-income countries in the regions Asia, Latina America, Middle East and Africa, and the former Soviet Union, as these regions need to both replace existing fossil generation capacity meet growing energy demand. Financing needs for adaptation are more difficult to define but is estimated at USD140-300 billion by 2030 and USD 280-500 billion annually by 2050 significantly exceeding the financial needs stated in NDCs (Chapter 15, 15.2.2).

Several initiatives are increasingly mobilising the financial sector. Increasing demand for transparency of climate-related exposure by companies, banks and funds is embodied in the Financial Stability Board's Task Force on Climate-related Financial Disclosure (TCFD) (Chapter 15, 15.6.3). The formation of the TCFD reflects a concern on the part of central banks that inadequate information about potential climate-related financial risk (physical/climate impacts and transition/climate policy) could lead to financial instability (recessions) (Carney 2015). The TCFD recommends that both investors and companies should consider climate change risks (physical and transition) in their strategies and capital allocation, so investors can make informed decisions that mitigate climate risk exposure (TCFD 2018). However, transparency alone may not be enough, there is a need for metrics and indicators of assets risk exposure (Campiglio et al. 2018; Monasterolo et al. 2017) .

The TCFD provides guidance but leaves it to actors to chart the way forward. Various reports have been produced on risks and opportunities to the financial sector (HSBC 2018), on physical (climate) and transition risks to asset portfolios (Goldstein et al. 2019; Schulten et al. 2019), and methodologies for assessments of transition-related impacts (EPRI 2018; UNEP-FI 2019, 2018). Although other frameworks exist (Dafermos and Nikolaidi 2018), attention has focused on "Value at Risk" (VaR), an aggregate measure of potential loss on a portfolio of assets over some time horizon (The Economist Intelligence Unit 2015; Dietz et al. 2016). In its broadest sense, it is an indicator of asset exposure to future physical (climate) and transition (policy) risks, and the sparse but growing literature points to significant VaR due to climate change (Schulten et al. 2019; Battiston et al. 2017; Campiglio et al. 2018; UNEP-FI 2018). Fossil fuel extraction and supply chains are particularly exposed to VaR (Chapter 15, 15.6.3).

The international community agreed in 2015 through the Addis Ababa Action Agenda (AAAA) "*to address the challenge of financing and creating an enabling environment at all levels for sustainable development*" (UNDESA 2015). The AAAA recognises the significant potential of regional co-operation and provides a forum for discussing the solutions pathways to common challenges faced by developing countries (Chapter 15, 15.6.4). At COP16 in Cancun, countries "established the Green Climate Fund (GCF) "*as an operating entity of the Financial Mechanism*" under Article 11 of the UNFCCC[1] to help finance the transition to a low-carbon economy. Advanced economies pledged $100 billion a year by 2020, but so far this target has not been met (Chapter 15, 15.6.4). Confronting the problem of insufficient funding remains a challenge (Cui and Huang 2018).

The World Bank and the IMF have been promoting research on the interplay between climate change and public financial management (Krogstrup and Oman 2019; IMF 2019b) In fiscal year 2018, 32.1 percent of the World Bank Group financing was climate change-related, a record-setting $20.5 billion[2], Led by both the IMF and the World Bank, the Coalition of Finance Ministers for Climate Action recognises the challenges of climate change, finance ministers' capacity to address them and enhance the opportunities a transition presents[3]. Long-term sources are required to meet financing needs across sectors and geographies. Developing country shortfall more acute driven by debt burden of governments. They point to responsibility of developed world to provide financing for both mitigation and adaptation projects, but such flows are insufficient. Efforts to recognize and engage the private sector are needed to mobilise SMEs as prime economic players in the efforts to tackle climate change. Low-carbon SMEs often face high up-front costs that are recovered by low-operationl costs albeit over a long-time horizon. This means they need stable sources of long-term financing. Financial challenges tend to be larger in end-use sectors like industry, transportation and buildings (Chapter 15, 15.2.1).

There is limited global analysis on incremental costs and investments (mostly focusing on investment costs) that reflects the reality of developing countries hindering efforts for robust negotiations on international public climate finance. Moreover, the realities vary greatly across sectors and geographies, so applying standardized assumptions does not provide robust insights. The cost of capital remains an important barrier to increased flows, being especially high in developing countries (Buhr et al. 2018) where much of the infrastructure still needs to be built. Modelled mitigation scenarios are usually based on globally uniform cost of capital, but implementation of observed regionally-differentiated rates reflecting country risk leads to an increased burden of mitigation on developed economies (Iyer et al. 2015). Iyer et al (2015) also implemented differentiated risk across different technologies with the same effect. A major challenge facing investors is the "*tragedy of the horizon*", the contrast between short-

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[1] https://unfccc.int/process/bodies/funds-and-financial-entities/green-climate-fund

[2] http://pubdocs.worldbank.org/en/606651532004021569/Fact-Sheet-World-Bank-Group-Fiscal-Year-2018-Climate-Finance.pdf

[3] http://pubdocs.worldbank.org/en/646831555088732759/FM-Coalition-Brochure-final-v3.pdf

termism in the financial sector and the longer-term lenses of climate impacts and political cycles (TCFD 2018). Climate-related investments in developing countries also suffer from structural barriers such as sovereign risk and exchange rate volatility (Guzman et al. 2018; Farooquee and Shrimali 2016) which affect not only climate-related investment but investment in general including in needed infrastructure development consistent with meeting the SDGs (Gray and Irwin 2003).

Climate finance flows and access are deeply affected by political uncertainty and lack of credible public commitments. Assumptions in modelled scenarios point to multiple challenges around mobilization of funds at the required scale (Rogelj et al. 2018) including establishment of favourable policy environments to reduce the cost of capital for both mitigation and adaptation projects. To improve financial flows to low-carbon investments, a stable and enabling policy environment could not only provide financial support but also set regulatory and tax regimes that incentivize long horizons, enhance information access and R&D, provide policy and financial de-risking measures.

Policies would need not only to increase amounts invested but also facilitate a shift in direction (Chapter 15, 15.6.2). This needs to take account also of ownership and political structures – for example, across 56 recipient countries in Asia and Africa, the surge of coal investments has been almost entirely supported by foreign State-Owned Enterprises, whereas private investment has flowed almost entirely into renewables (Zhou et al. 2018); Steffen and Schmidt (2019) also found that even within Multilateral Development Banks, 'public- and private-sector branches differ considerably', with public-sector lending used mainly in non-renewable and hydropower projects. In the end, however, the financial sector can only do so much, so political leadership is central (Chapter 15, 15.7). Reviewing the BRI projects to date, 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

Political economy scholars suggest that the politics of interest, (most especially economic interest) of key actors at subnational, national and global level is one of the most important determinants of climate (in) action (O'Hara 2009; Lo 2010; Tanner and Allouche 2011; Sovacool et al. 2015; Clapp et al. 2018; Lohmann 2017a; Newell and Taylor 2018; Lohmann 2017b). Political economy approaches can be crudely divided into the term as used by economists, which can be referred to as "economic approaches to politics", and those by other social scientists (Paterson and Laberge 2018). The latter literature emphasizes the intimate relation between industrial economic growth and climate change and more specifically the central role of structures of power, production, and a commitment to economic growth in either facilitating or hindering ambitious climate action. An important aspect of this is the central role of fossil fuels to economic development and especially in enabling the exponential expansion and globalization of economic activity, as well as the deep embedding of fossil energy in daily life (Malm 2015; Huber 2012; Di Muzio 2015; Newell and Paterson 2010).

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

One of the factors limiting the ambition of climate policy has been the ability of incumbent industries to shape government action on climate change (Newell and Paterson 1998; Breetz et al. 2018; Jones and Levy 2009; Geels 2014). Campaigns by oil and coal companies against climate action in the US and Australia are perhaps the most well-known and largely successful of these (Oreskes and Conway 2012). In other contexts, resistance by incumbent companies is more subtle but nevertheless has weakened policy design on emissions trading systems (Pinkse and Kolk 2012), limited the development of alternative fuelled automobiles (Wells and Nieuwenhuis 2012; Levy and Egan 2003), for example. Political economy suggests one part of the key to countering this is in the building of coalitions of actors to legitimise policy in the face of such opposition (Meadowcroft 2005; Levin et al. 2012; Meckling 2011). The interaction of politics, power and economics is central in explaining why countries with higher per-capita emissions, which logically have more opportunities to reduce, in practice take the opposite stance. This is often because of the vested interest of State-owned Enterprises (Wittneben et al. 2012; Polman 2015; Wright and Nyberg 2017), the alignment and coalitions of countries in climate negotiations (Gupta 2016; Okereke and Coventry 2016), and the patterns of opposition or support for climate policy among citizens (Swilling et al. 2016; Heffron and McCauley 2018; Ransan-Cooper et al. 2018; Turhan et al. 2019; Baker 2015) (with the “yellow vest” demonstrations in France in 2018 being one recent example).

1.4.6 Equity and justice

Equity is important for all Sustainable Development Goals (SDG), such as goals for no poverty, zero hunger, gender equality, affordable clean energy, reducing inequality, but also for climate action (Goal 10). In addition, equity issues are important reasons why it is difficult to reach a significant global agreement, as it is hard to agree on the optimal level of greenhouse gas mitigation (or emissions) and how mitigation should be distributed among countries (Kverndokk 2018). There are at least two reasons for this. First, optimal emission reductions depend on ethical considerations. Examples follow from simulations made on integrated assessment models (see, e.g., Chapters 3 and 4). As these models use different ethical parameters such as the time preference rate and the valuation of consumption between agents with different consumption levels, they also produce different optimal mitigation (see IPCC (2018a); and Chapter 3). Second, treaties that are considered unfair may be hard to implement (Klinsky et al. 2017; Liu et al. 2017). Lessons from experimental economics show that people may not accept a distribution that is considered unfair, even if there is a cost of not accepting (Gampfer 2014). As equity issues are important for reaching deep decarbonisation, the transition towards a sustainable development (Evans and Phelan 2016; Heffron and McCauley 2018; Okereke 2018) is also dependent on taking equity seriously in climate policies and international negotiations (Okereke and Coventry 2016; Martinez et al. 2019; Klinsky et al. 2017).

Both climate change and climate policies affect countries and people differently. Rich and poor countries will not be affected in the same way by climate change, and the highest impacts will be felt in the poor countries (Burke et al. 2015). The reason is mainly that these countries are more dependent on primary industries (agriculture, fisheries etc.) than rich countries, and that their infrastructure is also in a poorer condition. Costs of mitigation also differ across countries. Studies show there are large disparities of economic impacts of NDCs across regions, and also between countries relatively similar when it comes to the level of development, due to large differences in marginal abatement cost for the emission reduction target of NDCs (Akimoto et al. 2018; Fujimori et al. 2016; Edmonds et al.). The cheap mitigation options are often found in poor countries. But the opportunity cost may be higher in these countries if mitigation hamper their economic growth and the possibility to reduce poverty.

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

A climate treaty may help meeting some of the SDGs, but there may also be trade-offs between mitigating climate change and meeting some SDGs, see section 1.3. above and Chapter 17. Such a treaty will likely involve transfers from rich to poor countries, as agreed upon in the (UNFCCC 2010) see section 1.4.5 above and Chapter 15. The transfers will typically be transfers of mitigation and adaptation capital, or financial resources (from public as private funds) to support mitigation and adaptation activities, and may be motivated by strategical reasons as well as equity reasons (Kverndokk 2018). However, transfers of mitigation technology should be carefully designed to avoid so called rebound effects on emissions by reducing incentives for mitigation in the poor regions (Sarr and Swanson 2017; Glachant et al. 2017).

1.4.7 Social innovation and behaviour change

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

One example may be changes in diets, as diets have a major impact on emissions (Willett et al. 2019). Moving towards plant-based alternatives to meat could be an important way of cutting into emissions from diets (Eshel et al. 2019) However, diets are deeply entrenched in cultures and identities and extremely hard to change (Fresco et al. 2016).

Several social innovations may also have impacts on greenhouse gas emissions. Education is increasing across the world, and higher education will have impacts on fertility, consumption and the attitude towards the environment (Osili and Long 2008; McCrary, Justin and Royer 2011; Hamilton 2011). Further, a fall in poverty and an improvement in health will also have implications for fertility, energy use and consumption globally. Finally, social capital and the ability to work collectively may have large consequences for mitigation and the ability to adapt to climate change (Adger 2009). See also section 4.3.5 in IPCC (2014).

Climate change perception and how policies can affect this perception and then act accordingly is studied through different lenses from psychology (Weber 2016) to sociology (Guilbeault et al. 2018) and experimental economics (Allcott 2011).

1.4.8 Legal framework and institutions

Institutions comprises of formal and informal rules that shape action within a society (North 1990). Institution also refers to the functional arrangements and structures for making and implementing policy as well as the very capacity for governance. Understood in these terms, it become obvious that institutions can both facilitate or constrain climate policy-making and implementation in multiple ways. Institutions set the economic incentives for action or inaction on climate change both at national, regional and individual levels (Dorsch and Flachsland 2017; Sullivan 2017). A lot is often said about how price or cost influence how much nations, companies and individuals are willing to adopt renewable energy technologies and lifestyle (Creutzig et al. 2017; Tol 2018). However, the cost of low-carbon technologies are often themselves products of specific institutional constructs and practices, such as the pattern of subsidies or investment (Andrews-Speed 2016). Institutions entrench specific political decision-making processes, often empowering some interests over others. Several scholars have traced delay and sluggishness by states to pursue ambition climate mitigation policies to the activities of powerful interest groups who have vested interest in maintaining the current high carbon economic structures (Sullivan et al. 2018; Okereke and Russel 2010; Wilhite 2016).

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

By 2017, 70% of global GHG emissions are covered with either nationally binding climate legislation or climate strategies. In accordance with the development of NDCs, the share of global GHG emissions covered with national GHG emissions targets increased from 69% in 2014 to 89% in 2017. National action may be spurred by international process while national consensus may enhance global collective action (Lacobuta and Höhne 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 2016a). A common criticism of international institutions is their limited (if any) powers of compliance. In reality compliance tends to be high once countries have ratified and a Treaty is in force. All the Parties with targets under the Kyoto Protocol, for example, complied, and some at significant expense, mainly from investments in developing countries under the CDM (Shishlov et al. 2016). The problem was not non-compliance, but participation - the limited coverage of the initial targets, reduced further by US non-ratification and subsequent Canadian withdrawal, with still less participation in the next round (section 4.11).

Not every provision of the PA creates a legal obligation (Bodansky 2016a). The PA does not require parties to implement their NDCs but requires them to pursue domestic mitigation measures. On the other hand, the PA obliges developed country parties to provide financial assistance to developing countries. Legally bindingness of the Paris Agreement is undeniable since it is justiciable based on the consent of States in its implementation as contracting states (Bodansky 2016b). The bindingness of an agreement also depends on the costs (e.g., loss of reputation) to a state of nonparticipation, noncompliance, or withdrawal. Strong norms with high costs of violation are sometimes called 'binding' (IPCC 2014a; Hoffmann 2005, 2011).

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

1.4.9 Policy drivers

Although major transformations of economic systems have occurred in history, energy is fundamental to human well-being and the industrial revolution and economic growth since then has been powered by fossil fuels, and often, land clearance. The literature finds that transformation to different systems will hinge on conscious policy to change the direction in which energy, land-use and agriculture develop this century. Policy is inescapable in land-related systems (Chapter 7) and urban development (Chapter

8), and has already been a principal driver of improved energy efficiency in buildings (Chapter 9) and transport (Chapter 10), and significant in industry (Chapter 11).

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

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

Synergies and trade-offs arise partly because of the nexus of GHG emissions with other adverse impacts (eg. local air pollution) and critical resources (eg. 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/behavior; existing regimes governing markets and public actors; and the landscape level of strategic decision-making and regime changes (section 5.4). Chapter 13 conducts a thorough appraisal of policies for transformation in the context of sustainable development. Such assessment indicates the importance of policy as a driver of change for sustainable development at multiple levels and across many actors, with potential for benefits as well as costs at many levels.

National-level legislation may be particularly important to the credibility and long-term stability of policy to reduce the risks and hence cost of finance (Chapter 15) and for encouraging private sector innovation at scale (Chapter 16). Nash and Steurer (2019) find that seven national Climate Change Acts in European countries all act as 'living policy processes, though to varying extents'. As one significant example, the halving of CO_2 emissions in UK power generation reflects multiple policies, particularly since the UK's Climate Change Act (2008), which drew upon the Kyoto structure of binding commitments but requires domestic emission caps to be set 15 years ahead to enhance certainty. The energy regulator's duties were amended to protect 'present and future consumers', leading on to the UK's Electricity Market Reform, which both strengthened carbon pricing and supported a surge in renewable energy, which along with energy efficiency policies at EU, UK and sub-national levels led to these unprecedent reductions (Grubb and Newbery 2018).

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

1.4.10 International cooperation

The need for collective and urgent action on climate change is often mentioned as one of important reasons for strong international co-operation in the 21st century (Bodansky and Lavanya, 2017; Cramton et al., 2017; Falkner, 2016; Keohane and Victor, 2016). International cooperation is essential for tackling climates action because of the structure of the climate change problem (Bodansky and Lavanya, 2017; Keohane and Victor, 2016). First, the benefits of GHG emissions reduction are global and nonexcludable, making anthropogenic climate change a global commons problem (Falkner 2016a; Wapner and Elver 2017). Second, mitigation costs are only borne by countries taking action while the benefit of such action is not limited to them. Moreover, there is a tendency among governments to think that mitigation efforts will raise energy cost and adversely affect national economic competitiveness. All these creates strong incentives for free riding where states may wish to benefit from GHG reduction without taking their fair share of action (Keohane and Victor, 2016; Herman 2019). International cooperation has the potential to address these challenges by offering a platform for collaboration for multiple actors with diverse perceptions of the costs and benefits of collective action. International institutions offer opportunity for actors to engage in meaningful communication, and exchange of ideas about potential solutions (Cole 2015).

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

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

Scholars suggest that international collaboration work best when agreement is self-reinforcing with agreement greeting incentives for mutual gains and joint action (Keohane and Victor 2016). However, the structure of the climate challenge makes such as an arrangement hard to achieve.

The negotiation of Paris Agreement was done in the context of serious questions about how best to structure international climate cooperation to achieve better results given the limited progress made under Kyoto in terms of emission reduction (Bodansky 2016a; Okereke and Coventry 2016; Scavenius and Rayner 2018). The central component of the Paris Agreement is a pledge and review system of Nationally Determined Contributions (NDC) which seeks to combine top-down centralized elements (e.g. procedural obligations to prepare and communicate successive NDCs every five years, compliance with international transparency requirements) and bottom-up voluntary NDCs, the Paris Agreement as having a hybrid structure (Chan et al. 2018). This new agreement is designed to side-step the fractious bargaining that have characterised international climate cooperation (Marcu 2017a). However, it remains unclear the extent to which this new arrangement will result in more ambitious emission reduction. Since the Paris Agreement is based on a unilateral pledges and countries may assess others' efforts in determining their actions, comparability of domestic mitigation efforts will remain very important as means of measuring reporting and verifying action. These in turn would require strong form of international co-operation. Various metrics for comparing mitigation efforts could be envisaged (Aldy 2015). Countries may assess others' efforts in determining their actions through several platforms, such as Climate Change Cooperation Index (C3-I), Climate Change Performance Index (CCPI) 'Climate Laws, Institutions and Measures Index' (CLIMI) (Barmauer et. al 2013; Steve et. al 2014).

Article 6 of the Paris Agreement enables Parties to voluntarily cooperate in the implementation of their NDCs in order to allow for higher ambition and to promote sustainable development and environmental integrity (Marcu 2017b). Article 6.4 establishes a new sustainable development mechanism subject to international oversight. Article 6.2 allows Parties to cooperate directly with one another involving the use of internationally transferred mitigation outcomes towards nationally determined contributions and will have no formal international oversight. Research finds that even if all NDCs were implemented cost effectively in each nation, that the gross disparities in marginal cost still exist across countries. Such differences imply opportunities for improved resource allocation and overall reductions in cost. Fujimori, et al. (2016) found that welfare loss could be reduced by between equivalent to US$30–1240 billion, while Edmonds et al.(in review) find cost savings of US$250 billion/year from fossil fuel and industrial emissions sector improvements alone. Edmonds et al. go on to estimate that if independent implementation costs are taken as a willingness to pay for climate mitigation, an economically efficient regime could deliver an additional 5 $GtCO_2yr^{-1}$ in enhanced ambition, about a 50% increase with no additional cost to any party. Significant barriers exist to implementing the potential of Article 6 including the heterogeneity of NDCs, lack of well-defined rules. While such market-based mechanisms can be effective mitigation instruments, their inappropriate use could threaten environmental integrity. It is crucial to define how to apply corresponding adjustments in accounting and to ensure additionality. (Michaelowa et al. 2019; Müller and Michaelowa 2019). In the long run, the NDC structure lacks a set of incentive for low-ambition regions to increase ambition.

Climate change has become a focal issue in many other UN fora (e.g., UNEP, UNDP), non-UN multinational and transnational fora such as REDD+ Partnership. Major Economies Forum on Energy and Climate Change (MEF) and energy specific fora (e.g., IEA, IRENA, IPEEC). Climate change is also one of the major topics at the G7 and G20. There are also numerous international cooperation initiatives in clean energy R&D (e.g. EU Mission Innovation, IEA's Technology Collaboration Program) and integrated cooperative R&D centres (e.g. US-China Clean Energy Research Centre, ITER)(Van de Graaf and Westphal 2011; Aldy 2017; Chan et al. 2018; Kirton 2015). International cooperative initiatives between and among non-state (e.g., business, investors, civil society) and subnational (e.g., city, state) actors have also been emerging, taking the forms of public-private partnerships, private sector governance initiatives, NGO transnational initiatives, and subnational transnational initiatives (Bulkeley and Schroeder 2012; Roelfsema et al. 2018).

1.5 Frameworks, Methods and Analytical Tools

Climate Change is a problem unprecedented in its scope and scale. As such, it creates unique challenges for analysis, from quite divergent perspectives. The economist Nicholas Stern (2006) called it "the greatest market failure in history". The moral philosopher Stephen Gardiner (2006) described it as "the Perfect Moral Storm". Social scientists have come to describe it simply as a "super wicked problem" (eg. (Lazarus 2008; Levin et al. 2012): one which appears infernally, almost impossibly, difficult to solve through any of the traditional tools and assumptions of social organisation and analysis. In this section, we summarise some of the key analytic frameworks, methods and analytic tools for trying to understand and influence the forces and policy choices.

1.5.1 Scenarios and Narratives of the Future

Scenarios are plausible, internally consistent representations of potential future developments that are used to think through the potential consequences of various alternative external events. Events can be things such as alternative technology availability, alternative realizations of the physical world, alternative policies, alternative resource availability, and alternative socio-economic drivers. Numerical models are frequently used to create scenarios because they are reproducible, and if constructed well, ensure that all relevant data are accounted with nothing either double counted or left missing. That having been said, mental models are also used and are frequently the inspiration for more formal formulations. Scenario development and utilization are closely intertwined with the use of models in that both are used to explore alternative future developments either to better understand and anticipate eventualities—either desired or undesired—that can either be achieved or avoided or which might need management. Choices and challenges can be explored. Implementation of an expensive or ineffective or counter-productive policies that are put into effect in models and scenarios hurt no one. Whereas, bad, expensive, or counter-productive policies implemented in the real world have real adverse consequences. Models and scenarios need to be subjected to formal and informal validation to ensure that the scenarios and models used to produce them are in fact internally consistent representations of possible futures. Note that scenarios are not absolute forecasts of the future. Rather they provide forecasts of the future that are conditional on the assumed external events. Since all models are abstractions of the key relationships, no model will be perfect and hence no scenarios will be a perfect rendering of future developments. The important thing is that they provide sufficient insights to allow for decision makers to make better informed decisions than would have been possible without them. The key question is, are the scenarios and models suitable for purpose.

Scenarios play roles throughout the climate research field. The current research architecture for scenarios to inform climate science was laid out in Moss et. al (2010). Scenarios are used by climate modellers to provide information about emissions of greenhouse gases, aerosols and short-lived species that could be imagined. They also provide a common set of reference scenarios that allow climate models to be compared against each other without variation in their input drivers. In the AR5 climate modellers used four alternative emissions pathways, called Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011). The four scenarios provide climate drivers that had a variety of desirable properties. They spanned the range of the then-available open, per-reviewed literature with the highest available scenario, RCP 8.5, reaching 8.5 W m^{-2} climate forcing in the year 2100, with emissions and climate forcing still increasing in 2100. On the other extreme, RCP 2.6, was, at the time, the lowest climate forcing scenario that had appeared in the open, peer-reviewed literature. Two scenarios in the middle, RCP 4.5 and RCP 6.0, provided two alternative pathways in which policy intervention lead to the stabilization of climate forcing.

RCPs were developed by the integrated assessment modelling community for the climate modelling community. The RCPs are archived on the IIASA data base at (IIASA 2019). While they provided climate modellers the information they needed to explore a meaningful range of potential future climate change futures, they did not contain information that the climate impacts community could use. For example, they did not contain information about the socioeconomics (population and GDP) variables. They did not provide information about technology availability, and they did not provide information about the policy environment.

To better enable climate impacts researchers, as well as climate researchers, to have a common set of background scenarios a new set of scenarios, based on Shared Socioeconomic Pathways (SSPs) were created (Riahi et al. 2017; O'Neill et al. 2014). The SSPs were designed to facilitate the exploration of futures that spanned a range in terms of challenges to emissions mitigation and adaptation to climate change. While those metrics were never formally defined, they provide an architecture in which to not only bin existing and future scenarios but to build entirely new scenarios. A set of five reference scenarios were created to represent the four combinations of high and low challenges to mitigation and adaptation, plus a "middle of the road" scenario. Both descriptive, narrative, scenarios (O'Neill et al. 2014) and quantified scenarios (Riahi et al. 2017) were developed. The five reference scenarios in turn can be combined with consistent climate policy assumptions to explore the implications of limiting climate forcing to values ranging from 1.9 W m^{-2} (~1.5ºC) in 2100 to 8.5 W m^{-2}. In addition to climate limit values for the 3 RCPs (2.6, 4.5, and 6.0 W/m^2) a 3.7 W m^{-2} scenario has also been created as a benchmark to provide greater policy variety. It is important to note that SSPs were intended to be useful to both the climate modelling and climate impacts communities.

In the IPCC Special Report of 1.5 (IPCC 2018a)four scenarios were developed to illustrate alternative pathways that could achieve a limit to climate change of 1.9 W m^{-2} (~1.5ºC) in 2100. The 1.9 W m^{-2} the pathways differed as a reflection of the underlying socioeconomics. Three of the illustrative scenarios started with an SSP and then applied policies to achieve the limit to climate forcing. The three underlying SSPs were SSP1 (Sustainability), SSP2 (Middle of the Road), and SSP5 (Fossil-fueled Development). A fourth scenario, Low Energy Demand, explored a pathway to 1.9 W m^{-2} in 2100 that was predicated on a low energy demand development strategy.

Other, transformation-oriented scenarios have been developed to explore pathways that could achieve the SDGs by mid-century (TWI2050 - The World in 2050 2018). Other researchers have begun to explore the trade-offs and synergies across goals in scenarios, for example (Iyer et al. 2018).

Scenarios support both research and decision making. Scenarios and models that support national and global decision making are not necessarily the same as those which are used to support local and national decision making. SSPs and SDGs have been deployed to help provide a well-established point of reference and context in which other models and scenarios can be deployed to support local and regional analysis of sectoral issues (O'Neill et al. 2019). While we tend to think of scenarios as discrete representations of future developments, every element of a scenario has an associated uncertainty that surrounds it. That uncertainty usually goes unquantified. Scenario ensembles that map uncertainty in external drivers into a range of outcomes is one way to estimate the range of uncertainty.

Another technique, (Robust Decision Making, RDM) (Lempert 2019; Lempert et al. 2013, 2006) combines uncertainty and scenario analysis. RDM begins by developing an ensemble that contains a large number of scenarios and then, in consultation with the decision maker(s), selects a finite number of scenarios that explore the range of potential outcomes, positive and negative, to consider in detail. RDM incorporates uncertainty not through a single joint probability distribution but through sets of plausible probability distributions to capture deep uncertainty. Also note RDM uses robustness (e.g., less sensitivity to assumptions) instead of optimality to evaluate alternative policies.

A new scenario user that has emerged since the AR5 is the climate-related financial risk disclosure. The community was jump started by the creation of the Task force on Climate-related Financial Disclosure (TCFD) in 2016 by the Financial Stability Board (FSB). The TCFD monitors and makes recommendations about the global financial system particularly with regard to climate-related financial risk and disclosure. Scenarios are needed to provide the foundational information that allows banks, businesses and other financial institutions to evaluate the physical (climate impacts) and transactional (emissions mitigation policies) financial risks. Scenarios need to include global, regional and local climate change information. Scenarios also need to provide the impacts of policies and measures on market prices and demands for commodities. Users need to provide their own assessments regarding the likelihood of alternative scenarios.

Further discussion and examples of scenarios can be found in Annex C.

1.5.2 Economic and behavioral frameworks

Economic and behavioral frameworks seek to inform efficient ways to respond to climate change, to design mitigation strategies and to explain the inadequacy of action to date. Stern (2006) reference to climate change as "the greatest market failure in history" reflects its economic complexity, as well as scale. In addition, related perspectives from behavioural economics help explain individual behaviours in the face of climate change, and might help devise better mitigation policies - this is the first IPCC Assessment to have a chapter on behaviour and demand side (Chapter 5). This section gives a brief overview of the main issues.

1.5.2.1 Evaluating "Optimal choices" under dynamic uncertainty and distributional concerns

Economic perspectives strive to balance costs and benefits associated with mitigation (Nordhaus 2008), given that resources are limited and climate change competes with other priorities, or at least to examine ways to deliver agreed goals at least cost.

The IPCC Fifth Assessment noted that "almost every aspect of climate change — from the projection of emissions to impacts on climate and human responses — is marked by a degree of uncertainty and requires a strategy for managing risks" (IPCC (2014a) p.140). It included a full chapter (2) devoted to 'Integrated Risk and Uncertainty Assessment of Climate Change Response Policies.' This extended previous IPCC reports "in four ways:" by "expanding climate-related decisions to other levels of decision making" [AR5, Figure 2.2]; in "moving beyond primarily rational-economic" appraisal by "reviewing the psychological and behavioural literature on perceptions and responses to risk and uncertainty"; by "considering the pros and cons of alternative methodologies and decision aids from the point of view of practitioners;" and by "expanding the scope of the challenges associated with developing risk management strategies".

AR5 reflected limitations of cost-benefit analysis, as monetizing the full range of climate change impacts is extremely hard if not impossible. A particular focus of economic debate had been "fat-tail" risks, which stem from the scale, range and nature of climate uncertainties and the argument that the consequent risk of catastrophic climate instabilities would dominate a rational cost-benefit appraisal: Weitzman's (2009, 2008) "Dismal Theorem" argued that we could never gather enough evidence on these risks in time to avert them. In sharp contrast to the idea – and the psychological reactions - that uncertainty reduces the case for action, objectively, AR5 found that "the social benefit from investments in mitigation tends to increase when uncertainty in the factors relating GHG emissions to climate change impacts are considered (*medium confidence*)." Thus uncertainty tends to strengthen the economic case for more ambitious and urgent action, to avoid risks of extreme climate impacts which should rationally weigh more heavily than the costs of stronger mitigation.

Many more studies have shown this effect of including 'fat tail' risks of extreme consequences in cost-benefit analysis (Ackerman et al. 2010; Fankhauser et al. 2013; Dietz and Stern 2015); critics acknowledge the importance of the issue and conclude a significant carbon price (eg. "Somewhere between a few tens and a few hundreds $/tC" (Tol 2018)) is justified. Other important complications include the ethical underpinnings including concerns about undervaluing the legitimate interests of poorer and more vulnerable communities as well as future generations (AR5, Chapter 3, and next section). Whilst many economists have continued efforts to estimate a global 'social cost of CO_2 emissions'(National Academies of Sciences Engineering and Medicine 2017), others now argue that it is futile to seek an objective, globally acceptable estimate of climate change damages (eg.(Pezzey 2018)), which thereby challenges the idea of global cost-benefit appraisal.

The reality is that there is no global decision-maker and all aggregate estimates of global climate damage embody ethical assumptions (AR5 Chapter 3). This was highlighted most starkly in the economic case made by the US administration in 2017 to repeal the Obama clean energy legislation (US EPA 2017): this assessment did not contest the scientific consensus, but instead took as its central case that the US should bear no responsibility for impacts on other countries, along with discounting assumptions which had the net effect of ensuring that the 'cost-benefit' only counts relatively near-term impacts of US emissions on the US itself, discounting not only the rest of the world, but the future of US citizens as well, to a degree unsupported by economic rationales (Li and Pizer 2018; Adler et al. 2017).

All IPCC Assessments have noted an alternate economic approach is to focus on 'Cost-effectiveness analysis' - this circumvents the imponderables involved in establishing a global 'social cost of carbon emissions', by focusing on evaluating costs and optimal trajectories towards agreed goals that are the product of a political and scientific dialogue. Social choice theory (Arrow et al. 2011) ecognises the need for negotiation to reach a compromise amongst disparate views and interests, if no formal process (such as voting rules) is established. In practice this, informed directly by scientific assessment of risks, has become the norm as embedded for example in the fundamental objective of the UNFCCC to avoid dangerous interference, and its interpretation in the emissions Aim of in Paris Agreement.

Finally, economic perspectives tend to emphasize the importance of carbon pricing: in policy, so as to 'internalize' in economic decision-making the 'external' damages imposed by GHG emissions into; and in technoeconomic models, as an index of mitigation efforts. Carbon pricing is often seen in economics as the most cost-effective way to reduce emissions, given certain assumptions. Stern (2015) identifies six market failures which tend to complicate this logic, but along with most economists, insists that it remains an important part of effective policy.

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

1.5.2.2 Dynamic efficiency: inertia, innovation, finance and lock-in

'Efficient pathways' are also influenced by inertia, innovation, and 'lock-in' (Unruh 2002). Vogt-Schilb, Meunier, & Hallegatte (2018) show 'when starting with the most expensive option makes sense', because policy for deep decarbonisation needs to prioritise action on long-lived investments and infrastructure that could still be emitting for many decades. Newbery (2018) quantifies spillover benefits from learning-by-doing, arguing that early deployment of PV when it was expensive was economically beneficial. The remarkable cost reductions noted in section 4 occurred notably in countries that actively promoted the use of such emerging renewable technologies (eg. Nemet (2019)).

Research thus increasingly emphasises the need to understand climate transformation in terms of dynamic, rather than static, efficiency (eg. Gillingham & Stock, 2018). This means taking account of inertia, learning and various factors which make economic systems depend on the paths taken over long periods ('path-dependent'). Evidence on the timescales of major energy-related transitions is however quite divergent (eg. Sovacool (2016) vs (Grubler et al. 2016)).

Aghion, Hepburn, and Teytelboym (2019) identify at least five determinants of path dependence: *Knowledge spillovers* – a documented tendency for innovations to build upon prior, related innovations in cumulative ways; *Network effects* – when the attractiveness of a technology depends upon interrelated networks of other users or suppliers; *Switching costs* – the cost of switching to a different path eg. due to the need for different infrastructure and overcome incumbent interests; *Positive feedbacks* – when technologies benefit from scale; and *Complementarities* – when technologies have complementary roles, such as renewables and storage.

Models find that these dynamic effects typically justify greater up-front effort to change course than implied by traditional economic approaches, including by "subsidizing dynamically superior technologies [which can] prevent costly lockins" (Kalkuhl et al. 2012), a result extended to supporting their accelerated international diffusion (Schultes et al. 2018). Grubb and Wieners (2019) also show that including learning and path dependency tends to imply stronger initial action, and reduces potential divergence between cost-benefit vis-à-vis science-risk-based approaches (insofar as the system adjusts to constraints). Farmer et al. (2015) conclude that 'Four key issues—along with several others—remain inadequately addressed by economic models of climate change, namely: (1) uncertainty, (2) aggregation, heterogeneity and distributional implications (3) technological change, and most of all, (4) realistic damage functions.' Mercure et al. (2019) underline a fifth, namely the representation of finance, which along with innovation largely explains why the estimated impact of mitigation on GDP can differ widely, potentially even in sign, between different model types.

Thus, the economics of innovation and transformation for deep decarbonisation and low carbon development, may require different evaluation frameworks and tools compared to those traditionally employed by economists for simpler, more localised and short-term problems. The studies above conclude that employing these insights tends to amplify the economic case for more urgent action.

1.5.2.3 Deliberative and behavioural decision-making

Behavioral frameworks can be used to understand why individuals react to climate change the way they do. AR5 emphasized that decision processes often include both deliberative ('calculate the costs and benefits') and intuitive thinking, the latter utilizing emotion- and rule-based responses that are conditioned by personal past experience, social context, and cultural factors (intuitive thinking) (eg. (Kahneman, 2003), and that laypersons tend to judge risks differently than experts - for example, 'Intuitive' reactions are often characterised by biases to status quo and aversion to perceived risks and ambiguity (frequently, sticking with what we know and resistance to change (Kahneman and Tversky 2018). Many of these features of human reasoning create 'psychological distance' from climate change (Spence et al. 2012; Marshall 2014), which can impede adequate personal responses in addition to the collective nature of the problem.

One purpose of cost-benefit is attempting to overcome such biases by objectively calculating costs and benefits, though as noted this is fundamentally complex, and may carry a different risk of bias towards factors that can reasonably be measured or estimated, neglecting 'unknowns' – the central point of critiques by Weitzman and others (as cited above).

Behavioural biases and many other factors can also help explain why cost-effective energy efficiency measures or other mitigation technologies are not taken up as fast or as widely as the benefits might suggest: "Behavioral research, however, suggests a more complex, less idealized, view. People procrastinate; attention wanders. Peripheral factors subconsciously influence perceptions and decisions. These behavioral tendencies influence real-world outcomes and can inform interventions. For example, "we often resist actions with clear long-term benefits if they are unpleasant in the short run." (Allcott and Mulainathan (2010), p. 1204). Safarzyńska (2018) models the way in which behavioural factors may change response to carbon pricing relative to other instruments.

Understanding individual behaviours may thus help devise better policies to mitigate climate change (Pollitt and Shaorshadze 2011). The most fruitful area of enquiry in this context has been household energy use (e.g. Frederiks et al. (2015), Niamir et al. (2020) and many others). A key perspective is to eschew 'either/or' in the context of economic and behavioral frameworks in favour of an approach that emphasises synergies between the two: "(More) than 30 years of social and behavioral science research on household energy consumption demonstrates the power of combining behaviorally sensitive features—such as norms, social influence networks, and attention to convenience and quality assurance in program design—with financial incentives and information (Stern and Gardner 1981; Aigner 1984; National Research Council 1985; Gardner and Stern 2002; Stern et al. 2010).

An exciting development has been to harness randomized, controlled field trials in a representative population to predict the effects of behavioral interventions (Davenport 2009. Aigner 1984, Levitt and List 2009, McRae and Meeks 2016 and Gillan 2017).

1.5.3 Ethical Frameworks

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

1.5.3.1 Ethics and value

A large body of literature examines the critical role of values, ethics, attitudes, and behaviours as foundational frames for understanding and assessing climate action, sustainable development and societal transformation (IPCC WGIII (2014a) Chapter 3, (Jolly et al. 2015; Tietenberg and Lewis; Tàbara et al. 2019)). Most of the literature that adopt this frame offers it as a counter point or critique to what they say is too much attention of mainstream literature and policy discourse on climate action and sustainable development to the attainment or safe-guarding of economic growth of nations, corporations and individuals (Castree 2017; Gunster 2017). These perspectives highlight the dominance of economic utilitarianism in western philosophical thought as a key driver for unsustainable consumption and global environmental change (Hoeing et al. 2015; Popescu and Ciurlau 2016).

Entrenching alterative values that promote deep decarbonisation, environmental conservation and protection across all levels of society is viewed as foundational component of climate resilient and sustainable development and for achieving a safe climate world (Jolly et al. 2015; Evensen 2015; Popescu and Ciurlau 2016; Tàbara et al. 2019). While acknowledging the role of policy, technology, and finance, some scholars point out that a 'managerialist' approach that emphasize 'governance' but fails to examine and challenge the deeper values that underpin societies will not secure the deep change required to avert dangerous climate change and other environmental challenges (Hartzell-Nichols 2014; Groves et al. 2016). Patterson et. al (Patterson et al. 2018) have stressed the centrality of a commitment to social justice, 'particularly regarding the distribution of responsibilities, rights, and mutual obligations between nations' in navigating societal transformations.

Hannis (2015) has argued that the virtue of interdependence including an acknowledgement of intimate relationship to the non-human world offers an organising principle for environmental virtue that can catalyse enduring sustainable transformation. Acknowledging dependence on some larger reality, and does not require a total denial of self-regard or relinquishment of personal agency but a degree of humility, self-transcendence and respect for. For Neuteleers and Engelen (2015), a key aspect of this is to moving away from valuing nature only in market and monetary terms and strongly incorporating existential and non-material values.

Kasperbauer (2016) have called for a reconciliation of values aimed at encouraging ecological virtue with those aimed at protecting the freedoms required for personal autonomy. Such approach is required to counteract the tendency to free ride and to achieve the much-needed restraint on the over-exploitation of global commons. Within this framework, ecological virtue, moderation, fairness, and stewardship will all need be understood and promoted as directly contributing to a good life.

Frustration with the lack of progress in emission reduction despite increasing scientific evidence of anthropogenic climate change has led Bryck and Ellis (2016) to suggest the urgent need for more explicit focus on the emotional dimensions of decision making, to unpack '[t]he faults of our rationality' (p.642) and help elicit societies and individuals struggle to act in ways that focus less on monetary gain and more on environmental sustainability. Hackman (2016) has suggested that the individual states economic interests tend to be stronger than general interests for urgent action in the context of the climate change regime and calls for new renewed emphasis on trust and solidarity as foundations for global co-operation on climate change (Jolly et al. 2015). Hackman (2016) has suggested that the individual states economic interests tend to be stronger than general interests for urgent action in the context of the climate change regime and calls for new renewed emphasis on trust and solidarity as foundations for global co-operation on climate change. Jolly et. al (2015) argue that current approaches to SD fail because they do not emphasize of constraints on human behaviour, including constraints on economic activity. They argue that the current set of SDGs are weak and [in]compatible with sustainable development and argue for a new model that is centred on the 'moral imperatives laid out in philosophical texts on needs and equity, and recent scientific insights on environmental limits.'

Herrick (2018) has found that a sense of short-term interest among stakeholder tend to block thought reflection and deliberation need for climate adaption planning and rationales for subverting actions once implemented. He argues that proper management of self-perceptions guided by virtuous ethics and values is necessary to 'create situationally appropriate adaptation policy regime.' Hackman (2016) finds that flooding can be framed as a general external risk or as a matter of locational choice depending the prevailing values. Each framing results in radically different approach to addressing the risk. Hackman (2016) has found that short term thinking is a key barrier preventing policymakers from switching attention from maintenance mode to long term building capacity and systems required to achieve climate resilience.

Howell and Allen (2017) find that individuals, communities and countries that have strong altruistic concern about climate change impact on future generations tend to be more proactively engaged in climate mitigation and adaption. Jonsson and Nilsson (2014), Katz-Gerro (2015) and Braito (2017) among many others have all found that self-transcendent values such as universalism and benevolence, and moderation are positively related to pro-environmental behaviours.

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

Equity and just transition is one of the major lens for analyzing climate policy from a social science perspective (Harlan et al. 2015; Klinsky et al. 2017; Kemp-Benedict 2018). Equity perspectives highlight three asymmetries relevant for climate change (Okereke 2017; Okereke and Coventry 2016) (see also 1.4.7. above). The first is asymmetry in contribution, which highlights different contributions to climate change both in historical and current terms. Different contributions apply both within and between states as well as between generations (Caney 2016; Heyward and Roser 2016). The second dimension is asymmetry in impacts, which highlight the fact that the negative consequences of climate change will be borne disproportionately across countries, regions and communities. Moreover, it is often those that have contributed the least that stand to bear the greatest impact of climate change (Shi et al. 2016; IPCC 2014a).

Unequal distribution of the impacts of climate change also have gender aspects. Thirdly, equity perspectives highlight differences between groups and nations of power to participate in climate decision and governance. In addition, it is often noted that if attention is not paid to equity consideration, efforts designed to tackle climate change may end up exacerbating conditions of inequality among communities and between countries (Heffron and McCauley 2018). The implication is that to be sustainable in the long run, societal transformation to low carbon future must put consideration of justice at the centre. Some critical scholars suggest that the climate injustice is asymptotic of a more fundamental structural injustice that characterize social relations. On this view, the starting point for tacking climate change is to address the deeper inequality within societies (Routledge et al. 2018).

Avoiding adverse distributional consequences of mitigation policies underpins emphasis upon the need for a 'just transition' (see Chapter 17, Gollier and Weitzman, (2010); Weitzman (2013), Gollier and Hammitt (2014) for some recent contributions). Another approach to this debate has been to study the possibility that no generation has to reduce their wellbeing from climate mitigation. If climate mitigation is beneficial for the world, all generations should in principle be able to benefit from this. This will involve transfers across generations and several suggestions have been made in the literature such as a change from real capital investments to investments in natural capital or financing mitigation efforts today using governmental debt redeemed by future generations (see for instance (Broome 2012; Foley 2007; Heijdra et al. 2006; Karp and Rezai 2014; Hoel et al. 2019).

In economic analyses, distributions across countries may depend on the distribution of emissions targets (see, e.g., (Kverndokk and Rose 2008). The efficient distribution of burdens, is the one that gives the highest welfare, but this depends on how welfare, or the 'social welfare functions' are defined (IPCC 2014a). The choice of underlying ethical assumptions when defining welfare, will give very different outcomes when it comes to mitigation, see, e.g. Tol and Anthoff (2010).

Finally, the choice of policy instrument to mitigate greenhouse gas emissions may also give different distributional consequences. Often carbon pricing has been found to be regressive, in particularly in developed countries, i.e., giving a larger burden to those with lower income, while it is found to be progressive in developing countries (IPCC 2014a). Some measures are suggested to reduce the regressivity of carbon prices, such as using the tax revenue in favor of low-income groups, lump sum redistribution of tax revenues or differentiated carbon taxes (see, e.g. (Metcalf 2009; Klenert and Mattauch 2016; Stiglitz 2019)).

1.5.4 Frameworks for transition and transformation

As indicated, the Paris goals imply substantial transformations across many sectors. There are many different frameworks and concepts relevant to transformation, but it is clearly a complex process that involves close interrelationships between innovation, infrastructure and institutions, at many different levels, amongst other factors (Geels et al. 2017; Kramer 2018). Consequently, multiple disciplinary perspectives are needed (Turnheim et al. 2015; Geels et al. 2016; Hof et al. 2019).

Approaches include various economic perspectives, dedicated theories of technological transitions, and social science perspectives on the different actors in socio-economic systems. Each of these highlight different processes or actors that tend to dominate at different scales, but they can be reasonably associated in common across three main levels – which in Figure 1.7 we label as *micro, meso and macro.*

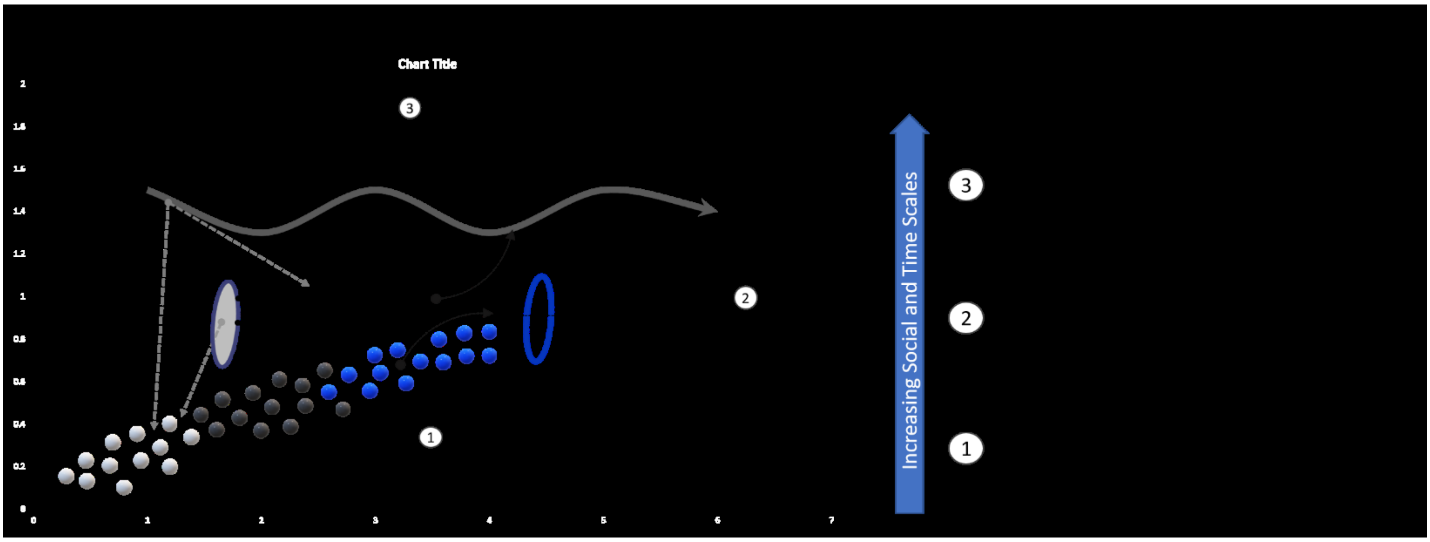

Figure 1.7 Frameworks for Transition: Multi-level perspective, economic domains and dominant actors

Source: Adapted by authors from Geels (2012) and Grubb (2014)

Dedicated *socio-technical (ST) transition theory* literature has somewhat converged on a 'multi-level perspective' pioneered by Geels (2002), summarised and applied to deep decarbonisation in Geels et. al (2017). Innovation first emerges at *micro* level and is tested through *technological niches* - where variations emerge, often protected from direct market competition (e.g. through R&D support, tax breaks, protected markets and the 'sweat equity' of inventors) (Smith et al. 2010; Smith and Raven 2012). These then strive to grow and compete in the existing, meso-level *socio-technical regimes*, which represent the rules and regulations, existing infrastructures and institutions, and established practices which define markets, and how these dynamics may vary across geographies (Hansen and Coenen 2015; Coenen and Benneworth 2012). Markets act as to select and amplify successful innovations, and weed out unsuccessful ones; innovation does occur in the meso level itself, but is generally more incremental and predictable. However, *macro* level changes of the *socio-technical landscape* – broad-ranging shifts in the governing structures, infrastructures and institutions, can change the ST regimes themselves. These changes may be driven by large-scale social, technological and ideological shifts, largely beyond the will of individual actors from the other two levels (Geels 2018).

With some clear parallels, recent decades have seen broadening of economic perspectives and theories. Grubb, Hourcade and Neuhoff (Grubb et al. 2014, 2015) classify these into three 'domains of economic decision-making', which correspond roughly to the behavioural, classical, and dynamic-strategic dimensions of modern economic theories noted in section 1.5.2 above. They correspondingly associate these three domains with different branches of economic theory, respectively (1) *behavioural and organisational*; (2) *neoclassical and welfare*, and (3) *evolutionary and institutional*, but emphasise that these are not alternatives but rather descriptions of processes which occur at different social and temporal scales.

Both these approaches in turn point to a more common and obvious delineation between key actors in society, namely individuals/communities; the private sector (particularly larger corporates); and public authorities (and sometimes, publicly-owned companies), at the respective levls. There are continual interactions between different levels, including between the first and third: Kuzemko et al (2016) note, "One specific instance in which niches can break through is if external landscape developments simultaneously 'create pressures on the regime that lead to cracks, tensions and windows of opportunity' (Geels 2010; Rotmans et al. 2001). An example of this is new scientific knowledge about climate change putting sustained pressure on current regimes of energy production and consumption to change."

More fundamentally, these interrelated 3-level perspectives help to clarify the agents and processes of transformative changes over time. Stable ST regimes imply that basic rules and regulatory structures are known and reliable as a basis for decision-making by market agents, providing foundations for the 'economically rational' tools of cost-benefit analysis, risk-return assessment, and cost and performance preferences of consumers, to dominate the behaviour of markets. Innovations which fit these structures prosper; those which don't fail or languish. However, over time, the pressures for change grow. Consumer preferences evolve, and innovations occur which may be desirable but struggle in the existing systems of regulation and infrastructure. Growing inequities arising from the accumulation of capital and power of incumbents breeds dissent, as does external damages which are not reflected in market prices; these micro-level concerns then directly impact on the macro, strategic and political landscape. Incumbents fight to preserve the status-quo rules, but eventually the pressures from both above and below force major changes in the ST regime. In such times of transition, the 'rational expectations' model of economic behaviour and calculus can be largely eclipsed: the uncertainties involved in shifts of meso-regimes are simply too large and unpredictable. The task of strategic planners at the macro-level – both public and private - is not to wield numbers and calculus, but to exercise judgement about the kinds of changes that are possible, desirable, or likely, as the norms and rules governing 'business-as-usual' shift to a new system. Historically, such shifts have tended to occur once every few decades.

Social transformation

There is often a social dimension to such transitions, which contribute ultimately to a complete transformation. It is increasingly argued that addressing climate change would require social transformation at perhaps the speed and scale that have not been witnessed previously in history (Hermwille 2016; O'Brien 2012; Feola 2015). However, despite its widespread reference, there is no clear and agreed upon definition of social transformation (Feola 2015). Instead, transformation has often been used as a metaphor, but this conceptually elastic approach has often led to vagueness (Strunz 2012). Feola (2015) identified eight concepts of social transformation in the literature, namely: i) Deliberate transformation; ii) Progressive transformation; iii) Regime shifts; iv) Societal transformations; v) Social practice; vi) Transformational Adaptation 1; vii) Transformational Adaptation 2; and viii) Socio-ecological transition. Conceptually, there are major disagreements on the key elements that constitute social transformation (Mustelin and Handmer 2013), hence there is no single theory on social transformation (Feola 2015; O'Brien 2012; O'brien and Sygna 2013). Given the urgency of the need for social transformation to address global change (O'Brien 2011), a new research agenda on the discipline is emerging, with an emphasis on increased research and greater dialogue amongst the diverse actors (Fazey et al. 2018).

In their detailed survey, Feola (2015) identified three levels of focus in the literature on social transformation: i) systems conceptualisation; ii) Notions of social consciousness (deliberate/emergent); iii) and outcome (descriptive/prescriptive). Social transformation comprises key elements, including capacity to transform (Folke et al. 2010), planning and interdisciplinarity (Woiwode 2013). In the broader literature on social transformation, Feola (2015) identified two types of transformation: transformational adaptation (reactive), and societal transformation (proactive). While transformational adaptation seeks to find ways of responding to the growing scale of the impacts of climate change, societal transformation seeks to reorient civilization towards a sustainable direction (Feola 2015). O'Brien (2016) identified 'three spheres' of transformation (practical, political and personal). O'Brien (2016) has also developed the idea of a quantum leap, drawing from Social Quantum Theory (SQT). Borrowing from quantum physics, SQT seeks to draw attention to the massive scale of transformation required to address climate change, especially as outlined in the Paris Agreement. SQT recognises and promotes people as the solution to climate change (O'Brien 2016). Overall, there seems to be a consensus in academia and policy on the general idea of transformation as a major fundamental change, as opposed to incremental minor change (Kapoor 2007). Questions remain about the relationship between transformation and transition. While both terms are increasingly used interchangeably, some maintain that transformation, unlike the transition which has its root in technical system theory, is much more sensitive to the role of politics and power in driving or hindering social change. A social transformation lens hence provides opportunity to explore the complex relationship between social, economic, cultural factors in shaping how societies frame and respond to climate change, the dialectic relationship between structure and agency and how differences in power and interest can work to facilitate or hinder deep and rapid change.

As noted, social transformations can take place at various levels. At the global, some scholars have suggested the use of phrases that denote scale and urgency. For instance, some have called for adopting and harnessing the important concept of 'apocalypse' as a focal point around which to mobilise social transformation (Skrimshire 2010). Other scholars have called for a focus on social transformation at the local level, specifically cities (Romero-Lankao et al. 2018) and local government (Amundsen et al. 2018).

Since social transformation may engender negative impacts (Butzer 2012), normative considerations are also crucial to ensuring effective social transformation. Values and visions are especially when choosing and incorporating the main values that would underpin social transformation (Tschakert et al. 2016). There is also need for equity and sustainability (O'Brien 2016), but also social justice (Patterson et al., 2018) in the pursuit of effective and ethical social transformation. In fact, climate justice can act as a catalyst for broader global justice (Goodman 2009). Thus, to achieve another 'Great Transformation', scholarship on social transformation has to Humanities, by going beyond natural processes, to include economic, social and cultural processes (Leggewie and Welzer 2010).

But achieving social transformation to address global climate change requires broader transformation especially in economic development (Inderberg et al. 2015). Special attention will also have to be paid to the more vulnerable global South (Burch et al. 2017). At the personal level, consideration of the impacts of social transformation such as mental health is also important (Fritze et al. 2008). Consideration of the role of power and politics will also be crucial (Manuel-Navarrete 2010; O'Brien 2016). Finally, social transformation would have to go beyond mitigation to also include adaptation to climate change (Pelling 2010; Pelling et al. 2015) p. 201).

1.5.5 Frameworks for Assessing Desirability and Feasibility of Decarbonization Pathways

As indicated throughout this introductory chapter, climate change action sits within wider societal concerns of sustainable development (section 3), is affected by numerous and varied forces (section 4), and can be understood and analysed from many different perspectives, reflecting different priorities and stages of economic development, disciplines, interests, and ethical and political stances (section 5). There is no single way of evaluating mitigation options and pathways: there are, rather, sets of challenges and choices to be made and these will vary over time.

Building on the framework introduced by Majone (1975) and Gilabert and Lawford-Smith (2012), we can first explore mitigation pathways using the lens of desirability in order to exclude those that, by changing the system to meet the climate target, violate or undermine some basic societal objective, as for example represented by other Sustainable Development objectives. Pathways that survive the desirability screening have to be evaluated for the feasibility of the outcomes that they entail. It should be kept in mind that feasibility is a malleable concept that might change in time and location depending on various factors as available technologies and maturity of institutions. Finally, policy outcome can be reached using with various policy instruments (reference to policy chapter) and their feasibility should also be assessed. By distinguishing desirability from political feasibility, it is possible to assign different flexibilities to each so that desirable goals (e.g. SDGs) can be made less flexible than political feasibility which can be made more contingent to contextual and enabling factors. For example, carbon tax revenues can be used to mitigate distributional concerns, but the question is whether what is deemed feasible can outpace the rate of depletion of the remaining carbon budget (Chapter 3.8.1).

The SR1.5 introduced a 'framework of feasibility', motivated by the question of whether 1.5ºC pathways were feasible, under six broad headings. In this Sixth Assessment, we use these dimensions to help assess the challenges of different national and global pathways consistent with the goals of the UNFCCC and Paris Agreement:

- **Geophysical**: What are the geophysical implications of different global emission pathways and the physical potentials for adaptation?
- **Environmental-ecological**: What are the implications for and potentials of ecosystem services and resources, including geological storage capacity and related rate of needed land-use change, and to what extent are they compatible with enhanced resilience?
- **Technological**: What technologies are available to support transformation?
- **Economic**: What economic conditions could support transformation?
- **Socio-cultural**: What conditions could support transformations in behaviour and lifestyles? To what extent are the transformations socially acceptable and consistent with equity?
- **Institutional**: What institutional conditions are in place to support transformations, including multi-level governance, institutional capacity, and political support?

These offer broad categories of assessment particularly of the *challenges* (or "barriers"), including the technological, economic, socio-cultural, and institutional *conditions* which might enable the geophysical and environmental-ecological challenges to be met. In SR1.5, this framework was applied to specific options on both mitigation (4.5.2) and adaption (4.5.3).

The assessment of potential national and global pathways in this AR6 emphasises that all pathways involve different challenges and require choices to be made. Continuing 'business as usual' is still a choice, which involves not making best use of new technologies, and risks local pollution and future stranded assets as well as the obvious geophysical risks.

More specifically, the seventeen specific Sustainable Development Goals for 2030 – and the more detailed 169 Sub-targets within them – emphasise the multiple goals that countries seek in the mid-term. Tackling climate change *in the context of sustainable development* can involve trade-offs between different goals, but more specifically, means making choices on how to minimise trade-offs and maximise synergies.

Thus, *feasibility* can be assessed in terms of the extent to which the six broad challenges can be addressed, to reach the Paris goals in the context of sustainable development. This will be strongly influenced by *enabling factors* – creating the conditions that help to overcome the challenges (Chapter 3.8.3). As suggested by Figure 1.3 sustainable development may then be understood as the overall set of frameworks, encompassing all the 2015 Agreements and wider conditions, which enable delivery of the Paris goals to be aligned with the wider goals of each society and actors within them.

In its Assessment framework, SR1.5 also distinguished the relevance of systemic, dynamic, and spatial effects, which influence all six dimensions.

Systemic effects would include the state and availability of General Purpose technologies, local integrated systems, and how international trade and foreign investment structures may serve to accelerate international technology diffusion, but potentially could also undermine local initiatives, depending upon how it is governed. Systemic effects differ with stages of development: the challenges and choices involved to rapidly decarbonise developed countries, at the right-hand side of Figure 1.4, may be very different from those involved in securing low carbon development pathways for the countries with much lower income, currently far to the left.

Dynamic effects involve both innovation in specific low carbon technologies, and in the regimes that govern sectoral systems (the meso level in Figure 1.7). Such innovation is central because it maximises the potential synergies between SDGs. For example, electric vehicles powered by renewable energy could help to meet multiple goals of climate change and local air quality drawing often upon largely domestic energy resources, but this combination requires different regimes and infrastructures at both local and national levels.

This also underlines the importance of *local effects*. Transport and urban system options for a developed, crowded city in confined space (eg. Singapore) may be very different from those available with large areas, or rapid urbanisation (eg. in sub-Saharan Africa). Decarbonising shipping may raise particular challenges for small island states that others do not face. Challenges of thermal comfort may be very different in hot or cold climates (though heat pumps could a useful technology for either). Local effects thus must also be considered in assessing the specific choices as represented by the SDGs.

Robustly addressing the multi-faceted challenges to the governance and feasibility of low-carbon transitions requires bridging different analytical approaches across both scales and disciplines since each in isolation may generate fragmented visualisations of the transition pathway, providing incomplete identification of associated challenges and opportunities (Chapter 3.8.2).

1.6 Multi-Level Governance

Previous sections have highlighted the complex interconnection between climate mitigation and the multiple factors that can both facilitate ambitious climate action and the diversity of analytical frames for interpreting the challenge, constructing and assessing response options. An overriding impression is that achieving the transition to a low carbon, climate resilient and sustainable world requires purposeful and largely coordinated planning and decisions at many scales of governance including municipal, subnational, national and global levels. This implies a need for multi-level governance of climate change to manage the complex economic, ethical, social and political systems required to addressing climate change will require action at many interacting authority structures across scale (Hooghe and Marks 2001; Betsill and Bulkeley 2006; Amundsen et al. 2010; Fuhr et al. 2018). The notion of polycentric climate governance highlights not only the multiple and interlinked jurisdictions involved in climate decision making but also the idea that choices and decision made in several other aspects of life often have implications for climate change (Cole 2015; Jordan et al. 2018a). Gomez-Echeverri (2018) is among many that have reiterated the close relationship between climate change and the broader goal of global sustainable development and highlighted that ‘Good and effective governance and strong institutional arrangements are key to the success of the Paris Agreement and the 2030 Agenda for Sustainable Development’.

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

We sketched in Section 4 some progress in domestic and international climate governance, but also how climate change presents strains upon multilateral cooperation. To an extent, these reflect the ‘globalisation paradox’ (Rodrik 2011), an ‘ineluctable tension’ between national self-determination (sovereignty), democracy, and the economic benefits of globalization.’ With climate change, the trade-off is not only against the collective economic benefits of globalization, but also the planetary risks arising from resistance to effective, co-operative governance. In this sense, governance is seen as an overarching concept for thinking about the 'steering mechanisms' (Dingwerth and Pattberg 2006) by which actors and institutions seek to shape action and outcomes. A narrow usage refers to how states make policy, including in novel ways aside from the direct use of state authority, eg. with partnerships, incentives, or 'nudges'.

At the international level, it is obvious that the implementation of the Paris Agreement will proceed in parallel with other activities in increasingly diverse landscape of loosely coordinated institutions, constituting "regime complex" (Keohane and Victor 2011), and new cooperative efforts demonstrate an evolution in the shifting authority given to actors at different level of governance (Chan et al. 2018). At national and subnational levels efforts to manage climate change will be interwoven with and embedded in the context of a much broader politics and societal goals including the purist of wellbeing. Hence, it has often been suggested that addressing climate change requires thinking about how to shift development pathways towards a more a more sustainable trajectory. The governance of the transformative changes required to address climate change will have to navigate the economic, ethical, and transitional dynamics perspectives outlined in this section 5, including the political dimensions that suffuse the analytical frames. The literature on climate governance suggest attention to a number of key factors that motivate the drivers or constrain action. The first is power dynamics. For some, climate governance is driven mainly power relations in the states system and therefore the interests of key states. Here, the underlying governance problem is the lack of supranational authority to help coordinate responses across sovereign states. Since states are assumed to pursue their own interests, effective global rules and institutions to govern climate change are more likely to emerge when those national interests can sufficiently align with the global interest (Victor 2011). Furthermore, widespread cooperation would only be expected when the additional (short term) costs implied by full cooperation are small, otherwise finding the temptation to 'free ride' on the actions of others to be fatal (Barrett 1994).

Economists have explored many solutions to such 'free-riding' and other coordination problems (reviewed in (Finus 2008)), including the potential for joint climate-SD benefits (eg. reduced air pollution) to motivate stronger action (eg. Finus and Rübbelke 2011). Another strand considers the use of trade measures to encourage participation (Nordhaus 2015). However (Barrett and Dannenberg 2016 *check ref*) conclude that retaliatory measures could also make this unstable, irrespective of other considerations.

A focus on short-term national self-interest potentially makes the approach even more limited if it empowers national lobbies. Campaigns against many climate policy initiatives, most prominently the carbon markets (especially offsets) have affected the perceived legitimacy (Paterson 2010; Nyberg and Wright 2015) of 'sending money abroad', without consideration of whether that might actually contribute to the global effort.

In general the conclusion from game-theory perspectives on international climate governance is problematic: it suggests that if self-interest is the only thing that drives state behaviour, combined with the traditional conception of climate change as entailing significant mitigation burdens for a long-term, collective, benefit (a "global public good"), the prospects for effective cooperation to solve the problem seem slim (Teytelboym 2018). A corresponding risk is if these combined assumptions and results serve to create self-fulfilling prophesies about state behaviour, and about the economic structure of the problem, ignoring some of the opportunities that could arise from strengthened cooperation and the synergies of more sustainable development (e.g. Mainali et al. 2018; Houghton 2009).

A second key factor is the quality and role of institutions. This acknowledges that the interests of states, businesses and other actors are powerful motivations for (in)action, but holds that institutions at international and national levels have the ability to mediate and direct interactions and exchanges in ways that can sustain cooperation and promote equity and fair rules and outcomes

The challenge is how to engender high quality and equitable participation from all stakeholders mostly necessary to ensure broad-based and effective outcomes.

With negotiations on a global stage, equity has been elusive, but central, in the broader struggles to make development more sustainable, and to share fairly the efforts required for conjoined development and climate policy (Klinsky and Winkler 2018). Equity has always been a multi-faceted principle that needs to be applied in a dynamic context in climate governance. The discussion of mitigation tends to bring a focus on 'equitable burden sharing' (with various metrics including responsibility, capacity, the right to development and measures of equality, (Höhne et al. 2014)), but equity has also widened to include impacts, adaptation, and support.

Practical experience indicates the on-the-ground benefits of supportive international institutional structures, including for example the development of PV in Africa (Baker and Sovacool 2017), but also the limits, even within the stronger framework of the EU if this is not accompanied by deeper national engagement beyond formal compliance.

The third factor is ideas, along with experimentation. Recognizing that climate governance warrants unprecedent scale and speed of transition, the climate change governance is projected more as self-consciously transformatiion – seeking process involving a context of ideas and experimentational across scales of authority, jurisdiction and scales (Hildén et al. 2017; Laakso et al. 2017; Gordon 2018; van der Heijden 2018; Kivimaa et al. 2017). These literatures emphasise the influential role of multiple largely uncoordinated searches for change and development in technologies, economies, value and behaviour at multiple places – irrespective of regulation that emanates from constituted authorities.. As such it entails significant innovation in governance.

On this view the focus should be on 'governance experiments' as ways to work out how to foster transitions in energy, food, transport or other systems (Berkhout et al. 2010; Hoffmann 2011; Bulkeley et al. 2015; Bernstein and Hoffmann 2018). This also entails recognising the multidimensional character of climate governance – seeking to govern at a range of scales (local to global) and types of location (factories, schools, streets, etc). In this spirit, (Berkhout et al. 2010; Roberts et al. 2018) emphasise the role of 'sustainability experiments', and more recently 'moving beyond experiments' (Turnheim and Kivimaa 2018), seeking to foster growth of new socio-technical regimes in energy, transport, manufacturing, food and buildings. They conclude that such experiments 'represent a significant new source of innovation and capability-formation, linked to global knowledge and technology flows, which could reshape emergent socio-technical regimes and so contribute to alternative development pathways. He et al. (2015) suggest that the benefits from such developments hold 'invaluable lessons for emerging economies to reach their own emission peaks without losing the momentum of growth.'

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

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

Rayner et al (2019) emphasise that *implementing* the Paris agreement will require different governance structures, beyond the multilateral system, adapted to sectoral needs. They identify five specific governance functions, and find that whilst the power sector and international transport have plausible international governance, for other key sectors international governance is weak or non-existent.

However, given the embedding of fossil energy not only in production but in consumption and thus daily life (Paterson 2007; Bulkeley et al. 2016; Szeman and Petrocultures Research Group 2016), much of the resistance to climate policy is not necessarily only by incumbent industries but from threats to established habits and practices. Experience also underlines the need for 'transition theories' to take into account the central importance of geography and domestic politics, with an Australian example which deterred obviously beneficial niches from profiting in the transition to electricity liberalisation (Chandrashekeran 2016).

The question is not whether governance can simply align private and public, or national and global interests. It is also whether it can help to shift perceptions, including the negative, burden-sharing narratives that often accompany international negotiations. Roberts et al. (2018) suggest three themes for integrating governance with political economy and transition dynamics: '1) the role of coalitions in supporting and hindering acceleration; 2) the role of feedbacks, through which policies may shape actor preferences which, in turn, create stronger policies; and 3) the role of broader contexts (political economies, institutions, cultural norms, and technical systems) in creating more (or less) favourable conditions for deliberate acceleration.'

These approaches go well beyond the normal focus of governance analysis focused upon governments, or even other public authorities and companies. Ultimately, it may to engage wide publics and their international networks in imagining low carbon societies (e.g. Levy and Spicer, 2013; Milkoreit, 2017; Nikoleris, Stripple and Tenngart, 2017; Wapner and Elver, 2017; Sonesson et al., 2019). How do we live in a net-zero emissions world? What does the economy look like? What do our cities and farms look like? And how might the social/political/cultural aspects of such transformations look? This too might ultimately be considered as part of the broadest kind of international governance.

1.7 Conclusions

The world has changed hugely since the IPCC Fifth Assessment. The Paris Agreement and the SDGs provided a new international context, but global intergovernmental cooperation is under intense stress. Growing direct impacts of climate change are unambiguous and growing movements in society are starting to affect the politics in countries and transnational organizations at many levels. Emissions growth has slowed but not stopped and 'declared national contributions' are inconsistent with the agreed Paris goals. A technology revolution is clearly under way, making significant contributions 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. Many countries are witnessing rising populism and nationalism which impedes effective international cooperation.

Multiple assessment frameworks, adapted to the realities of climate change mitigation, are therefore required. We suggest three main groups of assessment frameworks. Economic frameworks can provide insights about the trade-offs, cost-effectiveness and policies for delivering agreed goals, but need to take account of the dynamic, behavioural and distributional dimensions of our socioeconomic systems that emit greenhouse gases. Ethical frameworks are equally essential to inform both international and domestic discourse and decisions, including relating to international (and intergenerational) responsibilities, related financial systems, and domestic policy design in all countries. Explicit frameworks for analysing transition and transformation across multiple sectors, in turn, need to draw on both socio-technical transition literatures, and those on social transformation. Ultimately all these frameworks need to be combined to inform the decisions required to drive, support, and globalise, just transitions towards the Paris goals.

1.8 Knowledge gaps

1.9 Roadmap to the Report

This Sixth Assessment Report covers Mitigation in three main parts, as follows (Figure 1.8).

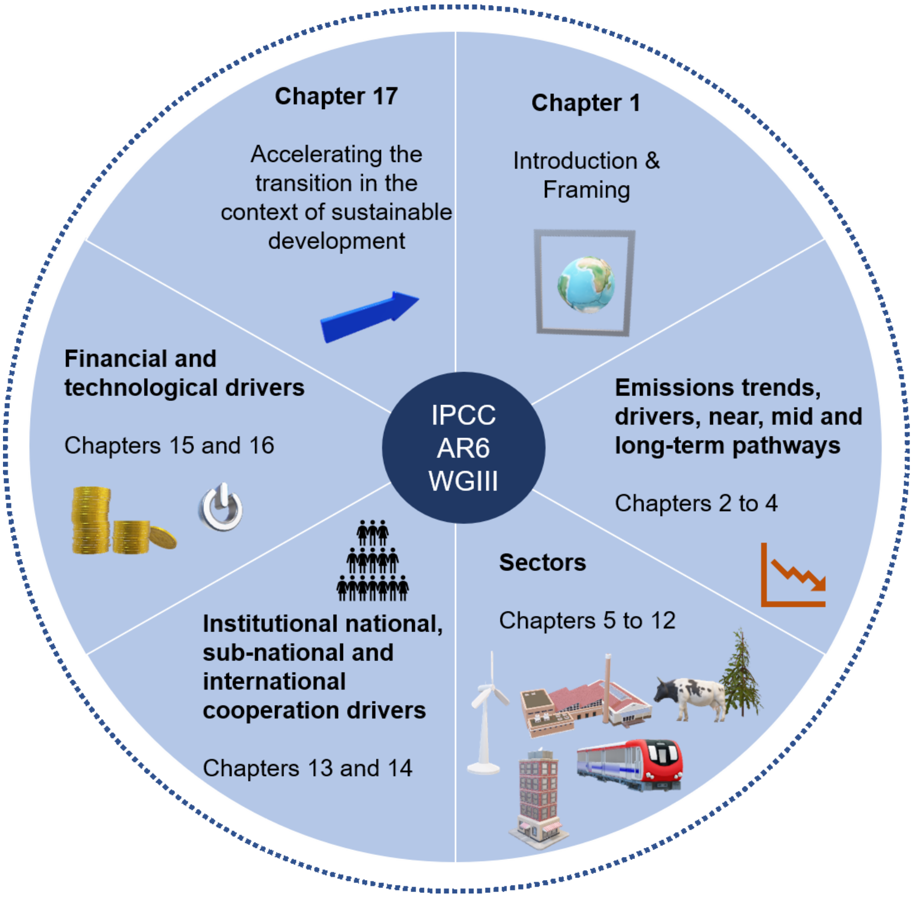

Figure 1.8 The Structure of AR6 Mitigation Report

Chapters 2-5 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 the results of long term global scenarios, including the projected economics and other characteristics of mitigation through to balancing of sources and sinks through the second half this century, and the implications for global temperature change and risks. 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 6-12 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 Agriculture, Forestry, and Other Land Uses (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 urbanization, as both a challenge and an opportunity for mitigation. Re- Chapters 9 and 10 then examine the detail of two of the 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 decarbonization for industrial systems.

- Finally in this section, Chapter 12 takes a cross-sectoral perspective, summarizing the costs and potentials across different sectors (and their co-benefits and co-costs) and comparing these with the integrated modeling assessments of Chapters 3 and 4; Chapter 12 also explores options which are inherently more cross-cutting, like the interactions of biomass energy, food and land, and aspects of mitigation not covered in the sector chapters including GHG removal and solar radiation management.

Four chapters then look at issues in implementation and governance of mitigation:

- Chapter 13 explores national and sub-national policies and institutions, bringing together lessons of policies examines in the sectoral chapters, as well as insights from service and demand-side perspectives (Chapter 5). The chapter compares governance approaches at multiple levels, including integrated analysis of sectoral and cross-sectoral governance and capacity-building, and the role and relationships of sub-national actors, and transboundary issues including trade. Chapter 14 then considers the roles and status of international cooperation, including international institutions, sectoral agreements and multiple forms of international partnerships, and the ethics and governance challenges of solar radiation management. Chapter 15 explores the role of investment and finance in mitigation, including current trends, the investment needs for deep decarbonization, and the complementary roles of public and private finance. This includes examining climate-related investment opportunities and risks (eg. 'stranded assets') and linkages between finance and investments in adaptation and mitigation. Chapter 16, another new chapter in AR6, looks at innovation, technology development and transfer – not so much on particular technologies (covered elsewhere) but as systemic issues that hold potential for transformative changes, and the challenges of management of such changes at multiple levels including the role of international cooperation.

Finally, Chapter 17 seeks to bring together the threads of the report, in terms of Accelerating the transition in the context of sustainable development, including practical pathways for joint responses to climate change and sustainable development challenges, given the reality of multi-objective policies across multiple scales. This include major regional perspectives, mitigation-adaptation interlinkages, and enabling conditions including the roles of technology, finance & cooperation for sustainable development.

Frequently asked questions

FAQ 1.1 What is climate change mitigation?

The Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". The UNFCCC thereby makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. The IPCC, in contrast, defines climate change as "a change in the state of the climate that can be identified (e. g., by using statistical tests) by changes in the mean and / or the variability of its properties, and that persists for an extended period, typically decades or longer", making no such distinction.

Climate Change Mitigation is a "human intervention to reduce the sources or enhance the sinks of greenhouse gases" (GHG) (See Glossary (Annex I)). The ultimate goal of mitigation (per Article 2 of the UNFCCC) is preventing dangerous anthropogenic interference with the climate system within a time frame to allow ecosystems to adapt, to ensure food production is not threatened and to enable economic development to proceed in a sustainable manner.

FAQ 1.2 What causes GHG emissions?

Anthropogenic GHGs come from many sources of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N2O), and fluorinated gases (HFCs, PFCs and SF6). CO_2 makes the largest contribution to global GHG emissions; fluorinated gases (F-gases) contribute only a few per cent. The largest source of CO_2 is combustion of fossil fuels in energy conversion systems like boilers in electric power plants, engines in aircraft and automobiles, and in cooking and heating within homes and businesses. While most GHGs come from fossil fuel combustion, about one third comes from other activities like agriculture (mainly CH_4 and N_2O), deforestation (mainly CO_2), fossil fuel production (mainly CH_4) industrial processes (mainly CO_2, N_2O and F-gases) and municipal waste and wastewater (mainly CH_4). (See 1.3.1)

FAQ 1.3 What is carbon neutrality?

Carbon neutrality means a balance between carbon emissions and removal. The net quantity of carbon released to the atmosphere is therefore zero, or carbon footprint, is zero. This balance is achieved by offsetting emissions with carbon sequestration, either through natural carbon sinks or the Carbon Capture and Storage (CCS) technology. Carbon sinks are systems which have the capacity to remove and store carbon from the atmosphere. Natural carbons sinks are mostly soils, forests and oceans.

Note that carbon neutrality is a relative term. It refers to the net state of a system with its associated system-accounting boundaries. For example, an individual corn plant may be carbon neutral in that the carbon it removes from the atmosphere during its growth is just offset by the carbon it returns to the atmosphere when it dies. But, if that corn plant is embedded in a larger system, for example the food system, its harvest, transport and processing might make the larger system non-carbon neutral.

Carbon Neutrality is often considered a synonym of Climate Neutrality or Net-zero Emissions. The UNFCCC (2019) defines Climate Neutrality as "achieved by balancing the amount of emissions generated with the Earth's natural capacity to absorb them.". The UNFCCC (2019) also highlights that neutrality does not necessarily mean zero emission, but instead, "reducing our current global emissions to the point where we reach a balance between our emissions and the absorptive capacity of the Earth.".

The IPCC (2019a) defines Net-zero Emissions as "achieved when emissions of greenhouse gases (GHGs) to the atmosphere are balanced by anthropogenic removals. Where multiple greenhouse gases are involved, the quantification of net-zero emissions depends on the climate metric chosen to compare emissions of different gases (such as global warming potential, global temperature change potential, and others, as well as the chosen time horizon).".

FAQ 1.4 What are interlinkages?

Interlinkages are linking connections between different parts having an effect over each other (Cambridge Dictionary 2019). In the context of climate change, interlinkages refer mostly to policies and instruments implemented simultaneously, institutions, governance structures, and between broader societal objectives such as climate mitigation and development (Gomez-Echeverri 2018; Bowman and Minas 2019). They often refer to different natural resources as well (see 1.4.2 for "nexus"). Interlinkages are normally assessed because they raise inherent trade-offs and synergies to be considered in policymaking, long-term strategies and pathways.

FAQ 1.5 What is input-output?

Input–output refers to a set of accounts for a system in which the flows of things going into and coming out of an activity are systematically accounted for by all elements of the system. This approach was famously applied to economic systems by Professor Wassily Leontief in the late 1930s for which he received the Nobel Prize in Economic Science in 1973. Models of economic system interactions have been developed on the principles originally put forward by Professor Leontief.

Economic input-output models, sometimes referred to as I-O models, are generally built on observed economic data either for a specific region (country, state, county, etc.) or global. Flows of goods and services are tracked from their origin to use, either a producing sector or final consumer. This basic information from which an input–output model is developed is contained in an interindustry transactions table, called the input-output table (Miller and Blair 2009). The input-output framework has been extended for several analytical purposes. One of which is incorporating environmental variables such as materials and GHG emission footprints (e.g. Wiedmann and Lenzen 2018; Lenzen et al. 2004, 2010).

Classic "Leontief" input-output models assume that the ratio of inputs to outputs is fixed. This method has been extended to non-stationary input-output ratios by computable general equilibrium (CGE) models.

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