Chapter 4: Mitigation and development pathways in the near- to mid-term

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Executive summary

This chapter focuses on accelerating mitigation and on shifting development pathways to increased sustainability, based on literature particularly at national scale. While previous WGIII assessments have discussed mitigation pathways, focus on development pathways is more recent. The timeframe is the near-term (now up to 2030) to mid-term (2030 to 2050), complementing Chapter 3 on the long-term (from 2050 onward).

An emissions gap persists, exacerbated by an implementation gap, despite mitigation efforts including those in near-universal nationally determined contributions. There is considerable literature on country-level mitigation pathways, including but not limited to NDCs. Country distribution of this literature is very unequal (*robust evidence, high agreement*). Current policies lead to median global GHG emissions of 63 $GtCO_2$-eq with a full range of 57-70 by 2030 and unconditional and conditional nationally determined contributions (NDCs) to 59 (55-65) and 56 (52-61) $GtCO_2$-eq, respectively (*medium evidence, high agreement*) (Table 4.1). This leaves a median estimated ***emissions gap*** of 14-23 $GtCO_2$eq for limiting warming to 2°C and 25-34 $GtCO_2$eq for limiting warming to 1.5°C relative to mitigation pathways (see Cross-Chapter Box 3, Figure 1). The magnitude of this emission gap calls into question whether current development pathways and efforts to accelerate mitigation are to achieve the Paris mitigation objectives. In addition, an ***implementation gap*** exists between the projected emissions of 'current policies' and the projected emissions resulting from the implementation of unconditional and conditional NDCs, and is estimated to be around 4 and 7 $GtCO_2$eq in 2030, respectively (Table 4.1) (*medium evidence, medium agreement*), with many countries requiring additional policies and associated climate action to meet their autonomously determined mitigation targets as specified under the first NDCs (*limited evidence*). There is, furthermore, a potential difference between mitigation targets set in NDCs *ex ante* and what is achieved *ex post*. A limited number of studies assess the implementation gaps of conditional NDCs in terms of finance, technology and capacity building support. The disruptions triggered by the Covid-19 epidemic increase uncertainty over range of projections relative to pre-COVID-19 literature. However, the information available to date does not suggest that median near-term emissions would be significantly different from the estimates above, as the decrease in emissions is expected to be short-term rather than structural {4.2}.

Given the gaps, there is a need to explore accelerated mitigation (relative to NDCs and current policies). There is increasing understanding of the technical content of accelerated mitigation pathways, differentiated by national circumstances, with considerable though uneven literature at country-level (*medium evidence, high agreement*). Transformative technological and institutional changes for the near-term include demand reductions through efficiency and reduced activity, rapid decarbonisation of the electricity sector and low-carbon electrification of buildings, industry and transport (*robust evidence, medium agreement*). A focus on energy use and supply is essential, but not sufficient on its own – the land sector and food systems deserve attention. The literature does not adequately include demand-side options and systems analysis, and captures the impact from non-CO_2 GHGs with medium confidence {4.2.5}. Countries and regions will have different starting points for transition pathways. Some factors include climate conditions resulting in different heating and cooling needs, endowments with different energy resources, patterns of spatial development, and political and economic conditions {4.2.5}.

Accelerated mitigation alone may run into obstacles. Various actors have developed an increasing number of mitigation strategies up to 2050 (mid-term). A growing number of such strategies aim at net-zero / carbon neutrality, but it is not yet possible to draw global implications due to the limited size of sample (*medium evidence; low agreement*) {4.2.4}. Non-state actors are also engaging in a wide range of mitigation initiatives. When adding up emission reduction potentials, sub-national and non-state international cooperative initiatives could reduce up to about 20 Gt of CO_2eq in 2030 (*limited evidence,* *medium agreement*) {4.2.3}. Yet perceived or real conflicts between mitigation and other SDGs can impede such action. If undertaken without precaution, accelerated mitigation is found to have significant implications for development objectives and macroeconomic costs at country level. For example, most country-level mitigation modelling studies in which GDP is an endogenous variable report negative impacts of mitigation on GDP in 2030 and 2050, relative to the reference. In all reviewed studies, however, GDP continues to grow even with mitigation (*robust evidence, high agreement*). The literature finds that employment effect of mitigation policies tends to be limited on aggregate, but can be significant at sectoral level (*limited evidence, medium agreement*) and that the detailed design of mitigation policies is critical for distributional impacts (*robust evidence, high agreement*), though further research is needed in that direction {4.3.3}. Important lock-ins must also be overtaken {4.4.3}.

Shifting development pathways towards sustainability offers a way to (i) broaden the range of levers and enablers that a society can use to provide enabling conditions and accelerate mitigation; and (ii) increases the chances of advancing at the same time towards mitigation and towards other development goals {Cross-Chapter Box 4, Figure 4.6, 4.3.4}. The way countries develop determines their capacity to accelerate mitigation and achieve other sustainable development objectives simultaneously (*medium-robust evidence, medium agreement*) {4.3.1, 4.3.2}. Yet meeting ambitious mitigation and development goals cannot be achieved through incremental change, hence the focus on shifting development pathways (*robust evidence, medium agreement*). Though development pathways result from the actions of a wide range of actors, it is possible to shift development pathways through policies and enhancing enabling conditions (*limited evidence, medium agreement*). For example, policies such as those listed in Table 4.9 are typically associated with broader objectives than greenhouse gas mitigation. They are generally conceived and implemented in the pursuit of overall societal development objectives, such as job creation, macro-economic stability, economic growth, and public health and welfare. However, they can have major influence on mitigative capacity, and hence can be seen as tools to broaden mitigation options (*medium evidence, medium agreement*). There are practical options to shift development pathways in ways that advance mitigation and other sustainable development objectives, supporting political feasibility, increase resources to meet multiple goals, and reduce emissions (*limited evidence, high agreement*). Concrete examples assessed in section 4.4.1 include examples of historical shifts, where countries intentionally moved their development pathway, and scenarios of possible future development pathways, in the form of modelling and narratives. These examples differ by context. They include sectoral change, as well as transformational changes across whole economies and societies. Shifting development pathways can jointly support mitigation and adaptation {4.4.2}. Some studies explore the risks of high complexity and potential delay attached to shifting development pathways {4.4.3}.

The literature identifies a broad set of enabling conditions that can both foster shifting development pathways and accelerated mitigation, along five categories {4.4.1, Figure 4.7} (*medium evidence, high agreement*). Policy integration is a necessary component of shifting development pathways, addressing multiple objectives. To this aim, mobilising a range of policies is preferable to single policy instruments (*robust evidence, high agreement*) {4.4.1.2}. Governance for climate mitigation and shifting development pathways is enhanced when tailored to national and local contexts. Improved institutions and governance enable ambitious climate action and help bridge implementation gaps (*medium evidence, high agreement*) {4.4.1.3}. Accelerated mitigation and shifting development pathways necessitates both re-directing existing financial flows from high- to low-emissions technologies and systems and to provide additional resources (*robust evidence, high agreement*) {4.4.1.4}. At the national level, it is also essential to create fiscal space for actions promoting the SDG agenda and thereby broadening the scope of mitigation (*medium evidence, medium agreement*). Changes in behaviour and lifestyles are important to move beyond mitigation as incremental change, and when supporting shifts to more sustainable development pathways will broadening the scope of mitigation (*medium evidence, medium agreement*) {4.4.1.5}. The direction of innovation matters (*robust evidence*, *high agreement*) {4.4.1.6}.

Equity can be an important enabler of deeper ambition for accelerated mitigation, dealing with the distribution of costs and benefits and how these are shared as per social contracts, national policy and international agreements. Transition pathways have distributional consequences such as large changes in employment and economic structure (*robust evidence*, *high agreement*). To that regard, the just transition concept has become an international focal point tying together social movements, trade unions, and other key stakeholders to ensure equity is better accounted for in low-carbon transitions {Figure 4.8}. Effectiveness of cooperative action and the perception of fairness of such arrangements are closely related, in that pathways that prioritise equity and allow broad stakeholders participation can enable broader consensus for the transformational change implied by deeper mitigation efforts (*robust evidence*, *medium agreement*) {4.5}. Hence, equity is an ethical imperative, but it is also instrumentally important. {4.5}.

In sum, this Chapter suggests that the immediate tasks are to broaden and deepen mitigation in the near-term if the global community is to deliver emission reductions at the scale required to keep temperature well below 2°C and pursue efforts at 1.5°C. Deepening mitigation means more rapid decarbonisation. Shifting development pathways to increased sustainability (SDPS) broadens the scope of mitigation. Putting enabling conditions in place support both.

Accelerating mitigation: The literature points to well-understood policy measures and technologies for accelerating mitigation, though the balance depends on country specificities: 1) decarbonising electricity supply to produce net zero CO_2, including through renewable energy, 2) radically more efficient use of energy than today; 3) electrification of end-uses (including transport / electric vehicles; 4) dramatically lower use of fossil fuels than today; 5) converting other uses to low- or zero-carbon fuels (e.g., hydrogen, bioenergy, ammonia) in hard-to-decarbonise sectors; 6) setting ambitious targets to reduce methane and short-lived climate forcers. Setting targets for net zero may provide a vision, which policy measures help achieve.

Broadening opportunities by focusing on development pathways and considering how to shift them: Some of the policy measures may yield rapid results, whereas other, larger transformations may take longer. The literature points that given inertia, putting in place the conditions to shifting development pathways to increased sustainability rapidly is essential. Focusing on SDPS also provides a broader set of tools to accelerating mitigation and achieve other sustainable development goals. Though there is increasing experience with pricing carbon directly or indirectly, decision-makers might consider a broader toolbox of enablers and levers that is available in domains that have not traditionally been climate policy. In a nutshell, think about climate whenever you make choices about development, and *vice versa*.

4.1 Introduction

The recent IPCC on Global Warming of 1.5°C (SR15) report made clear that the next three decades are critical if we are to reach the long term mitigation goals of the Paris Agreement (IPCC 2018a). The present Chapter assesses the literature on mitigation and development pathways over that timeframe, in the near- (up to 2030) and mid-term (up to 2050).

It considers three questions: (1) Where are we heading now? That is, what is the current state of affairs with respect to climate mitigation? (2) Where do we want to go? I.e., how should the state of affairs shift to tackle the climate crisis and achieve sustainable development objectives? and (3) How do we shift there? I.e., what interventions are at societies' disposal to bring about the necessary change?

Where are we heading now? Despite the drop in emissions due to the COVID-19 crisis, the gap between projected emissions based on nationally determined contributions (NDCs) in 2030 and emissions pathways compatible with the temperature goals set in the Paris Agreement remains large (4.2.2). In addition to a persistent emissions gap, we face an implementation gap, with uncertainty whether current policies are sufficient to achieve mitigation targets in NDCs, and whether sufficient support is available. Continuing along the same pathways that led to high emissions will not address the problem (*robust evidence, high agreement*).

The analysis of the gap is conducted together with Chapter 3 (see Cross-Chapter Box 3). Chapter 3 is working backward from the long-term goals, including temperature, and assesses mitigation in the long-term (beyond 2050 up to 2100 or even 2300) to draw the near- and mid-term implications of long-term temperature and mitigations goals. Chapter 4, on the other hand, works forward from current and planned mitigation (including NDCs) and from current development paths to assess the implications for near- and mid-term Greenhouse Gases (GHG) emissions and development goals.

Where do we want to go? Opportunities exist to bridge the emissions and implementation gaps. Some countries, regions, cities, communities and non-state actors are taking the leadership in transformational change. And the literature offers a wide range of accelerated mitigation pathways, deepening decarbonisation closer to the pace and scale required. But there are two problems. Firstly, incremental change is not enough: Mitigation policies grafted on to existing development pathways are unlikely to achieve rapid and deep emission reductions. Secondly, even if carefully designed, climate policies to accelerate mitigation may have adverse consequences for other development objectives. As a complement to mitigation action, taking action to shift development pathways towards sustainability broadens the range of mitigation options, while increasing the possibility to meet other development priorities at the same time (*medium evidence, high agreement*).

Development pathways and shifting them to increased sustainability are introduced in Chapter 1, and constitute a thread throughout the report (see glossary entry on development pathways, and Cross-Chapter Box 4 on shifting sustainable pathway towards sustainability). The influence of development pathways on emissions and mitigative capacity is discussed in Chapter 2. Examples of shifts in development pathways can be found in Chapter 3 (via the illustrative pathway called "shifting pathway"), the importance of behavioural change as societies make decisions that intentionally shift their future development pathway in Chapter 5, across all sectors in the systems Chapters (6-12) and, to the extent that the pathways are sustainable, Chapter 17.

How can one shift development pathway and accelerate mitigation? The literature does not provide a complete handbook for shifting development pathways and accelerating mitigation. The literature does, however, shed light on key enabling conditions—improving governance and institutional capacity, fostering behavioural change and technological innovation, delivering adequate policy, and provision of finance (see Figure 4.7 on enabling conditions)—to support both accelerated mitigation and shifts in development pathways in the near- and mid-term. Just transitions, while they will differ by context, are critical to addressing unavoidable distributive consequences (*robust evidence, high agreement*).

Enabling conditions necessary to accelerate mitigation and shift development pathways are discussed in depth in Chapters 5, 13, 14, 15 and 16. In addition, Chapters 13 and 14 detail the policy instruments that could help shift development pathways and accelerate the scale and pace of mitigation, while Chapter 4 describes those in broad strategies terms. Chapter 13 adds more texture on institutional and governance machinery; policy choice, design and implementation; as well as policy formulation processes, actors and structure across scales.

Since development pathways and mitigation options depend to large extent on national objectives and circumstances, this chapter is primarily concerned with literature at national level (or in the case of the European Union, at regional level), while Chapter 3 is primarily concerned with literature at global scale. The national scale selected in this Chapter requires attention as national mitigation pathways cannot be linked directly to global mitigation goals (see Box 4.1). This chapter is also concerned mostly with economy-wide development and mitigation pathways, as distinct from detailed sectoral work that is assessed in the systems chapters 6 to 12. The present chapter also assesses literature on non-state action.

Chapter 4 draws on five major strands of literature: (1) an emerging literature on development pathways – conceptual, empirical, and model-based, including at the national and sub-national scales; (2) a rapidly expanding, model-based, literature on mitigation pathways in the near- and mid-term (Lepault and Lecocq 2020); (3) studies of NDCs and mid-century strategies; (4) a broader literature on transformation and shifts in development pathways, including from non-climate literatures; and (5) a significant literature on equity, including just transitions. This is supported a database of country-level mitigation scenarios at country level assembled for the preparation of this Chapter (see Annex C, section II.3.2.3).

The Chapter also draws on past IPCC reports. In AR5, all mitigation pathways were assessed in a single chapter (Clarke et al. 2014), which focused mostly on the long-term. The special report on global warming of 1.5°C (SR1.5) included a chapter on mitigation pathways compatible with the temperature goal in the Paris Agreement (Rogelj et al. 2018a), mostly at the global level. Development pathways have also been explored, albeit less frequently, in past IPCC reports starting with the Special Report on Emissions Scenarios (Nakicenovic et al. 2000). Some early framing of development pathways was included in the Third Assessment Report (William R. Moomaw et al. 2001), further developed in the Fourth Assessment Report (Sathaye et al. 2007). A chapter of AR5 updated key findings on drivers such as consumption, finance, technology and more (Fleurbaey et al. 2014a). The special report on global warming of 1.5°C (SR1.5) considered strengthening mitigation (de Coninck et al. 2018a) in the context of poverty, inequality and sustainable development (Roy et al. 2018).

Chapter 4 is organised so that both the accelerated mitigation perspectives and the innovative development pathways perspectives are assessed. The chapter recasts emissions within the broader context of development pathways, and examines how shifting development pathways can have a major impact on mitigative capacity and broadening mitigation options.

Section 4.2 demonstrates that collective mitigation actions fall short of pathways that keep in reach the Paris temperature goals in the long-term. Section 4.3 introduces development pathways (given its relative novelty in IPCC assessments), considers the implications of mitigation for development and *vice versa*, and articulates an approach on *both* accelerating mitigation *and* shifting development pathways.

Section 4.4 discusses how to shift development pathway and accelerate the scale and pace of mitigation, and what levers are available to policy makers. It points out that development pathways also drive adaptation and adaptative capacity, and discusses various risks associated with shifting development pathways and accelerated mitigation strategies. Finally, these transformations are put in the context of equity and just transition for an effective societal climate response.

4.2 Mitigation actions across scales

4.2.1 Mitigation targets and measures in nationally determined contributions

A central instrument of the Paris Agreement is the Nationally Determined Contributions (NDCs), submitted by each country reflecting national efforts to reduce GHG emissions and build resilience to the impacts of climate change. Every five years, collective progress will be compared against long-term goals of the Paris Agreement. Considering the outcome of a global stocktake, countries will prepare subsequent NDCs, showing progression in their ambition and enhance international cooperation (UNFCCC 2015a).

Prior to COP21, in 2015, most countries submitted their INDCs (Intended Nationally Determined Contributions), which include mitigation targets for 2025 or 2030. INDCs become first NDCs on ratification and/or after national governments' revision, and by December 2020, the official NDC registry contained 188 first NDCs, equivalent to 99% of total anthropogenic GHG emissions, as of 2019, and three second NDC. Countries will take the first stock in 2023 based on their progression towards achieving the objectives of their second NDC, to be submitted by 2020 (UNFCCC 2015a).

Submitted NDCs vary in content, scope and background assumptions. First NDCs contain mitigation targets, and in many cases also provisions about adaptation. Baseline years vary from 1990 to 2015. Nearly half of the mitigation targets in first NDCs are expressed in terms of deviation below business-as-usual, while others include fixed-level targets (either reductions or limitations compared to base years), intensity targets (in terms of GHG, CO_2 or energy) or policies and measures (UNFCCC 2016a). Some developing countries included unconditional targets, while others included conditional ones, the latter with higher ambition if finance, technology and capacity building support from other developed countries is provided (UNFCCC 2016a). In some NDCs, the additional mitigation is quantified, in others not.

Most first NDCs cover all specific sectors, including AFOLU and LULUCF, and communicate specific targets for individual sub-sectors to support their overall mitigation targets. Concrete actions and priority areas are more detailed in the energy sector, with increased share of renewable energies and energy efficiency plans being highlighted in the majority of NDCs. Given the uncertainty behind LULUCF emission and removal accounting (Grassi et al. 2017; Jian et al. 2019), several countries stated that their framework for accounting is still to be defined and will be considered in later NDC submissions. There are also variabilities about the GHG included and the global warming potentials (GWPs) used to aggregate emissions. Most countries only refer to carbon dioxide, methane and nitrous oxide emissions aggregated based on IPCC AR2 or AR4 metrics, while few NDCs also included fluorinated gases and used IPCC AR5 GWPs.

There is considerable literature on country-level mitigation pathways, including but not limited to NDCs. Country distribution of this literature is very unequal (*robust evidence, high agreement*). In particular, there is a growing literature on (I)NDCs, with a wide scope which includes estimate of emissions levels of NDCs (see section 4.2.2.2); alignment with sustainable development goals (Caetano et al. 2020; Campagnolo and Davide 2019; Fuso Nerini et al. 2019; Antwi-Agyei et al. 2018); ambition (Höhne et al. 2018; Vogt-Schilb and Hallegatte 2017; Hermwille et al. 2019); energy development (Scott et al. 2018); and the legality of downgrading NDCs (Rajamani and Brunnée 2017). Other studies note that many NDCs contain single-year mitigation targets, and suggest that a multi-year trajectory is important for more rigorous monitoring (Elliott et al. 2017; Dagnet et al. 2017).

The literature also points out that beyond the 'headline numbers', information in (I)NDCs is difficult to analyse (Pauw et al. 2018). Information for 'clarity, transparency and understanding' is to be communicated with NDCs, although initial guidance was not specific (UNFCCC 2014). While the adoption of the Paris rule-book provided some greater specificity (UNFCCC 2018a,b), the information included in the NDCs remains uneven. Many NDCs omit important mitigation sectors and do not adequately provide details on costs and financing of implementation (Pauw et al. 2018). Countries are also invited to explain how their NDCs are fair and ambitious, though the way this has been done so far has been criticised as insufficiently rigorous (Winkler et al. 2018).

As of December 2019, the peer-reviewed literature on NDCs extends to about 580 journal articles in total, covering many different aspects of NDCs. About 40% of this literature mentions pathways or scenarios, but only a subset of those articles include quantitative estimates that are relevant for the NDC assessment in Section 4.2.2. The regional distribution is not uniform but focuses mostly on large emitting countries. It reveals a large predominance of studies about China (though not necessarily from authors in China) with some 125 articles (20% of total). Other countries and regions with a large body of literature on NDCs include India (12%), Brazil (8%), the European Union (7.5%), Indonesia and Japan (5% each). This regional distribution is consistent with the wider literature on mitigation (Lepault and Lecocq 2020) (see Box S1 in the Supplementary Material to this Chapter), possibly with the exception of the United States which is underrepresented in the literature on NDCs compared to the wider mitigation literature. [*to be updated for FGD*]

4.2.2 Aggregate effects of NDCs and other mitigation efforts relative to long-term mitigation pathways

4.2.2.1 Introduction

Near-term mitigation targets submitted as part of NDCs to the UNFCCC, as well as currently implemented policies, provide a basis for assessing potential emissions levels up to 2030 at the national, regional and global level. The following sections present an evaluation of the methods used for assessing projected emissions under NDCs and current policies (Section 4.2.2.2), and the results of these assessments at global, regional and national level (Section 4.2.2.3). This is followed by an assessment of the implementation gap between what currently implemented policies are expected to deliver and what the ambitions laid out under the full implementation of the NDCs would achieve (Section 4.2.2.4). Finally, a comparison of ambitions across different countries or regions (Section 4.2.2.6) is presented and the uncertainties of projected emissions associated with NDCs and current policies are estimated, including a discussion of measures to reduce uncertainties in the specification of NDCs (Section 4.2.2.7).

The literature reviewed in this section includes globally comprehensive assessments of NDCs and current policies, both from the peer-reviewed and non-peer-reviewed literature (but not unpublished model results) as well as synthesis reports by the UNFCCC Secretariat, government reports and national studies.

The aggregate effects of NDCs provide information on where emissions might be in 2025/2030, working forward from their recent levels. Chapter 3 of this report works backwards from temperature goals, defining a range of long-term global pathways consistent with 1.5°C, 2°C and higher temperature levels. By considering the two together, it is possible to assess whether NDCs are collectively consistent with 1.5°C, 2°C and higher temperature pathways (see Cross-Chapter Box 3, p.4-20).

4.2.2.2 Methods to project emissions under NDCs and current policies

A variety of different methods are used to assess emissions implications of NDCs and current policies over the time horizon to 2025 or 2030. It is important to distinguish between projections explicitly submitted as part of an official communication to UNFCCC (e.g., Biennial Report, Biennial Update Reports or National Communications) and independent studies.

Methods that are used in independent studies (but that can also underlie the official communications) can broadly be separated into two groups,

(i) system modelling studies which analyse policies and targets in a comprehensive modelling framework such an integrated assessment, energy systems or integrated land-use model to project emissions (or other indicators) of mitigation targets in NDCs and current policies, either at the national or global scale (noting some differences in the systems), and

(ii) hybridised approaches that typically start out with emissions pathways as assessed by other published studies (e.g., the IEA World Energy Outlook, national emissions pathways such as those specified in some NDCs) and use these directly or apply additional modifications to them.

System modelling studies are conducted at global, regional and national scales. Global models provide an overview, are necessary for assessment of global phenomena (e.g., temperature change), can integrate climate models and trade effects. National models typically include more details on sectors, technology, behaviour and intersectoral linkages, but often use simplifying assumptions for international trade (e.g., the Armington elasticity approach). Critically, they can also better reflect local socio-economic and political conditions and their evolution (i.e., national development pathways). A variety of modelling paradigms are found, including optimisation and simulation models, myopic and with foresight, monolithic and modular (see Annex C: Scenarios and modelling methods).

Among the hybridised approaches which are mostly used to generate globally comprehensive projections, three broader categories can be distinguished, (i) studies that extrapolate from existing estimate (nationally from NDC scenarios) or globally from IEA WEO), (ii) combinations of model projections for some and researchers' estimates for other countries; and (iii) studies of the impacts of policies on baseline or business-as-usual pathways (which much debate in the literature on different baselines).

Beyond the method applied, studies also differ in a number of dimensions, including their spatial resolution and coverage, their sectoral resolution and coverage, the GHGs that are included in the assessment, the GWPs (or other metrics) to aggregate them, the set of scenarios analysed (Reference/Business-As-Usual, Current Policies, NDCs, etc.), and finally the degree to which individual policies and their impact on emissions are explicitly represented (see Table S4.1).

First, the studies are relevant to different spatial levels, ranging from macro-scale regions with globally comprehensive coverage (Section 4.2.1) to national level (Section 4.2.2) and subnational and company level in a few cases. It is important to recognise that globally comprehensive studies typically resolve a limited number of countries individually, in particular those that contribute a high share to global emissions, but have poor resolution of remaining countries or regions, which are assessed in aggregate terms. Conversely, studies with high resolution of a particular country tend to treat interactions with the global scale in a limited way. The recent literature includes attempts to provide a composite global picture from detailed national studies (Bataille et al. 2016a; DDPP 2015; Roelfsema et al. 2019).

A second dimension in which the studies are different is their comprehensiveness of covering different emitting sectors. Some studies focus on the contribution of a single sector, for example the Agriculture, Forestry and Other Land Use (AFOLU) sector (Fyson and Jeffery 2019; Grassi et al. 2017) or the energy system (including both energy supply and demand sectors), to emission reductions as specified in the NDC. Such studies give an indication of the importance of a given sector to achieving the NDC target of a country and can be used as a benchmark to compare to comprehensive studies, but adding sectoral contributions up represents a methodological challenge.

Third, GHG coverage is different across studies with some focusing on CO_2 only, while others taking into account the full suite of Kyoto gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6, see glossary). For the latter, different metrics for aggregating GHGs to a CO_2-equivalent metric are being used, typically GWP 100 from different IPCC assessments (see Table 4.1)

Fourth, typically studies cover a set of scenarios, though how these scenarios are defined varies widely. The literature reporting IAM results often includes *Nationally Determined Contribution* (NDC), which are officially communicated, and *Current Policies* (CP) as interpreted by modellers. Studies based on national modelling, by contrast, tend to define scenarios reflecting very different national contexts. In both cases, modellers typically include so-called *No Policy Baseline* scenarios (alternatively referred to as R*eference or Business-as-Usual scenarios)* which do not necessarily reflect currently implemented policies and thus are not assessed as reference pathways (see section 4.3.3.1). There are also various approaches to considering more ambitious action compared to the CP or NDC projections that are covered in addition.

Five, studies differ in the way they represent policies (current or envisioned in NDCs), depending on their internal structure. For example, a subsidy to energy efficiency in buildings may be explicitly modelled (e.g., in a sectoral model that represents household decisions relative to building insulation), represented by a proxy (e.g., by an exogenous decrease in the discount rate households use to make choices), or captured by its estimated outcome (e.g., by an exogenous decrease in the household demand for energy, say in an energy system model or in a compact CGE). Detailed representations (such as the former example) do not necessarily yield more accurate results than compact ones (the latter example), but the set of assumptions that are necessary to represent the same policy will be very different.

Finally, policy coverage strongly varies across studies with some just implementing high level targets specified in policy documents and NDCs while others represent the policies with the largest impact on emissions and some looking at very detailed measures and policies at subnational level. In addition, in countries with rapidly evolving policy environments, slightly different cut-off dates for the policies considered in an emission projection can make a significant difference for the results (Dubash et al. 2018).

In addition to assessing the emissions outcomes of NDCs, some studies report development indicators, meaning a wide diversity of socio-economic indicators (Altieri et al. 2016; Bataille et al. 2016a; Jiang et al. 2013; Benavides et al. 2015; Chai and Xu 2014; Delgado et al. 2014; La Rovere et al. 2014a; Paladugula et al. 2018; Parikh et al. 2018; Zevallos et al. 2014; Zou et al. 2016), the share of low carbon energy (Bertram et al. 2015; Riahi et al. 2015), renewable energy deployment (Roelfsema et al. 2018), production of fossil fuels (SEI et al. 2020) or investments into low-carbon mitigation measures (McCollum et al. 2018a) to track progress towards long-term temperature goals.

4.2.2.3 Projected emissions under NDCs and current policies by 2025/2030

Table 4.1 presents the evidence base for the assessment of projected emissions of NDCs and current policies until 2030. It covers 28 countries and regions responsible for about 82% of global GHG emission and draws quantitative estimates from 40 studies (see Table S4.1 in the Supplementary Material to Chapter 4). The table allows comparing emission projections from national and globally comprehensive studies as well as official communications by countries to the UNFCCC at the national/regional level. The global aggregates presented in Table 4.1 derive from globally comprehensive studies only and are not the result of aggregating country projections up to the global level. As different studies report different emission indicators, the table includes four different indicators: CO_2 and GHG emissions, in- or excluding AFOLU emissions. Where possible, multiple indicators are included per study.

Globally comprehensive studies.

The UNFCCC Secretariat has assessed the aggregate effect of NDCs twice. The first report considered the intended NDCs in relation to 2°C (UNFCCC 2015b), whereas the second considered NDCs also in relation to 1.5 °C (UNFCCC 2016b).

A range of globally comprehensive studies (den Elzen et al. 2016; Luderer et al. 2016; Rogelj et al. 2016, 2017; Vandyck et al. 2016; Rose et al. 2017; Vrontisi et al. 2018) which estimate aggregate emissions outcomes NDCs and current policies have previously been assessed in IPCC SR1.5, Cross-Chapter-Box 11.

Current policies lead to median global GHG emissions of 63 $GtCO_2$-eq with a full range of 57-70 by 2030 and unconditional and conditional NDCs to 59 (55-65) and 56 (52-61) $GtCO_2$-eq, respectively (*medium evidence, high agreement*) (Table 4.1). Globally comprehensive and national-level studies project emissions of current policies and NDCs to 2025 and 2030 and, in general, are in good agreement about country-level emission projections based on modelled current policies and NDCs.

These estimates are close to the ones provided by the IPCC SR1.5, Cross-Chapter-Box 11, and the UNEP emissions gap report (UNEP 2020)[a].

[*Note to reviewers: The estimates reported in the First Order Draft of this chapter 4 used AR4 100-year GWPs for calculating GHG emissions, as GWP values for AR6 were being developed, whereas the present Second Order Draft chapter use* 100-year GWPs from WGI for AR6]

Globally, the implementation gap between projected emissions of current policies and the unconditional and conditional NDCs is estimated to be around 4 and 7 $GtCO_2$eq in 2030, respectively (Table 4.1) (*medium evidence, medium agreement*), with many countries requiring additional policies and associated climate action to meet their autonomously determined mitigation targets as specified under the NDCs (*limited evidence*).

[*Nationally determined contributions (NDCs) in this chapter are the first NDCs, as communicated in 2015 and 2016. With some first NDCs having been updated by the end of 2020, others expected in 2021 due to COVID-19, and the UNFCC secretariat planning to publish an initial synthesis report by February 2021 and a more complete update by COP26 in November 2021, the chapter team intends to update the estimates (to the extent available) between the SOD and FGD for studies that have been covered in the methods section by the time of the SOD so that AR6 can provided new information in addition to SR1.5*.]

National studies

A large body of literature on national and regional emissions projections, including official communications of as part of the NDC submissions and independent studies exist. A subset of this literature provides quantitative estimates for the 2030 timeframe. As highlighted in Section 4.2.1, the number of independent studies varies considerably across countries with an emphasis on the largest emitting countries which is reflected in Table 4.1 (see Table S4.1 in the Supplementary Material to Chapter 4). A few deviations between these groups of studies merit further attention. For China, global studies show higher projections of current policies and NDCs in 2030 by several hundred $MtCO_2$eq per year compared to national studies, but the ranges across the two groups of studies overlap. The opposite situation is found for Australia where global studies project lower emission growth in both current policy and NDC scenarios than national studies. Despite these differences for a few countries the

FOOTNOTE: [a] Note that the statistical metrics reported are slightly different across the reports. For example, IPCC SR1.5 reported the 25th to 75th range while the UNEP emissions gap report uses median and 10th to 90th percentile ranges. In addition, this report applies 100-year GWPs from AR6 to aggregate across different GHG emission species, whereas 100-year GWPs from AR4 were applied in IPCC SR1.5 and UNEP 2020. The application of AR6 GWPs on average leads to increase of estimates by about 5% and ranges are wider due to the difference in statistical error metrics.

comparison shows that there is generally good agreement between the different types of studies, so therefore providing evidence that these quantitative estimates are fairly robust.

Sectoral studies

Sectoral studies are essential in understanding the contributions of concrete measures of NDCs and current policies. For example, approximately 98% of NDCs include the energy sector in their mitigation contributions and around 50% of which include a specific target for renewables share (Stephan et al. 2016). Transport is covered explicitly in 75% of NDCs, although specific targets for the sector exist in only 21% of NDCs (PPMC and SLoCaT 2016). Measures or targets for buildings are referred to explicitly in 27% of NDCs (GIZ 2017). 36% of NDCs include targets or actions that are specific to the agriculture sector (FAO 2016). LULUCF (mitigation) is included in 80 % of all submitted NDCs, and 59 % included adaptation, and 29 % referred to REDD+ in their NDCs.

Greater sectoral expertise and involvement will be critical to accomplishing development and climate goals due to enhanced availability of information and expertise on specific sectoral options, greater ease of aligning the NDC with sectoral strategies, and greater awareness among sector-level decision-makers and stakeholders (NDC Partnership 2017; Fekete et al. 2015). Sector-specific studies are assessed in the sectoral chapters (6-11) of this report.

Table 4.1 Assessment of projected emissions of current policies and NDCs by 2030 for 28 individual countries/regions and the world.

Region[a]	GHG share [%][b]	Type[c]	# studies[d]	Current Policies 2030 emissions			NDC 2030 emissions (conditional/unconditional)		
				CO_2 only [$GtCO_2$] median (min - max)[e]		Kyoto GHGs[c] [$GtCO_2$-eq] median (min - max)[e]	CO_2 only [$GtCO_2$] median (min - max)[e]		Kyoto GHGs[c] [$GtCO_2$-eq] median (min - max)[e]
				incl. AFOLU[f]	fossil fuels	incl. AFOLU[f]	incl. AFOLU[f]	fossil fuels	incl. AFOLU[f]
World	100	global	42	45.5 (40.1 - 51.5)	38.9 (35 - 45.2)	62.9 (57.3 - 69.8)	39.5 (36.1 - 45.2)/ -	34.9 (30 - 39.3)/ -	55.8 (52.4 - 61.2)/58.9 (55.3 - 64.6)
CHN	26	global	32	11.8 (11.1 - 14.6)	11 (8.98 - 14.2)	14.9 (13 - 18.4)	- /11.5 (10 - 12)	- /10.1 (6.94 - 12.1)	- /15 (13 - 16)
		national	6	12.1	11.8 (10.8 - 12.8)	15.2 (13.6 - 15.8)	- /12.5	- /11.1 (11 - 11.2)	13.1/15.7 (13.1 - 15.8)
USA[g]	13	global	29	5.13 (4.02 - 6.77)	5.26 (4.11 - 6.62)	5.92 (5.01 - 7.02)	- /4.01 (3.31 - 4.24)	- /4.14 (3.5 - 5.29)	- /4.54 (4.13 - 5.02)
		national	5	4.53 (4.06 - 4.99)	4.72 (4.09 - 5.36)	6.33 (5.22 - 6.82)	- /3.4	- /3.49	- /4.42
EU	8.4	global	19	2.71 (2.08 - 3.12)	2.83 (2.1 - 3.7)	3.54 (2.69 - 4.18)	- /2.33 (2.07 - 2.6)	- /2.48 (2.09 - 2.82)	- /3.21 (2.68 - 3.27)
		national	1	3.07					
		official	3			3.29 (2.87 - 3.72)			
IND	7.2	global	31	3.97 (3.04 - 5.77)	3.66 (2.54 - 5.74)	5.04 (4.23 - 7.53)	3.29 (3.07 - 4.22)/ -	2.93 (2.36 - 3.79)/ -	5.05 (4.33 - 5.91)/6.11 (5.16 - 6.36)
		national	9	3.61 (3.28 - 3.99)	3.61 (2.92 - 3.93)	5.75 (5.2 - 5.96)	3.55 (3.52 - 3.59)/3.25	3.52 (3.52 - 3.53)/2.89	5.33/5.1
RUS	4.7	global	20	2.03 (0.845 - 2.61)	1.84 (1.35 - 2.62)	2.56 (1.64 - 4.12)	- /1.59 (0.843 - 1.88)	- /1.54 (1.37 - 1.79)	- /2.59 (2.01 - 3.07)
		national	3		1.5	2.63		- /1.5	- /2.55
		official	2			2.17			- /2.8
JPN	2.7	global	25	1.12 (0.872 - 1.34)	1.04 (0.869 - 1.27)	1.07 (0.958 - 1.48)	- /0.945 (0.897 - 1.24)	- /0.909 (0.858 - 1.18)	- /1.05 (0.955 - 1.06)
		national	8	1.14 (1.12 - 1.57)	1.1 (1.06 - 1.47)	1.29 (1.22 - 1.72)	- /0.927 (0.915 - 1.18)	- /0.927 (0.874 - 1.14)	- /1.05 (1.01 - 1.3)
		official	1						- /1.05
BRA	2.6	global	22	1.08 (0.779 - 1.43)	0.57 (0.424 - 1.12)	1.83 (1.52 - 2.17)	- /0.652 (0.387 - 0.99)	- /0.502 (0.0966 - 0.784)	- /1.32 (1.14 - 1.79)
		national	3	0.899	0.47	1.93	- /0.805	- /0.467	- /1.32
		official	1						- /1.28

IDN	2	global	15	1.21 (1.05 - 1.98)	0.71 (0.658 - 0.898)	2.11 (1.46 - 2.52)	1.18 (0.823 - 1.44)/ -	0.685 (0.523 - 0.798)/ -	1.95 (1.23 - 2.27)/2.31 (1.89 - 2.4)
		official	1						2.04 (1.99 - 2.1)/2.39
CAN	1.6	global	19	0.642 (0.404 - 0.786)	0.496 (0.383 - 0.738)	0.696 (0.526 - 0.964)	- /0.424 (0.34 - 0.49)	- /0.385 (0.301 - 0.636)	- /0.534 (0.503 - 0.62)
		national	2	0.541		0.728	- /0.405		- /0.552
		official	1			0.687			
MEX	1.5	global	18	0.595 (0.572 - 0.644)	0.539 (0.302 - 0.569)	0.821 (0.741 - 0.891)	0.511 (0.481 - 0.568)/ -	0.456 (0.273 - 0.564)/ -	0.658 (0.638 - 0.804)/0.802 (0.644 - 0.809)
		official	1						0.642/0.782
AUS	1.4	global	11	0.43 (0.339 - 0.521)	0.368 (0.354 - 0.486)	0.556 (0.473 - 0.59)	- /0.356 (0.281 - 0.43)	- /0.333 (0.246 - 0.396)	- /0.463 (0.407 - 0.511)
		national	2			0.589			
		official	2			0.551 (0.547 - 0.554)			
KOR	1.4	global	16	0.679 (0.548 - 0.774)	0.635 (0.488 - 0.915)	0.698 (0.689 - 0.824)	- /0.547 (0.5 - 0.649)	- /0.498 (0.446 - 0.611)	- /0.513 (0.5 - 0.597)
		national	6	0.75 (0.75 - 0.808)	0.702 (0.702 - 0.759)	0.84 (0.84 - 0.898)	- /0.563 (0.514 - 0.563)	- /0.565 (0.49 - 0.565)	- /0.599 (0.565 - 0.599)
		official	1						
SAU	1.4	global	5	0.574	0.657 (0.485 - 0.83)	1.07 (0.725 - 1.16)	0.574/ -	0.653 (0.484 - 0.822)/ -	0.717/ -
TUR	1.2	global	12	0.45 (0.445 - 0.455)	0.437 (0.374 - 0.48)	0.615 (0.516 - 0.834)	- /0.45 (0.444 - 0.456)	- /0.437 (0.374 - 0.484)	- /0.946 (0.555 - 1.02)
		official	1						- /0.945
ZAF	1.1	global	18	0.459 (0.354 - 0.615)	0.437 (0.341 - 0.582)	0.64 (0.459 - 0.838)	- /0.36 (0.272 - 0.421)	- /0.347 (0.243 - 0.447)	0.421/0.521 (0.401 - 0.65)
		official	1						- /0.535 (0.421 - 0.65)
KAZ	0.84	global	1			0.47			0.298/0.338
THA	0.8	global	2			0.433 (0.432 - 0.433)			0.46/0.491
		national	3	0.435	0.398	0.604	0.345/0.365	0.323/0.339	0.448/0.479
ARG	0.79	global	12	0.306 (0.173 - 0.378)	0.214 (0.181 - 0.353)	0.529 (0.352 - 0.553)	0.207 (0.171 - 0.244)/ -	0.208 (0.182 - 0.225)/ -	0.415 (0.337 - 0.43)/0.542 (0.345 - 0.548)
		national	1			0.449 (0.438 - 0.459)			
		official	1						0.419/0.548

VNM	0.79	global	1						0.651/0.817
		national	3	0.357	0.285		0.357/0.357	0.285/0.285	
UKR	0.54	global	1			0.437 (0.433 - 0.44)			- /0.557
PHL	0.48	global	2			0.256			0.0863/ -
ETH	0.36	global	2			0.257 (0.215 - 0.298)			0.176 (0.167 - 0.184)/ -
		national	1	0.0201	0.0199				
COL	0.34	global	2			0.247 (0.247 - 0.248)			0.271 (0.271 - 0.271)/0.31 (0.309 - 0.31)
KEN	0.19	global	2			0.138 (0.127 - 0.15)			0.125 (0.125 - 0.126)/ -
		national	2	0.0259	0.0242		0.0205/ -	0.0188/ -	
MAR	0.17	global	2			0.109 (0.0881 - 0.131)			0.127 (0.104 - 0.149)/0.127 (0.104 - 0.149)
PRT	0.13	national	1						- /0.0295 (0.0286 - 0.0305)
CHE	0.1	global	1						- /0.026
		national	1	0.0243	0.0224				
MDG	0.069	global	1						0.0361/ -
		national	2				0.0696 (0.0679 - 0.0712)/ -	0.00427 (0.00262 - 0.00592)/ -	

Notes: [a] Countries are abbreviated by their ISO 3166-1 alpha-3 letter codes. EU denotes the European Union. [b] 2018 Share of global Kyoto GHG emissions, excluding FOLU emissions, based on EDGAR inventory (see Section 2.2.1.3). [c] Type distinguishes between independent globally comprehensive studies (that also provide information at the country/region level), independent national studies and official communications via Biennial Reports, Biennial Update Reports or National Communications. [d] GHG emissions expressed in CO_2-eq emission using AR6 100-year GWPs (see Section 2.2.2 for a discussion of implications for historical emissions). GHG emissions from scenario data is recalculated from individual emission species using AR6 100-year GWPs. GHG emissions from studies are rescaled using 2018 GHG emissions from the EDGAR inventory. [e] If more than one value is available, a median is provided and the full range of estimates (in parenthesis). To avoid a bias due to multiple estimates provided by the same model, only one estimate per model, typically the most recent update, is included in the median estimate. In the full range, multiple estimates from the same model might be included, in case these reflect specific sensitivity analyses of the "central estimate" (e.g., (Baumstark et al. 2020; Rogelj et al. 2017)). [f] Note that FOLU emissions from national GHG inventories and global/national land use models are generally different due to different accounting approaches (Grassi et al. 2018, 2020)(see Section 7.2.3 and Cross-Chapter Box 3). [g] The estimates for the USA are based on the NDC submitted prior to the withdrawal from the Paris Agreement.

4.2.2.4 Estimated impact of COVID-19 and governmental responses on emissions projections

The impacts of COVID-19 and national governments' economic recovery measures on current (see Section 2.2.2) and projected emissions of individual countries and globally under current policies scenarios until 2030 may be significant, although estimates are highly uncertain and vary across the few available studies. The analyses published to date (November 2020) are based on limited information about how COVID-19 has affected the economy and hence GHG emissions across countries so far in 2020, and also based on assumptions about COVID-19's longer term impact. Moreover, the comparison of pre- and post-COVID-19 projections captures the impact of COVID-19 as well as other factors such as the consideration of recently adopted policies not related to COVID-19, as well as methodological changes.

Across different studies available (IEA 2020; Dafnomilis et al.; Kikstra et al. 2020; Climate Action Tracker 2020; UNEP 2020), the impact of the general slowdown of the economy due to the COVID-19 pandemic and its associated policy responses would lead to a reduced estimate of global GHG emissions in 2030 of about 2 to 6 $GtCO_2eq$, equivalent to 3 to 9 per cent, compared to the pre-COVID-19 estimates (see Table S4.2 for details, including estimates for major economies). These estimates suggest that aggregated outcomes of current policies and NDCs in 2030 as presented in Table 4.1 might also be downwards corrected by this amount.

As indicated by a growing number of studies at the national and global level, how large medium- to long-term emissions implications of the COIVD-19 pandemic are, to a large degree depends on how stimulus or recovery packages are designed (Wang et al. 2020; Gillingham et al. 2020; Forster et al. 2020; Malliet et al. 2020; Le Quéré et al. 2020; Obergassel et al. 2020; IEA 2020; UNEP 2020).

4.2.2.5 Tracking progress in implementing and achieving NDCs

Legally, the NDCs are not yet implemented before 2020 and countries are required to submit their first biennial transparency report on progress made in implementing and achieving NDCs under Article 4 of the Paris Agreement before 31 December 2024 only (UNFCCC 2018a). Thus, no official data exists yet on tracking progress of individual NDCs. However, the rules for tracking progress were agreed at COP24 through the biennial transparency report (UNFCCC 2018a).

Meanwhile, there is some literature at global and national level that aims at assessing whether countries are on track or progressing towards implementing their NDCs and to which degree the NDCs collectively are sufficient to reach the temperature targets of the Paris agreement (van den Berg et al. 2019; Peters and Geden 2017; Höhne et al. 2018). Most of these studies focus on major emitters such as G20 counties and with the aim to inform countries to strengthen their ambition regularly, e.g., through progress of NDCs and as part of the global stocktake (Peters et al. 2017; Höhne et al. 2018). However, a limited number of studies assess the implementation gaps of conditional NDCs in terms of finance, technology and capacity building support Some authors conclude that finance needed to fulfil conditional NDCs exceeds available resources or the current long-term goal for finance (USD100 billion yr^{-1}) (Pauw et al. 2019); others suggest that assessment of financial resources for forest-related activities as an approach to triggering conditional NDCs (Kissinger et al. 2019). The literature suggests that consistent and harmonised approach to track progress of countries towards their NDCs would be helpful (den Elzen et al. 2019; Peters et al. 2017; Höhne et al. 2018), and negotiations on a common tabular format are due to conclude in 2020.

Globally, the implementation gap in 2030 between current policy scenarios and the unconditional and conditional NDCs is estimated to be around 4 and 7 $GtCO_2$-eq, respectively (Table 4.1). In other words, many countries will need to implement additional policies to meet their self-determined mitigation targets as specified under the NDCs. Studies that assess the level of projected emissions under current policies indicate that new policies (that have been implemented since the first assessment of the NDCs in 2015 and are thus covered in more recent projections) have reduced projections, by about 2 $GtCO_2eq$

since the adoption of the Paris Agreement in 2015 to 2019 (Climate Action Tracker 2019; den Elzen et al. 2019; UNEP 2020).

4.2.2.6 Assessments of fairness and ambition of NDCs

Most countries provided information on how they consider their NDCs to be fair and ambitious in the NDCs submitted to UNFCCC and many of these NDCs refer to specific national circumstances such as social, economic and geographical factors when outlining why they are fair and ambitious. Further, several Parties provided information on specific criteria for evaluating fairness and ambition, including criteria relating to: responsibility and capability; share of emissions; development and/or technological capacity; mitigation potential; cost of mitigation actions; the degree of progression or stretching beyond the current level of effort; and the link to objectives and global goals (UNFCCC 2016a).

According to its Article 2.2, the Paris Agreement will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances, the latter clause being new, added to the UNFCCC principle (Rajamani 2017; Voigt and Ferreira 2016). Possible different interpretations of equity principles lead to different assessment frameworks (Lahn 2017; Lahn and Sundqvist 2017).

Various assessment frameworks have been proposed to analyse fair share ranges for NDCs. The literature on equity frameworks including quantification of national emissions allocation is assessed in section 4.5. Recent literature has assessed equity, analysing how fairness is expressed in NDCs in a bottom-up manner (Cunliffe et al. 2019; Mbeva and Pauw 2016; Winkler et al. 2018). Some studies compare NDC ambition level with different effort sharing regimes and which principles are applied to various countries and regions (Robiou du Pont and Meinshausen 2018; Robiou Du Pont et al. 2017; Holz et al. 2018; Peters et al. 2015; Pan et al. 2017; van den Berg et al. 2019). Others propose multi-dimensional evaluation schemes for NDCs that combine a range of indicators, including the NDC targets, cost-effectiveness compared to global models, recent trends and policy implementation into consideration (Aldy et al. 2017; Höhne et al. 2018). Yet other literature evaluates NDC ambition against factors such as technological progress of energy efficiency and low-carbon technologies (Jiang et al. 2017; Wakiyama and Kuramochi 2017), synergies with adaptation plans (Fridahl and Johansson 2017), the potential to deploy carbon dioxide removal technologies in the future which are to date not mentioned in NDCs (Fyson et al. 2020; Pozo et al. 2020; Peters and Geden 2017).

4.2.2.7 Uncertainty in estimates

There are many factors that influence the global aggregated effects of NDCs. There is limited literature on systematically analysing the impact of uncertainties on the NDC projections with some exception (Benveniste et al. 2018; Rogelj et al. 2017). The UNEP Gap Report (UNEP 2017a) discusses uncertainties of NDC estimates in some detail. The main factors include variations in overall socio-economic development; uncertainties in GHG inventories; conditionality; targets with ranges or for single years; accounting of biomass; and different GHG aggregation metrics (e.g., GWP values from different IPCC assessments).

Some studies assume successful implementation of all of the NDCs' proposed measures, sometimes including varying assumptions to account for some of the NDC features which are subject to assumed conditions related to finance and technology transfer. Countries "shall pursue domestic mitigation measures" under Article 4.2 of the Paris Agreement (UNFCCC 2015c), but they are not legally bound to the result of reducing emissions (Winkler 2017a). Some authors consider this to be a lack of a strong guarantee that mitigation targets in NDCs will be implemented (Nemet et al. 2017). Others point to growing extent of national legislation to provide a legal basis for action (Iacobuta et al. 2018) (see Chapter 13). These factors together with incomplete information in NDCs mean there is uncertainty about the estimates of anticipated 2030 emission levels.

The aggregation of targets results in large uncertainty (Rogelj et al. 2017). In particular, clarity on the contributions from the land use sector to NDCs is needed "to prevent high LULUCF uncertainties from undermining the strength and clarity of mitigation in other sectors" (Fyson and Jeffery 2019). Methodological differences in LULUCF emission accounting between scientific studies and national GHG inventories (as submitted to UNFCCC) further complicate the comparison and aggregation of emissions of NDC implementation (Grassi et al. 2018, 2020)(see Section 7.2.3 and Cross-Chapter Box 3). This uncertainty could be reduced with clearer guidelines for compiling future NDCs and explicit specification of technical details, including energy accounting methods, harmonised emission inventories (Rogelj et al. 2017) and finally, increased transparency and comparability (Pauw et al. 2018).

Cross-Chapter Box 3 Comparison of NDCs and current policies with the 2030 GHG emissions from long-term temperature pathways

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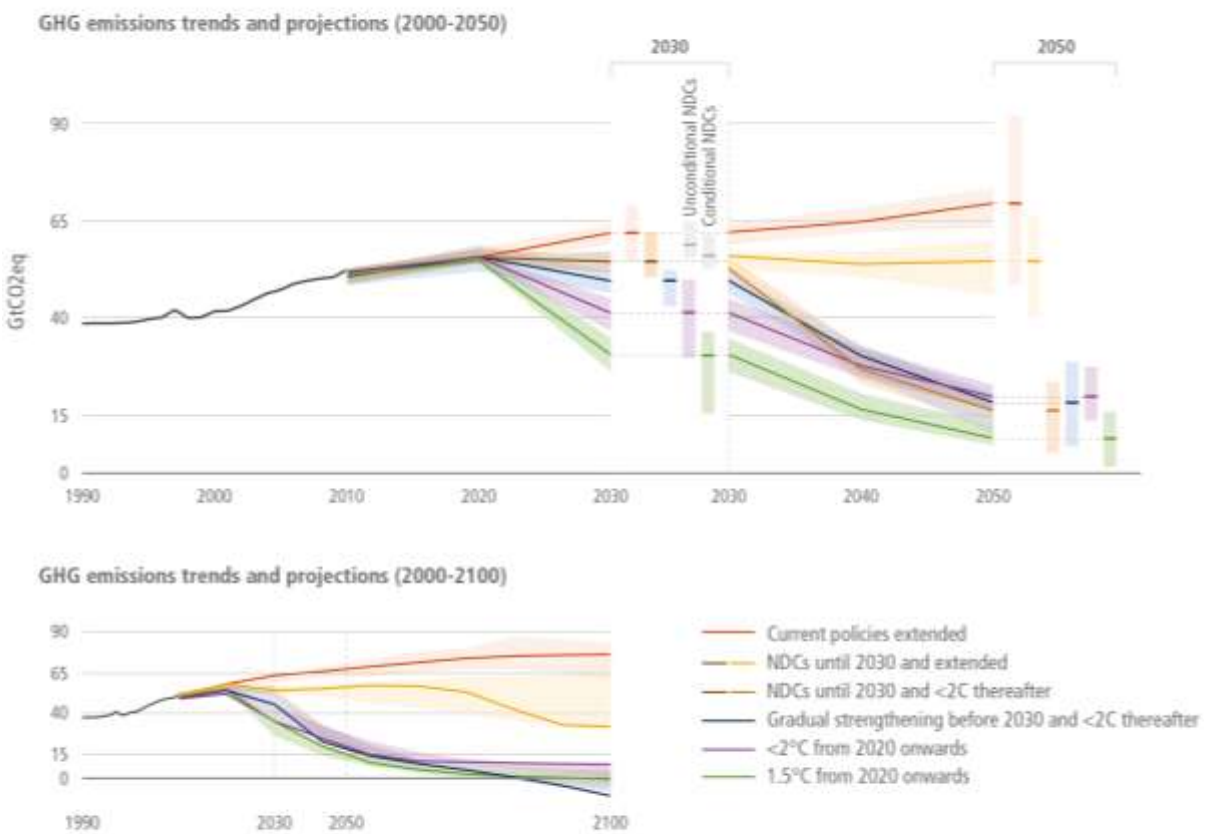
Introduction

The Paris Agreement (PA) sets a long-term goal of holding the increase of global average temperature to ‘well below 2°C above pre-industrial levels’ and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels. This is underpinned by the ‘aim to reach global peaking of greenhouse gas emissions as soon as possible’ and ‘achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century’ (UNFCCC 2015d). The PA adopts a bottom-up approach in which countries determine their contribution to reach the PA’s long-term goal. These national targets, plans and measures are called ‘nationally determined contributions’ or NDCs.

The NDCs are the central instrument of the PA to achieve its long-term goal. It thus combines a global goal with a country-driven (bottom-up) instrument to a hybrid climate policy architecture to strengthen the global response to climate change. All signatory countries committed to communicating nationally determined contributions including mitigation targets, every five years. While the NDCs mostly state targets, countries are also obliged to pursue domestic mitigation measures to achieve the objectives. The literature examines the emissions outcome of the range of policies implemented to reach these targets.



Cross-Chapter Box 3, Figure 1 Aggregate GHG emission outcomes of NDCs and long-term mitigation pathways consistent with global temperature limits. Shown are emission ranges that would emerge when

assuming the full implementation of current unconditional and conditional NDCs (grey bars, median and full range) and global pathways from the AR6 scenario database that can be grouped into six types: pathways with near-term emissions developments in line with (1) current policies and (2) NDCs, respectively, and extended with comparable ambition levels beyond 2030, pathways holding warming below 2°C (66% chance) with near term emissions developments reflecting (3) ambition levels in current NDCs and (4) a gradual strengthening of mitigation action beyond NDCs, respectively, and mitigation pathways undertaking immediate action from 2020 onwards towards (5) holding warming below 2°C (66% chance) and (6) limiting warming to 1.5°C by 2100 with low (<0.1°C) overshoot (50% chance), respectively. The upper panel shows the emission pathways until 2050 (median and 25th-75th percentiles) with their emissions ranges in 2030 and 2050 broken out in full (median and 5th-95th percentiles). The lower panel shows the ranges (25th -75th percentiles) for the six types of emissions pathways over the 21st century and a selection of five associated illustrative pathways (IPs).

Notes: GHG emissions are expressed in CO_2-equivalent based on 100-year GWPs from AR6. Projected emissions for the current policies and NDCs scenarios from Section 4.2.2 (Table 4.1) show median and full range. The policy cut-off dates of individual studies are listed in Table S4.1 in the Supplementary Material of Chapter 4. Note that NDC estimates are based on the first round of submission to the UNFCCC and do not include recent updates most notably those that have been submitted since November 2020. Historical GHG emissions are based on Chapter 2 assessment (Section 2.2.2). Selected IPs that match five of the six pathway types are: CurPol (current policies extended), ModAct (NDCs until 2030 and extended), <2-GS (gradual strengthening before 2030 and <2°C thereafter), <2-NBZ (<2°C from 2020 onwards), and <1.5-SP (<1.5°C from 2020 onwards)

Emissions gap

A comparison between the projected emission outcomes of current policies, the NDCs (unconditional and conditional, see Section 4.2.2) and mitigation pathways acting immediately, i.e. from 2020 onwards, on reaching different temperature goals in the long-term (see Section 3.3.3) allows identifying different 'emission gaps' in 2030 (Figure 1). First, the implementation gap between 'current policies' and unconditional and conditional NDCs is estimated to be around 4 and 7 $GtCO_2eq$ in 2030, respectively (Section 4.2.2 and Table 4.1). Second, the comparison of unconditional (conditional) NDCs and cost-effective long-term mitigation pathways gives rise to a 2030 median emissions gap of 25-34 $GtCO_2eq$ (22-31 $GtCO_2eq$) for limiting warming to 1.5°C with no or low (<0.1°C) overshoot (50% chance) and 14-23 $GtCO_2eq$ (11-20 $GtCO_2eq$) for limiting warming to 2°C (66% chance)[b]. GHG emissions of NDCs are broadly consistent with 2030 emission levels of cost-effective long-term pathways staying below 3°C.

Other 'gap indicators'

Beyond the quantification of different GHG emissions gaps, there is an emerging literature that identifies gaps between current policies, NDCs and long-term temperature in terms of other indicators, including for example the deployment of low-carbon energy sources, energy efficiency improvements, fossil fuel production levels or investments into mitigation measures (Roelfsema et al. 2020; SEI et al. 2020; McCollum et al. 2018b).

A 2030 gap in the contribution of low-carbon energy sources to the energy mix in 2030 between current policies and cost-effective long-term temperature pathways is calculated to be around 7%-points (2°C) and 13%-points (1.5°C) by Roelfsema et al. (2020). The same authors estimate an energy intensity improvement gap 10% and 18% for 2030 between current policies pathways and 2°C and 1.5°C pathways, respectively. SEI et al. (2020) estimates the 'fossil fuel production gap', i.e. the level of countries' planned fossil fuel production expressed in their carbon content to be 120% and 50% higher compared to the fossil fuel production consistent with 1.5°C and 2°C pathways, respectively, as

FOOTNOTE: [b] The emission gap ranges provided here correspond to the difference between minimum and maximum emissions estimates of NDCs and the median of the 1.5 and 2°C pathways.

assessed in IPCC SR1.5 (Rogelj et al. 2018a). The methodology used for this estimation is very similar to how emissions gaps are derived (SEI et al. 2019, Appendix A). The gap of global annual average investments in low-carbon energy and energy efficiency in 2030 between following current policy on the one hand and achieving the NDCs, the 2°C and 1.5°C targets on the other hand, is estimated to be approximately USD 130, 320, or 480 billion per year (McCollum et al. 2018b).

It is important to note that such comparisons are less straight forward as the link between long-term temperature goals and these indicators is less pronounced compared to the emission levels themselves; they are therefore associated with greater uncertainty compared to the emissions gap.

Adaptation

NDCs have been an important driver of national adaptation planning, with cascading effects on sectors and sub-national action, especially in developing countries. Yet, only 40 developing countries have quantifiable adaptation targets in their current NDCs; 49 countries include quantifiable targets in their national legislation (UNEP 2018a).

The Working Group II contribution to this assessment finds that the overall extent of adaptation-related responses in human systems is low {*high confidence*} and that there is limited evidence on the extent to which adaptation-related responses in human systems are reducing climate risk (IPCC AR6 WGII, O'Neill et al. 2020, Section 16.3.2.3). Thus there is an adaptation gap (UNEP 2018a), and bridging that gap requires enablers including institutional capacity, planning and investment (UNEP 2016). Estimates of adaptation costs vary greatly across studies. Recent studies based on climate change under RCP8.5 report adaptation costs for developing countries of up to 400 (300 in RCP2.6) billion USD2005 in 2030 (IPCC AR6 WGII, New et al. 2020, Figure CCB FINANCE.1). Of the NDCs submitted in 2015, fifty countries estimated adaptation costs of USD 39 billion annually. Both public and private finance for adaptation is increasing, but remains insufficient and constitutes a small fraction (4-8%) of total climate finance which is mostly aimed at mitigation. The pledge of developed countries of mobilising finance for developing countries to address adaptation needs globally as part of the Paris Agreement are insufficient: By 2030 the adaptation needs are expected to be 3 to 6 times larger than what is pledged, further increasing towards 2050 (UNEP 2016). (IPCC AR6 WGII, Ch. 17, New et al. 2020)

4.2.3 Mitigation efforts in subnational and non-state action plans and policies

The decision adopting the Paris Agreement stresses the importance of "stronger and more ambitious climate action" by non-government and subnational stakeholders, "including civil society, the private sector, financial institutions, cities and other subnational authorities, local communities and indigenous peoples" (UNFCCC 2015e). Non-state actors, e.g., companies and civil society, and subnational actors, e.g. cities and regions, have emerged to undertake a range of largely voluntary carbon mitigation actions (Hsu et al. 2019, 2018) both as individual non-state actors (NSA in the following) and through national and international cooperative initiatives (ICIs) (Hsu et al. 2018). ICIs take a variety of forms, ranging from those that focus solely on non-state actors to those that engage national and even local governments. They can also range in commitment level, from primarily membership-based initiatives that do not require specific actions to those that require members to tackle emissions reductions in specific sectors or aim for transformational change.

Quantification of the (potential) impact of these actions is still limited. Almost all studies estimate the potential impact of the implementation of actions by NSA and ICI, but do not factor in that they may not reach their targets. The main reason for this is that there is very limited data currently available from individual actors (e.g., annual GHG inventory reports) and initiatives to assess their progress towards their targets. A few studies have attempted to assess progress of initiatives by looking into the initiatives' production of relevant outputs (Chan et al. 2018). Quantification does not yet cover all commitments and only a selected number of ICIs are analysed in the existing literature. Most of these studies exclude commitments that are not (self-)identified as related to climate change mitigation, those that are not connected to international networks, or those that are communicating in languages other than English.

Non state action could make significant contributions to achieving the Paris climate goals (*limited evidence, high agreement*). However, efforts to measure the extent to which non-state and subnational actors go beyond national policy are still nascent (Kuramochi et al. 2020; Hsu et al. 2019) and we do not fully understand the extent to which ambitious action by non-state actors is additional to what national governments intend to do. Subnational and non-state climate action may also have benefits in reinforcing, implementing, or piloting national policy, in place of or in addition to achieving additional emissions reductions (Broekhoff et al. 2015; Hsu et al. 2017; Heidrich et al. 2016).

Quantification of commitments by individual NSAs are limited to date. Attempts to quantify aggregate effects in 2030 of commitments by individual non-state and subnational actors are reported by (Kuramochi et al. 2020; Hsu et al. 2019). (Kuramochi et al. 2020) estimate potential mitigation by more than 1,600 companies, around 6,000 cities and many regions (cities assessed have a collective population of 579 million, and regions 514 million). Individual commitments by these subnational regions, cities and companies could reduce GHG emissions in 2030 by 1.2 to 2.0 $GtCO_2eq\ yr^{-1}$ compared to current national policies scenario projections, reducing projected emissions by 3.8%–5.5% in 2030, if commitments are fully implemented and do not lead to weaker mitigation actions by others (Figure 4.1 left). In several countries, NSA commitments could potentially help meet or exceed national mitigation targets.

Quantification of potential emission reductions from international cooperative initiatives have been assessed in several studies, and recently synthesised (Hsu et al. 2020; Lui et al. 2020), with some initiatives reporting high potential. In Table 4.2 and Figure 4.1, we report estimates of the emissions reductions from 19 distinct sub-national and non-state initiatives to mitigate climate change. The table shows wide ranges of potential mitigation based on current, target or potential membership, as well as a wide diversity of actors and membership assumptions. When adding up emission reduction potentials, sub-national and non-state international cooperative initiatives could reduce up to about 20 Gt of CO_2eq in 2030 (*limited evidence, medium agreement*).

Table 4.2 Emissions reduction potential for sub-national and non-state international cooperative initiatives by 2030

Sector	**Leading Actor**	**Name**	**Scale**	**Target(s)**	**2030 emissions reduction potential compared to no policy, current policies or NDC baseline (GtCO$_2$eq yr^{-1})**		**Membership assumptions**
					Min	***Max***	
Energy efficiency	Intergovernmental (UNEP)	United for Efficiency (U4E)	Global (focus on developing countries)	Members to adopt policies for energy-efficient appliances and equipment	0.6	1.25	Current membership
Energy efficiency	Intergovernmental	Super-efficient Equipment and Appliance Deployment (SEAD) Initiative	Global	Members to adopt current policy best practices for energy efficiency product standards	0.5	1.7 (excl. China)	Current membership
Buildings	Business	Architecture 2030	Global (focus on North America)	New buildings and major renovations shall be designed to meet an energy consumption performance standard of 70% below the regional (or country) average/median for that building type and to go carbon- neutral in 2030	0.2	0.2	Current membership
Transport	Business (aviation sector)	Collaborative Climate Action Across the Air Transport World (CAATW)	Global	Two key objectives: 1) 2% annual fuel efficiency improvement through 2050, 2) Stabilise net carbon emissions from 2020	0.3	0.6	Current membership
Transport	Business	Lean and Green	Europe	Member companies to reduce CO_2 emissions from logistics and freight activity by at least 25% over a five-year period	0.02	0.02	Current membership
Transport	Hybrid	Global Fuel Economy Initiative (GFEI)	Global	Halve the fuel consumption of the LDV fleet in 2050 compared to 2005	0.5	1.0	Current membership

Transport	Business	Below50 LCTPi [1)]	Global	Replace 10% of global transportation fossil fuel use with low-carbon transport fuels by 2030	0.5	0.5	Scaled-up global potential
Renewable energy	Business	European Technology & Innovation Platform Photovoltaic (ETIP PV)	Europe	Supply 20% of electricity from solar Photovoltaic PV technologies by 2030	0.2	0.5	Current membership
Renewable energy	Intergovernmental (African Union)	Africa Renewable Energy Initiative (AREI)	Africa	Produce 300 GW of electricity for Africa by 2030 from clean, affordable and appropriate forms of energy	0.3	0.8	Current membership
Renewable energy	Hybrid	Global Geothermal Alliance (GGA)	Global	Achieve a five-fold growth in the installed capacity for geothermal power generation and a more than two-fold growth in geothermal heating by 2030	0.2	0.5	Targeted capacity
Renewable energy	Business	REscale LCTPi [1)]	Global	Support deployment of 1.5 TW of additional renewable energy capacity by 2025 in line with the IEA's 2°C scenario	5	5	Scaled-up global potential
Renewable energy	Business	RE100 initiative	Global	2,000 companies commit to source 100% of their electricity from renewable sources by 2030	1.9	4	Targeted membership
Forestry	Hybrid	Bonn Challenge / Governors' Climate and Forests Task Force (GCFTF) / New York Declaration on Forests (NYDF)	Global	End forest loss by 2030 in member countries and restore 150 million hectares of deforested and degraded lands by 2020 and an additional 200 million hectares by 2030	3.8	8.8	Scaled-up global potential
Non-CO_2 emissions	Government	Climate & Clean Air Coalition (CCAC)	Global	Members to implement policies that will deliver substantial short-lived climate pollutant (SLCP) reductions in the near- to medium-term (i.e., by 2030) for HFCs and methane	1.4	3.8	Current membership
Non-CO_2 emissions	Intergovernmental	Zero Routine Flaring	Global	Eliminate routine flaring no later than 2030	0.4	0.4	Current membership

	(World Bank)						
Multisectoral	Cities and regions	Under2 Coalition	Global	Local governments (220 members) aim to limit their GHG emissions by 80 to 95% below 1990 levels by 2050	4.6	5	Current membership
Multisectoral	Cities and regions	Global Covenant of Mayors for Climate & Energy (GCoM)	Global	Member cities have a variety of targets (+9,000 members)	1.4	1.4	Current membership
Multisectoral	Cities and regions	C40 Cities Climate Leadership Group (C40)	Global	94 member cities have a variety of targets, aiming for 1.5°C compatibility by 2050. The network carries two explicit goals: 1) to have every C40 city develop a climate action plan before the end of 2020 (Deadline 2020), which is "deliver action consistent with the objectives of the Paris Agreement" and 2) to have cities achieve emissions neutrality by 2050	1.5	3	Current membership
Agriculture	Business	Climate Smart Agriculture (CSA) LCTPi [1)]	Global	Reducing agricultural and land-use change emissions from agriculture by at least 50% by 2030 and 65% by 2050. 24 companies and 15 partners	3.7	3.7	Scaled-up global potential
Multisectoral	Business	Science Based Targets initiative (SBTi)	Global	By 2030, 2,000 companies have adopted a science- based target in line with a 2°C temperature goal	2.7	2.7	Targeted membership

Source: (Hsu et al. 2020)

Note [1] As of December 2020 most of the LCTPi initiatives are defunct, except the Climate Smart Agriculture programme

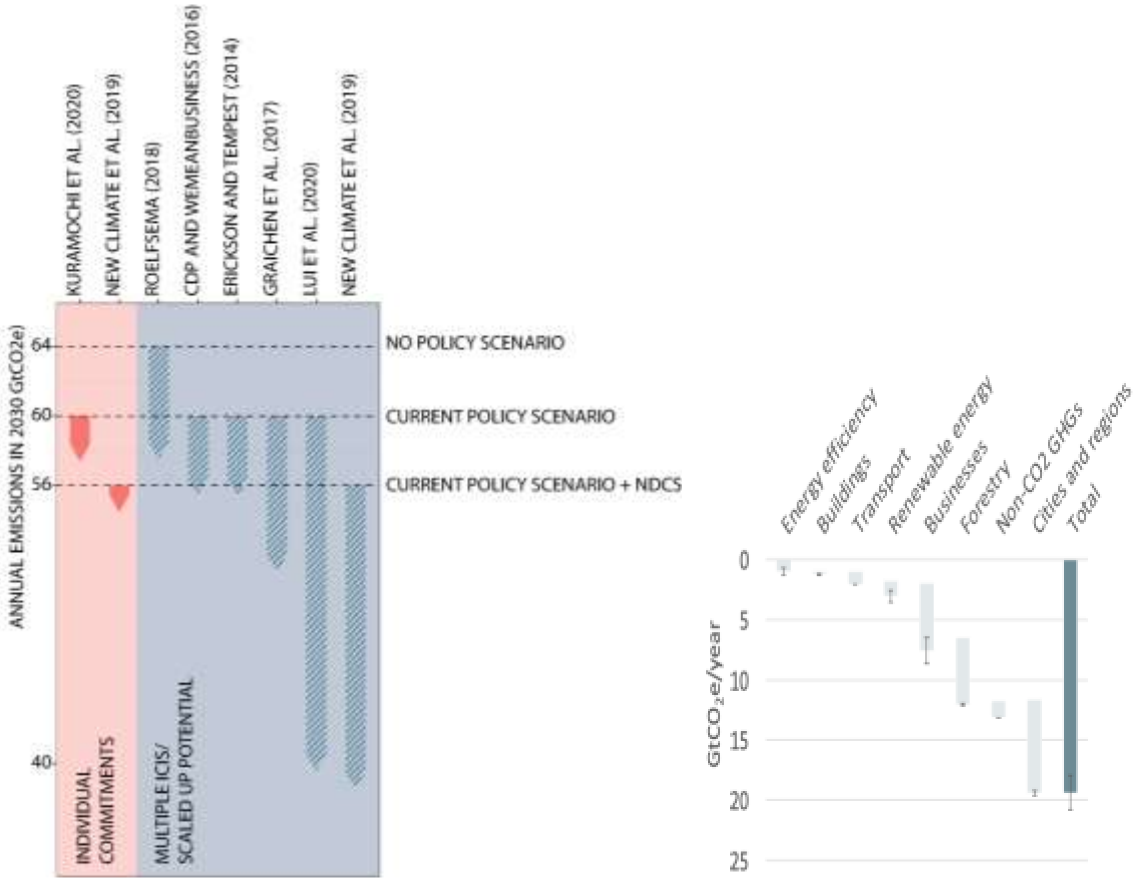


Figure 4.1 Emissions reduction potential for non-state and sub-national actors by 2030.

Source: Data in left panel from Hsu et al. (2020), right panel from Lui et al. (2020).

Non-state action may be broader than assessed in the literature so far, though subject to uncertainty. The examples in Table 4.2 and Figure 4.1 do not include initiatives that target the emissions from religious organisations, colleges and universities, civic and cultural groups, and, to some extent, households, and in this sense may underestimate sub-national potential for mitigating emissions, rather than overestimate it. That said, the estimates are contingent on assumptions that subnational and non-state actors achieve commitments – both with respect to mitigation and in some cases membership - and that these actions are not accounted for in nor lead to weakening of national actions.

Care is to be taken not to depict these efforts as additional to action within national NDCs, unless this is clearly established (Broekhoff et al. 2015). There are potential overlaps between individual NSA and ICI, and across ICIs – Kuramochi et al. (2020) propose partial and conservative partial effect methods to avoid double counting when comparing ambition, a matter that merits further attention. As the diversity of actions increased, the potential to count the same reductions multiple times increases.

Equally important to note here is that none of the studies reviewed in Figure 4.1 quantified the potential impact of financial sector actions, e.g., divestment from emission intensive activities (see Section 15.3 for a more detailed discussion of how financial actors and instruments are addressing climate change). Moreover, only a limited number of studies on the impact of actions by diverse actors go beyond 2050 (see

Table 4.2), which may reflect analysts' recognition of the increasing uncertainties of longer time horizons. Accurate accounting methods can help to avoiding counting finance multiple times, and methods across mitigation and finance would consider counting carbon market flows and the tons reduced. As Figure 4.1 and Table 4.2 indicate, activities by businesses have potential to significantly contribute to global mitigation efforts. For example, the SBTi (Science-Based Targets Initiative) encourages companies to pledge to reduce their emissions at rates which according to SBTI would be compatible with global pathways to well below 2°C or 1.5°C, with various methodologies being proposed (Faria and Labutong 2019; Andersen et al. 2020). Readers may note, however, that the link between emissions by individual actors and long-term temperature goals cannot be inferred without additional assumptions (see Box 4.1)

Initiatives made up of cities and subnational regions have an especially large potential to reduce emissions, due to their inclusion of many actors, across a range of different geographic regions, with ambitious emissions reduction targets, and these actors' coverage of a large share of emissions (Kuramochi et al. 2020). Hsu et al.(2019) find largest potential in that area. Several subnational regions like California and Scotland have set zero emission targets (Höhne et al. 2019), supported by short- and medium-term interim goals (Scottish Government 2020; State of California 2018). Sharing of effort across global and sub-global scales has not been quantified, though one study suggests that non-state actors have increasingly adopted more diverse framings, including vulnerability, human rights and transformational framings of justice (Shawoo and McDermott 2020). Initiatives focused on forestry have very high emissions reduction potential due to the current high deforestation rates, and due to the ambitious targets of many of these forestry initiatives, such as the New York Declaration on Forest's goal to end deforestation by 2030 (Höhne et al. 2019; Lui et al. 2020). On the other hand, uncertainties in global forest carbon emissions (and therefore potential reductions) are high and despite a multitude of initiatives in the sector, actually measured deforestation rates have not declined since the initiative was announced in 2014 (see Chapter 7).

Initiatives focused on non-CO_2 emissions, and particularly on methane, can achieve sizable reductions, in the order of multiple $GtCO_2eq\ yr^{-1}$ (see Table 4.2). The Global Cement and Concrete Association (formerly the Cement Sustainability Initiative), which includes 30% of the world's cement production, has contributed to the development of consistent energy and emissions reporting from member companies in its nearly 20-year history. The CSI also suggested possible approaches to balance GHG mitigation and the issues of competitiveness and leakage (Cook and Ponssard 2011). The member companies of the GCCA (CSI) have become better prepared for future legislation on managing GHG emissions and developed management competence to respond to climate change compared to non-member companies in the cement sector (Busch et al. 2008).

It is also important to note that individual NSA and ICI that commit to GHG mitigation activities are often scarce in many crucial and 'hard-to-abate' sectors, such as iron and steel, cement and freight transport (see Chapters 10 and 11). Subnational and non-state action efforts could help these sectors meet an urgent need to accelerate the commercialisation and uptake of technical options to achieve low zero emissions (Bataille 2020). Discourse analysis finds five storylines in urban governance texts that support transformation of cities to carbon neutrality – the diverse meanings of carbon neutrality, new economy, city as laboratory, technological fixes and reframing 'good' urban citizenship (Tozer and Klenk 2018).

4.2.4 Mid-century low-emission strategies at the national level

An increasing amount of literature describes mitigation pathways for the mid-term (up to 2050). We assess literature reflecting on the UNFCCC process (Section 4.2.4.1), other official plans and strategies (4.2.4.2) and academic literature on mid-century low-emission pathways at the national level (4.2.4.3). At time of writing, a limited number of countries had already submitted their long-term low GHG emission development strategies to the UNFCCC, though more had adopted mid-term mitigation strategies. After the Paris Agreement and the IPCC SR1.5 Report, the number of academic papers analysing domestic emission pathways compatible with the 1.5°C target has been increasing. Interest in net zero emissions is also growing, as suggested inter alia by the fact that more than 100 countries are already part of the Climate Ambition Alliance: Net Zero 2050. Overall, Governments have developed an increasing number of mitigation strategies up to 2050 (mid-term). Several among these strategies aim at net-zero or carbon neutrality, but it is not yet possible to draw global implications due to the limited size of sample (*limited evidence, limited agreement*).

Box 4.1 Direct links between an individual actor's mitigation efforts in the near-term and global temperature goals in the long-term cannot be inferred; making direct links requires clear distinctions of spatial and temporal scales and explicit treatment of ethical judgements made

Global average temperature in 2100 will depend on the sum of all countries' GHG emissions all the way to that point in time. Global warming, to an approximation, is a function of cumulative emissions over time. It is not the function of any single country's mitigation efforts, nor any individual actor's. As a result, individual country emission pathways in the near- to mid-term cannot be linked to a long-term temperature without additional assumptions specifying (i) the GHG emissions and removals of other countries up the mid-term; and (ii) the GHG emissions and removals of all countries beyond the near- and mid-term. In fact, a given emission pathway in the near- to mid-term at the national level could be tied to *any* long-term temperature level, depending on the assumptions made about other countries, and emissions and removals beyond the target dates. Nonetheless, the literature on national mitigation pathways frequently refers to mitigation pathways up to 2030 or 2050 using long-term temperature limits in the Paris Agreement (i.e., "2°C" or "1.5°C scenario"). The assumptions made about mitigation efforts in other countries as well as about emissions beyond 2030 or 2050 are not always explicit. When they are, three main routes are typically followed: (i) divide a global mitigation pathway consistent with the long-term temperature via an explicit effort sharing scheme across countries (see 4.2.2.6 and 4.5); (ii) derive from a global IAM a uniform carbon price trajectory necessary to reach a given long-term temperature, and apply it to a country model—in that case the assumptions about emissions in other countries remain implicit; and (iii) assuming all countries follow the same path, such as all reaching net-zero GHG emissions in 2050 (not required under the Paris Agreement, but a typical way of modelling pathways consistent with the 1.5°C limit in the literature, see section 4.2.4).

4.2.4.1 GHG Mitigation target under UNFCCC and Paris Agreement

The Paris Agreement requests that Parties should strive to formulate and communicate long-term low GHG development strategies by 2020. (Note that by "long-term", the UNFCCC means 2050, which is the end point of the "mid-term" horizon range in the present report.) As of December 17, 2020, 26 countries had submitted long-term strategies (Table 4.3).

Most long-term strategies target 80% emissions reduction in 2050 relative to a reference (1990, 2000 or 2005). In addition, the number of the countries with net zero GHG or GHG neutrality targets by 2050 has been increasing after IPCC SR1.5 was published. In Germany, for example, the long-term target was updated from 80-95% reduction of GHG emissions in 2050 relative to 1990 level to GHG neutrality by 2050.

Table 4.3 Countries submitting long-term low GHG emission development strategy (as of December 17, 2020)

[NOTE: In final version of Chapter 4, this Table might be replaced by reference to relevant summary table of long-term strategies on the UNFCCC website, https://unfccc.int/process/the-paris-agreement/long-term-strategies]

Country	Date submitted	GHG reduction target
USA	Nov. 16, 2016	80% reduction of GHG in 2050 compared to 2005 level
Mexico	Nov. 16, 2016	50% reduction of GHG in 2050 compared to 2000 level
Canada	Nov. 17, 2016	80% reduction of GHG in 2050 compared to 2005 level
Germany	Nov. 17, 2016 Rev: Apr. 26, 2017 Rev. May 4, 2017	Greenhouse gas neutrality by 2050 (Old target: 80-95% reduction of GHG in 2050 compared to 1990 level)
France	Dec. 28, 2016 Rev: Apr. 18, 2017	75% reduction of GHG in 2050 compared to 1990 level
Benin	Dec. 12, 2016	
Czech Republic	Jan. 15, 2018	80% reduction of GHG in 2050 compared to 1990 level
UK	April 17, 2018	80% reduction of GHG in 2050 compared to 1990 level
Ukraine	July 30, 2018	66-69% reduction of GHG in 2050 compared to 1990 level
Republic of the Marshall Islands	Sept. 25, 2018	Net zero greenhouse gas emissions by 2050
Fiji	Feb. 25, 2019	Negative emissions in 2050 (Very High Ambition scenario)
Japan	June 26, 2019	80% reduction of GHG in 2050, and decarbonised society as early as possible in the 2nd half of 21st century
Portugal	Sept. 20, 2019	Carbon neutrality by 2050
Costa Rica	Dec. 12, 2019	Decarbonised economy with net-zero emissions by 2050
European Union	March 6, 2020	Net-zero GHG emissions by 2050
Slovakia	March 30, 2020	Climate neutrality by 2050
Singapore	March 31, 2020	Halving emissions from its peak to 33 $MtCO_2eq$ by 2050, with a view to achieving net-zero emissions as soon as viable in the second half of the century.
South Africa	Sep. 23, 2020	Net zero carbon economy by 2050
Finland	Oct.5, 2020	Carbon neutrality by 2035; 87.5-90% reduction of GHG in 2050 to 1990 level (excluding land use sector)
Norway	Nov. 25, 2020	Being a low-emission society by 2050
Latvia	Dec. 9, 2020	Climate neutrality by 2050 (non-reducible GHG emissions are compensated by removals in the LULUCF sector)
Spain	Dec. 10, 2020	
Belgium	Dec. 10, 2020	

Austria	Dec. 11, 2020	Climate-neutral by no later than 2050
Netherlands	Dec. 11, 2020	Reduction of GHG emissions by 95% by 2050 compared to 1990 level.
Sweden	Dec. 11, 2020	Zero net emissions of greenhouse gases into the atmosphere latest by 2045

4.2.4.2 Other national emission pathways to mid-century

At the 2019 Climate Action Summit, a total of 77 countries indicated their aim to reach net zero CO_2 emissions by 2050. Several countries have adopted official mitigation strategies all the way up to 2050, that are not yet reflected in the communications to the UNFCCC (Table 4.4). Table 4.4 lists the countries that have a national net zero target in laws, strategies or other communications by 2050 (The Energy and Climate Intelligence Unit 2019). Bhutan and Suriname have achieved carbon neutrality. France second "low-carbon national strategy" adopted in 2020 has an objective of carbon neutrality by 2050 (about 55 $MtCO_2$ gross emissions, offset by domestic carbon sinks in agriculture and forestry). Net zero is also the basis of the recent revision of the official notional price of carbon for public investment in France (Quinet et al. 2019). The Committee on Climate Change of the UK shows the necessary options in each sector to reach net zero GHG emissions and it concludes that delivering net-zero GHGs by 2050 is technically feasible but highly challenging (Committee on Climate Change 2019). Germany has introduced a three-step path to climate neutrality by 2050; The first step is a 65% reduction of emissions relative to 1990 levels by 2030. The second step is a complete switch to climate- neutral technologies, leading to a 95% cut in emissions. The third step is the balancing of residual emissions through carbon capture and storage (Görz et al. 2020). In addition to the countries in Table 4.4, EU reported net zero GHG emission pathways by 2050 under the Green Deal (European Commission 2019). Many other countries in the world discuss their targets. China and Korea have not yet submitted their long-term strategies to UNFCCC, but they have announced they would aim at carbon neutrality by 2060 and net zero GHG emission by 2050, respectively (UN 2020a,b). Japan's new target for net zero GHG emissions by 2050 was announced in 2020 (UN 2020c). As of November 30, 2020, a total of 121 countries participated in Climate Ambition Alliance: Net Zero 2050 together with businesses, investors, cities and regions.

Table 4.4 Countries with a national net zero target by 2050 (as of November 30, 2020)

[*NOTE: In final version of Chapter 4, this Table might be replaced by reference to relevant summary table of Net Zero Tracker website; https://eciu.net/netzerotracker*]

Country	Target year	Target status	Source
Suriname		Achieved	Suriname INDC
Bhutan		Achieved	Royal Government of Bhutan National Environment Commission
Hungary	2050	In Law	Climate Ambition Alliance: Net Zero 2050
United Kingdom	2050	In Law	The Climate Change Act
Sweden	2045	In Law	Climate Policy Framework
New Zealand	2050	In Law	Zero Carbon Act
France	2050	In Law	Energy and Climate Law

Denmark	2050	In Law	The Climate Act
Slovenia	2050	In Policy Document	Integrated National Energy and Climate Plan
Austria	2040	In Policy Document	Integrated National Energy and Climate Plan for Austria
Switzerland	2050	In Policy Document	Climate Neutral Switzerland
Ireland	2050	In Policy Document	Climate Action Plan 2019
Portugal	2050	In Policy Document	Roadmap for Carbon Neutrality by 2050
Norway	2050	In Policy Document	Norwegian Climate Act
Marshall Islands	2050	In Policy Document	2050 Climate Strategy
Iceland	2040	In Policy Document	Climate Action Plan 2018 - 2030
Germany	2050	In Policy Document	Climate Action Plan 2050
Finland	2035	In Policy Document	Carbon Neutral Finland
Costa Rica	2050	In Policy Document	National Decarbonisation Plan
China	2060	In Policy Document	Xi Jinping's UN General Assembly address
Japan	2050	In Policy Document	Speeches and Statements by the Prime Minister
South Africa	2050	In Policy Document	South Africa Low Emission Development Strategy 2050
Chile	2050	Proposed Legislation	Chile charts path to greener future
European Union	2050	Proposed Legislation	European Climate Law
Spain	2050	Proposed Legislation	Spain declares climate emergency
Fiji	2050	Proposed Legislation	Fiji Low Emission Development Strategy
Korea	2050	Proposed Legislation	Speeches and Statements by the President

4.2.4.3 Mid-century low emission strategies at the national level in the academic literature

Since the 2000s, an increasing number of studies have quantified the emission pathways to mid-century by using national scale models. In the early stages, the national emission pathways were mainly assessed in the developed countries such as Germany, UK, France, the Netherlands, Japan, Canada, and USA. In Japan, for example, the 2050 Japan Low-Carbon Society scenario team (2008) assessed a 70% reduction scenario, and summarised the necessary measures to “Dozen Actions towards Low-Carbon Societies.”

In the developing countries, China, India, South Africa assessed their national emission pathways. For example, a Scenario Building Team (2007) quantified the Long Term Mitigation Scenarios for South Africa. It shows the sectoral emission reduction potential and marginal cost corresponding to 4 different “with additional measures” in South Africa.

Prior to COP21, most of the literature on mid-century mitigation pathways at the national level was dedicated to pathways compatible with a 2°C limit (see Box 4.1 for a discussion on the relationship between national mitigation pathways and global, long-term targets). After COP21 and the IPCC special report on 1.5°C, more attention is being paid to scenarios that reach net-zero emissions by 2050.

Figure 4.2 provides a snapshot of this literature. For a selected set of countries, it shows the mid-century emission pathways at national scale that have been registered in the IIASA national mitigation scenario database built for the purpose of this Report (see Annex C section II.3). Overall, the database contains scenarios for 50 countries. Total GHG emission are the most comprehensive information to assess the pathways on climate mitigation actions, but energy-related CO_2 emissions are the most widely populated data in the scenarios. As a result, Figure 4.2 shows energy-related CO_2 emission trajectories. Scenarios for EU countries show reduction trends even in the reference scenario, whereas developing countries and non-European developed countries such as Japan and USA show emissions increase in the reference. In most countries plotted on Figure 4.2, studies have found that reaching net zero energy related CO_2 emissions by 2050 is feasible, although the number of such pathways is limited.

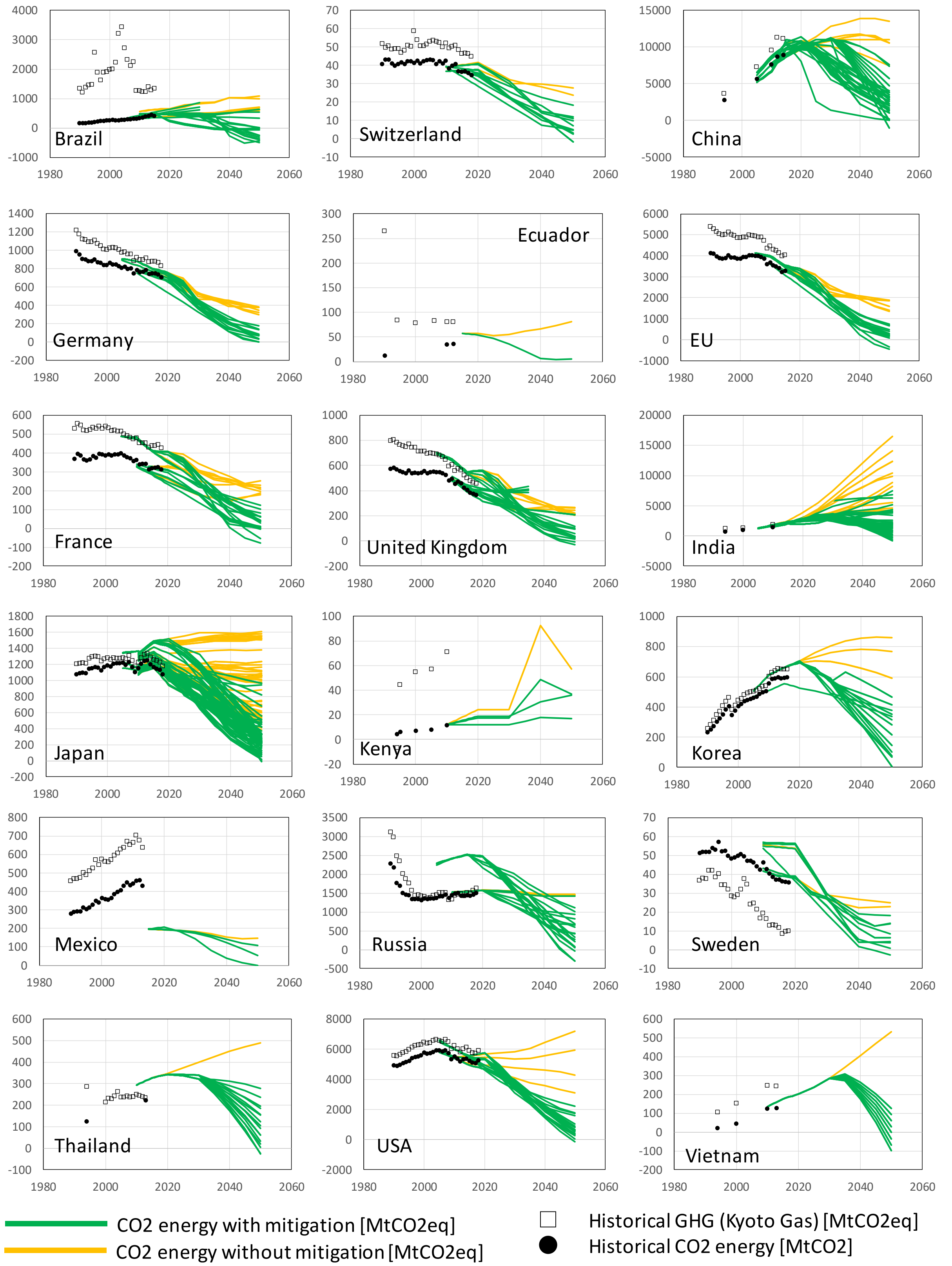


Figure 4.2 Energy related CO_2 emission pathways to mid-century from existing studies (Unit: $MtCO_2$)

Source of the historical data: Greenhouse Gas Inventory Data of UNFCCC (https://di.unfccc.int/detailed_data_by_party)

[Note: When the AR6 national database is updated, these figures will be updated.]

The literature underlines the differences induced by the shift from "2°C scenarios" (typically assumed to imply mitigation in 2050 around 80% relative to 1990) to 1.5°C scenarios (typically assumed to imply net-zero emissions in 2040) (see Box 4.1 on relationship between national pathways and global long term temperature goals). For example, Oshiro et al. (2018) shows the difference between the implications of a 2°C scenario (80% reduction of CO_2 in 2050) and a 1.5 °C scenario (net zero CO_2 emission in 2050) for Japan. For a net zero CO_2 emission scenario, Bioenergy with Carbon Capture and Storage (BECCS) is a key technology, and the emissions from energy sector in Japan have to be negative in 2050. The building and transport sectors will have to be almost zero, requiring energy efficiency improvement and electrification. Drastic reduction activities will have to be introduced immediately, and, as a result, the mitigation target in the present Japan's NDC is considered not sufficient to achieve a 1.5°C scenario. Jiang et al. (2018) also show the possibility of negative emissions in the power sector in China by 2050. Samadi et al. (2018) indicate the widespread use of electricity-derived synthetic fuels in end-use sectors as well as behavioural change for the 1.5 degree scenario in Germany.

In addition to those analyses, Vishwanathan et al. (2018), Chunark and Limmeechokchai (2018) and Pradhan et al. (2018b) developed national scenarios in India, Thailand and Nepal, respectively, compatible with a global 1.5°C. Unlike the studies mentioned in the previous paragraph, they translate the 1.5°C goal by introducing in their model a carbon price trajectory estimated by global models as sufficient to achieve the 1.5°C target. Because of the high economic growth and increase of GHG emissions in the reference case, CO_2 emissions in 2050 do not reach zero. Finally, the literature also underlines that to achieve a 1.5°C target, mitigation measures relative to non-CO_2 emissions become important, especially in developing countries where the share of non-CO_2 emissions is relatively high. La Rovere et al. (2018) consider mitigation actions in AFOLU sector.

Chapter 3 reported on multi-model analyses, comparison of results using different models, of global emissions in the long term. At the national scale, multi-model analyses are still limited, though such analyses are growing as shown in Table 4.5. By comparing the results among different models and different scenarios in a country, the uncertainties on the emission pathways including the mitigation measures to achieve a given emission target can be assessed.

Table 4.5 Examples of research projects on country-level mitigation pathways in the near- to medium-term under the multi-national analyses

Project name	Features
DDPP (Deep Decarbonisation Pathways Project)	16 countries participated and estimated the deep decarbonisation pathways from the viewpoint of each country's perspective using their own models (Waisman et al. 2019).
COMMIT (Climate Policy assessment and Mitigation Modelling to Integrate national and global Transition pathways)	This research project assessed the country contributions to the target of the Paris Agreement (COMMIT 2019).
MAPS (Mitigation Action Plans and Scenarios)	The mitigation potential and socio-economic implications in Brazil, Chile, Colombia and Peru were assessed (La Rovere et al. 2018; Benavides et al.

	2015; Zevallos et al. 2014; Delgado et al. 2014). The experiences of the MAPS programme suggests that co-production of knowledge by researchers and stakeholders strengthens the impact of research findings, and in depth studies of stakeholder engagement provide lessons (Boulle et al. 2015; Raubenheimer et al. 2015; Kane and Boulle 2018), which can assist building capacity for long-term planning in other contexts (Calfucoy et al. 2019).
CD-LINKS (Linking Climate and Development Policies – Leveraging International Networks and Knowledge Sharing)	The complex interplay between climate action and development at both the global scale and some national perspectives were explored. The climate policies for G20 countries up to 2015 and some levels of the carbon budget are assessed for short-term and long-term, respectively (Rogelj et al. 2017).
APEC Energy Demand and Supply Outlook	Total 21 APEC countries assessed 2 degree scenario which follows the carbon emissions reduction pathway included in the IEA Energy Technology Perspectives (IEA 2017) by using the common framework (APERC 2019).
Low-Carbon Asia Research Project	The low carbon emission scenarios for several countries and cities in Asia were assessed by using the same framework (Matsuoka et al. 2013). The mitigation activities were summarised into 10 actions toward Low Carbon Asia to show a guideline to plan and implement the strategies for an LCS in Asia (Low-Carbon Asia Research Project 2012).
CLIMACAP–LAMP	This is an inter-model comparison exercise that focused on energy and climate change mitigation in Latin America (Clarke et al. 2016).
DDPP-LAC (Latin American Deep Decarbonisation Pathways project)	6 countries in Latin America analysed the activities in AFOLU (agriculture, forestry and land use) commonly (Bataille et al. 2020).
MILES (Modelling and Informing Low-Emission Strategies)	This is an international research project which covers 5 countries and 1 region in order to build capacity and knowledge on low-emissions development strategies both at a national and global level, by investigating the concrete implications of INDCs for the low-carbon transformation by and beyond 2030 (Spencer et al. 2015).

Another type of multi-model analysis is international, i.e., different countries join the same project and use their own national models to assess a pre-agreed joint mitigation scenario. By comparing the results of various national models, such projects help highlight specific features of each country. More robust mitigation measures can be proposed if different types of models participate. These activities can also contribute to the capacity building in developing countries.

4.2.5 What is to be done to accelerate mitigation?

This section describes insights on accelerating mitigation of GHG emissions that can be drawn from recent literature on pathways that are beyond NDCs in different regions and countries.

The literature reports an increasing number of accelerated mitigation pathways and of mitigation plans to implement acceleration. There is increasing understanding of the technical content of accelerated mitigation pathways, across different countries and regions. The literature, however, does not adequately include demand-side options and systems analysis, nor does it correctly capture the impact from non-CO_2 GHGs.

4.2.5.1 Drivers to accelerate mitigation

Research has shown that targets and pathways considered consistent with well below 2˚C or 1.5˚C (see Box 4.1) (including 80% reduction in 2050 from 1990, and 100% renewable electricity scenarios) are technically feasible, although significant increases in adoption of carbon capture and sequestration (CCS) and other carbon sinks, renewable energy, electrification, and other new and transformative technologies in demand sectors will be needed as well as increased end use energy efficiency. To be realised, higher carbon price and emission trading scheme may be needed, combined in policy packages with a range of other policy measures.

In China, India, Japan and other Southeast Asian countries, key drivers for more aggressive action related to climate change, have stemmed also out of regional concerns over health and air quality related to air pollutants and short-lived climate pollutants (Ashina et al. 2012; Kuramochi et al. 2017; Oshiro et al. 2018; Aggarwal 2017; Jiang et al. 2018; Dhar et al. 2018; Xunzhang et al. 2017; Khanna et al. 2019; China National Renewable Energy Centre 2019; Energy Transitions Commission and Rocky Mountain Institute 2019). In North America, a few pathway studies have focused on power sector decarbonisation in the U.S., and demand-side reductions in Canada (Hammond et al. 2020; Vaillancourt et al. 2017; Jayadev et al. 2020; Hodson et al. 2018; Victor et al. 2018; Bahn and Vaillancourt 2020). In Latin America, much of the existing pathways emphasise supply-side mitigation measures, finding that power sector and bioenergy (where resources are available) utilisation offers the greatest mitigation opportunities (Nogueira de Oliveira et al. 2016; Lap et al. 2020; Herreras Martínez et al. 2015; Arango-Aramburo et al. 2019). The European Union-28's recently announced 2050 climate neutrality goal is explored by pathways that emphasise complete substitution of fossil fuels with electricity, low carbon fuels, particularly renewables; demand reductions through efficiency and conservation, and novel fuels and end-use technologies (Capros et al. 2019; Zappa et al. 2019; Louis et al. 2020; Duscha, Vicki, Wachsmuth, Jakob, Eckstein, Johannes, Pfluger 2019). Africa's future pathways will be shaped by its goal of increasing energy access, and the limited literature so far has focused on cleaner expansion of power supply alongside end-use efficiency improvements (Hamilton and Kelly 2017; Oyewo et al. 2020, 2019; Wright et al. 2019).

4.2.5.2 Characteristics of accelerated mitigation pathways

Major characteristics of the reviewed accelerated mitigation pathways across different regions, including some pathways specifically identified by the authors as '1.5˚C compatible', are:

- Energy efficiency, conservation, and reducing energy use in all energy demand sectors (buildings, transport, and industry) are included in nearly all literature that addresses future demand growth (Jiang et al. 2013, 2016; Saveyn et al. 2012; Altieri et al. 2016; Hanaoka and Masui 2018; Thepkhun et al. 2013; Chilvers et al. 2017; Chiodi et al. 2013; Schmid and Knopf 2012; Oshiro et al. 2017a; Shahiduzzaman and Layton 2017; Fragkos et al. 2017; Elizondo et al. 2017; Ouedraogo 2017; Lee et al. 2018; Schiffer 2015; Deetman et al. 2013; Zhou et al. 2019; McNeil et al. 2016; Lefèvre et al. 2018; Sugiyama et al. 2019; Kato and Kurosawa 2019; Jacobson et al. 2019, 2017; Dioha and Kumar 2020; Dioha et al. 2019; Nieves et al. 2019; Oshiro et al. 2018; Kuramochi et al. 2017; Ashina et al. 2012; Vaillancourt et al. 2017; Khanna et al. 2019; Victor et al. 2018; Duscha, Vicki, Wachsmuth, Jakob, Eckstein, Johannes, Pfluger 2019; Hodson et al. 2018; Capros et al. 2019; Nogueira de Oliveira et al. 2016)
- Electrification of industrial processes (up to 50% for EU and China) and adoption of fuel-cell vehicles (30-60% for trucks in Canada) and district heating and cooling in industry, transport, and building sectors (Ashina et al. 2012; Chiodi et al. 2013; Deetman et al. 2013; Fragkos et al. 2017; Massetti 2012; Mittal et al. 2018; Oshiro et al. 2017b; Oshiro et al. 2018; Saveyn et al. 2012; Vaillancourt et al. 2017; Zhou et al. 2019; Xunzhang et al. 2017; Hammond et al. 2020; Jiang et al. 2018; Capros et al. 2019).
- Lower CO_2 emissions fuels, particularly renewable, non-fossil, and some biofuels, are seen as necessary in all pathways but the extent of deployment depends on resource availability. Some

countries have set targets of up to 100% renewable electricity, while others such as Brazil and France rely on increasing biofuels up to 40-45% of total or industry energy consumption by 2050.

- Carbon capture and storage (CCS) is considered necessary in many of the studies reviewed (Ashina et al. 2012; Chilvers et al. 2017; Jiang et al. 2013; Kuramochi et al. 2018; Herreras Martínez et al. 2015; Massetti 2012; Mittal et al. 2018; Oshiro et al. 2018; Xunzhang et al. 2017; Roberts et al. 2018; Solano Rodriguez et al. 2017; Thepkhun et al. 2013; Vishwanathan et al. 2018; Kato & Kurosawa, 2019; van der Zwaan et al., 2014). Beyond other measures, CO_2 removal (including CCS) from sources with no identified mitigation measures to reduce emissions are considered necessary to help achieve net negative emissions (Deetman et al. 2013; Massetti 2012; Solano Rodriguez et al. 2017). In particular, the potential deployment scale of CCS in accelerated mitigation pathways are on the order of up to 200 $MtCO_2$ yr^{-1} in Japan (Kato and Kurosawa 2019) and deployment in 33-50% of total electricity generation in Latin America (van der Zwaan et al. 2016). Some limitations of CSS are elaborated in section 3 below.

As assessed above, the literature reflects on increasing numbers of countries indicating aims to reach net zero CO_2 by 2050 (4.2.4, Table 4.4). These targets, together with those for net zero GHG emissions (see glossary entries on net zero CO_2 emissions and net zero GHG emissions), set visions for accelerating mitigation. Specific policies, measures and technologies are needed to reach such targets. These include, broadly, decarbonising electricity supply to produce net zero CO_2, including through renewable energy, radically more efficient use of energy than today; electrification of end-uses (including transport / electric vehicles; 4) dramatically lower use of fossil fuels than today; converting other uses to low- or zero-carbon fuels (e.g., hydrogen, bioenergy, ammonia) in hard-to-decarbonise sectors; and setting ambitious targets to reduce methane and short-lived climate forcers. Options are assessed in more detail in the following sections.

4.2.5.3 Accelerated decarbonisation of electricity through renewable energy

Power generation could decarbonise much faster with scaled up deployment of renewable energy and storage that are both relatively mature, available, and decreasing in costs. R&D investment to lower storage costs and improve performance will be needed. Higher penetration of renewable energy in the power sector is a common theme in the EU scenarios (EU has more zero emission electricity, phasing out coal in Germany, Ireland), U.S., China, and India, but also in resource-rich countries such as Brazil.

Figure 4.3 shows an increasing share of renewable electricity in most countries historically, with further increases projected in many decarbonisation pathways. Targets for very high shares of renewable electricity generation – up to 100% - are shown for a number of countries, with the global share projected to range from 60% to 70% for 1.5°C with no overshoot (C0) to below 2°C (C4) scenarios. Countries/states that have made rapid increases in shares of renewables and have set 100% targets include Scotland (target of 100% by 2020), Austria (2030) and Denmark (2035) and California (2045). The EU, in particular Germany, has also made significant progress, see Figure 4.3. 100% renewable adoption for electricity generation by 2050 is found to be feasible for 143 countries with only a 9% average increase in economic costs (considering all social costs) if annual electricity demand can be reduced by 57% (Jacobson et al. 2017, 2019). Studies for countries and regions with high shares of renewable energy include:

- The EU 2050 net climate neutrality goal can be met with 100% renewable power generation, including use of renewable electricity to produce hydrogen, biofuels, and synthetic hydrocarbons, but will require significant increases in transmission capacity (Duscha, Vicki, Wachsmuth, Jakob, Eckstein, Johannes, Pfluger 2019; Zappa et al. 2019). A 1.5C pathway for the EU includes 85% renewable generation, with battery, pumped hydro, and chemical storage for variable renewables (Capros et al. 2019).

- In France, for example, 100% renewable generation could include 62% from wind, 26% from solar PV, and 12% from ocean, but would require additional imports or curtailed demand to address variability issues (Krakowski et al. 2016).
- Other research (Schmid and Knopf 2012) suggests that reducing Germany's total CO_2 emissions by 85% in 2050 compared to 1990 levels requires phase-out of coal by 2020 and adoption of large-scale renewable generation.
- For South Africa to achieve its 2050 development and 2°C-compatible climate mitigation objectives through a rapid decarbonisation strategy, the electricity sector needs to decarbonise by phasing-out coal entirely by 2050 with accelerated adoption of solar PV; and wind generation; CCS is not considered feasible before 2025 (Altieri et al. 2015; Beck et al. 2013). Its abundant solar PV and wind resource potential and land availability suggest that greater than 75% power generation from solar PV and wind are feasible under accelerated decarbonisation pathways (Oyewo et al. 2019; Wright et al. 2019).
- For the U.S., accelerated mitigation pathways include up to 40% power generation from solar PV and wind by 2050 (Hodson et al. 2018; Jayadev et al. 2020). Renewable generation and nuclear are expected to contribute more than half of CO_2 reductions needed in 2050 for pathway consistent with maintaining 450ppm (Victor et al. 2018) .
- Under cost optimisation scenarios for Brazil, renewable energy including biomass could account for more than 30% of total electricity generation and in a high tax scenario, total CO_2 emission reductions could exceed 50% by 2050 (Nogueira de Oliveira et al. 2016), indicating policy intervention needs to happen to achieve accelerated transition.
- In Colombia, where hydropower resources are abundant and potential also exist for solar and wind, a 1.5C pathway would require 57% renewable power generation by 2050 (Arango-Aramburo et al. 2019).
- Japan sees a need for 25% of power generation from hydrogen with electrolysis to reduce CO_2 emissions by 80% by 2050, and hydrogen accounting for as much as 5-10% of total primary energy supply by 2050 in its deep mitigation scenarios (Kato and Kurosawa 2019; Sugiyama et al. 2019)
- One view of China's 1.5C pathway includes 59% renewable power generation, including 21% wind, 16.6% solar, 14% hydro, 7.6% biomass by 2050 (Jiang et al. 2018). India's 1.5C pathway also includes 52% renewable power generation including 34% from solar PV, 12% from wind, and 6% from hydro, and would require storage needs for 35% of generation (Parikh et al. 2018).

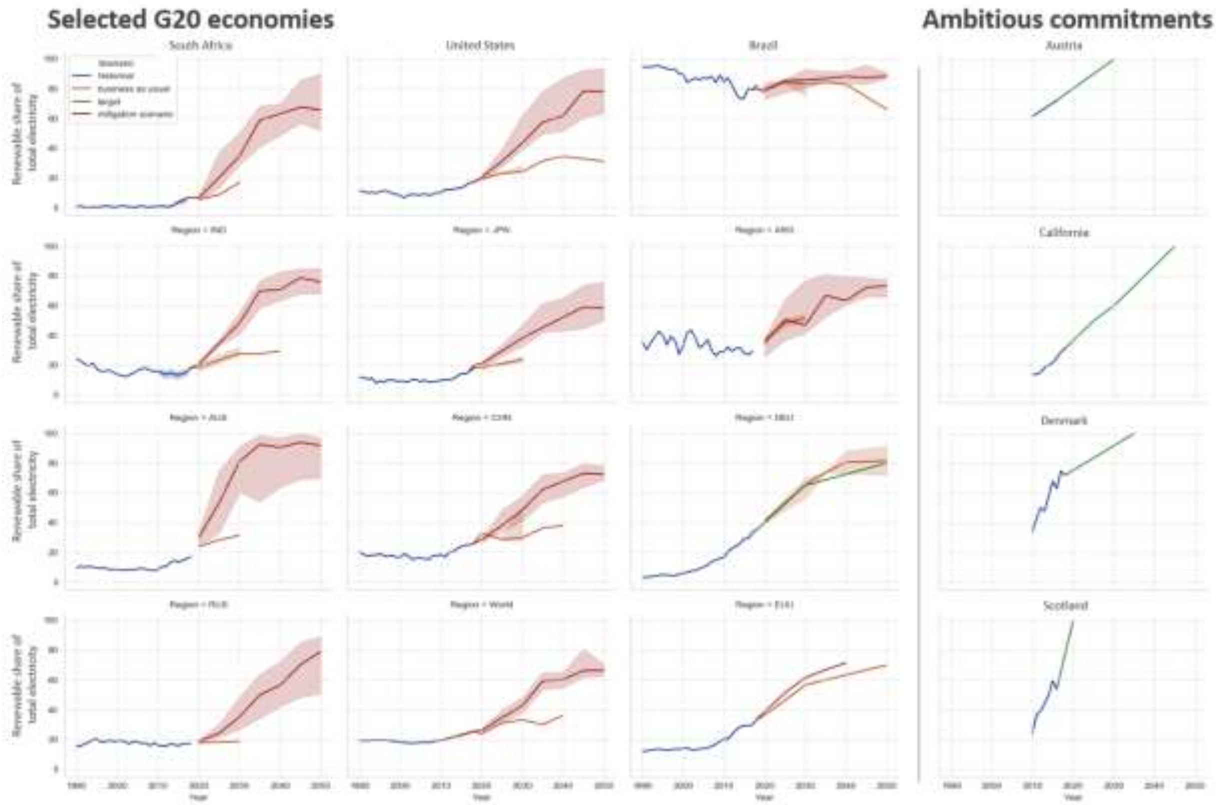


Figure 4.3 Historical and projected levels and targets for the share of renewables in electricity generation.

Sources: IEA energy balances for past trends, IPCC AR6 scenario dataset including national model and regional versions in global models (10th to 90th percentile of 1.5 with no overshoot (C0) to below 2°C (C4) scenarios), national / regional sources

4.2.5.4 Bioenergy plays significant role in resource abundant countries in Latin America and parts of Europe

Bioenergy could account for up to 40% of Brazil's total final energy consumption, and a 60% share of fuel for light-duty vehicles by 2030 (Lefèvre et al. 2018), and is considered most cost-effective in transport and industrial applications (Lap et al. 2020). BECCS in the power sector is also considered cost-effective option for supply-side mitigation (Herreras Martínez et al. 2015; Lucena et al. 2016; Borba et al. 2012).

Bioenergy also plays a prominent role in helping Northwest EU countries meet their 2050 CO_2 reduction targets that are consistent with below 2°C scenarios. Domestic biomass alone can help Germany meet its 95% CO_2 reduction by 2050 goal, and biomass and CCS together are needed to reduce CO_2 by 80% by 2050 in the Netherlands (Mikova et al. 2019). France's mitigation efforts also focus on biofuel and significant increases in biomass use, including up to 45% of industry energy by 2050 for its net GHG neutrality goal (Doumax-Tagliavini and Sarasa 2018; Capros et al. 2019)

While BECCS is needed in multiple accelerated mitigation pathways, large-scale land-based negative emissions technologies may not prove feasible or as effective as expected, and its large-scale deployment may result in ecological and social impacts, suggesting it may not be a viable carbon removal strategy in the critical 10-20 year window (Vaughan and Gough 2016; Boysen et al. 2017; Dooley and Kartha 2018). The effectiveness of BECCS could depend on choice of biomass, fate of initial above ground biomass, fossil fuel emissions offset – carbon removed through BECCS could be offset by losses due to land-use change (Harper et al. 2018). Large-scale BECCS may push planetary boundaries for freshwater use, exacerbate land-system change, significantly alter biosphere integrity and biogeochemical flows (Heck et al. 2018).

4.2.5.5 CCS may be needed to mitigate emissions from the remaining fossil fuels that cannot be decarbonised, but the economic feasibility of deployment is not yet clear

In Brazil, BECCS and CCS in hydrogen generation are more feasible while CCS in thermal power plants is considered more challenging, and costs could range from USD70 – 100/t CO_2 (Nogueira de Oliveira et al. 2016; Lucena et al. 2014).

In China, CCS as seen as necessary for remaining coal and natural gas generation out to 2050 (Jiang et al. 2018; Energy Transitions Commission and Rocky Mountain Institute 2019). Seven to 10 CCS projects with installed capacity of 15 GW by 2020 and total CCS investment of 105 billion RMB (2010 RMB) are projected to be needed by 2050 under a 2°C compatible pathway (Jiang et al. 2016;Jiang et al. 2013; Lee et al. 2018). Under 1.5C pathway, China would need 100% CCS in the remaining 12% of power generation from coal and gas power and 250 GW of BECCS (Jiang et al. 2018). Combined with expanded renewable and nuclear development, total estimated investment of RMB 2.8 trillion is needed by 2020 / 2030, and RMB 2.9 trillion by 2050, equal to 5% of China's total GDP in 2020, 1.3% in 2030, and 0.6% in 2050 (Jiang et al. 2016).

In Japan, CCS and increased bioenergy adoption plus waste-to-energy and hydrogen-reforming from fossil fuel are all needed in the power sector (Ashina et al. 2012; Oshiro et al. 2017, 2018). CCS is needed to reach greater than 70% CO_2 reduction by 2050 (Kato and Kurosawa 2019).

In parts of the EU, after 2030, CCS also becomes profitable with expected rising CO_2 prices (Schiffer 2015) and is seen as necessary in some net GHG neutrality pathways (Capros et al. 2019). For France and Sweden, CCS and BECCS are needed to meet net GHG neutrality by 2050 goals (Millot et al. 2020).

For Italy, zero-emission electricity is achievable with a combination of renewable and coal, natural gas, and biomass equipped with CCS (Massetti 2012).

4.2.5.6 Nuclear power is considered strategic for some countries, while others plan to reach their mitigation targets without additional nuclear power.

Although not expected to have a significant role currently or in the future, nuclear energy is considered necessary as part of accelerated mitigation pathways in Brazil (Lucena et al. 2016).

In the USA, nuclear is expected to contribute 23% of CO_2 reductions needed to reduce GHG emissions by 80% from 2005 levels by 2050 (Victor et al. 2018). Deep power sector decarbonisation pathways could require 2.3x increase in nuclear capacity (Jayadev et al. 2020).

For China to meet a 1.5C pathway or achieve carbon neutrality by 2050, 14% to 28% of power generation in 2050 would need to be from nuclear (Jiang et al. 2018; China National Renewable Energy Centre 2019; Energy Transitions Commission and Rocky Mountain Institute 2019).

France developed its nuclear strategy in response to energy security concerns after the 1970s Oil Crisis, but has now committed to reducing nuclear power generation to 50% by 2035 (Millot et al. 2020).

In Italy, nuclear development faces low public acceptance but could potentially help accelerate the energy transition with greater dispatchability and reliability. Reviving nuclear development would require more effective public campaigns on nuclear benefits and accelerated construction of final waste repositories (Bersano et al. 2020).

Some analyses find deep mitigation pathways, including net carbon neutrality and 80-90% reduction from 2013 levels, are possible for EU-28 and Japan, respectively, without additional nuclear power, but would require a combination of bio- and novel fuels and CCS or land-use based carbon sinks (Kato and Kurosawa 2019; Duscha, Vicki, Wachsmuth, Jakob, Eckstein, Johannes, Pfluger 2019).

Radically more efficient use of energy than today, including electricity, is a complementary set of measures, explored in the following.

4.2.5.7 Efficient cooling, SLCFs and co-benefits

In warmer climate regions undergoing economic transitions, improving the energy efficiency of cooling and refrigeration equipment is often important for managing peak electricity demand and can have co-benefits for climate mitigation as well as short-lived climate forcers (SLCF) reduction, as expected in India, Africa, and Southeast Asia in the future.

- In South Africa, key strategies for combating expected CO_2 emissions growth from increased energy access and electrification include improving industry and building energy efficiency and more use of renewables including biomass (Ouedraogo 2017; Altieri et al. 2016).
- Air conditioner adoption is rising significantly in low- and middle-income countries as incomes rise and average temperatures increase, including in Southeast Asian countries such as Thailand, Indonesia, Vietnam, and the Philippines, as well as Brazil, Pakistan, Bangladesh, and Nigeria (Biardeau et al. 2020). Cooling appliances are expected to increase from 3.6 billion to 9.5 billion by 2050, though up to 14 billion could be required to provide adequate cooling for all (Birmingham Energy Institute 2018). Current technology pathways are not sufficient to deliver universal access to cooling or meet the 2030 targets under the UN Sustainable Development Goals, but energy efficiency, including in equipment efficiency like air conditioners, can reduce this demand and help limit additional emissions that would further exacerbate climate change (UNEP and IEA 2020; Dreyfus et al. 2020; Biardeau et al. 2020). Some countries (India, South Africa) have started to recognise the need for more efficient equipment in their mitigation strategies (Paladugula et al. 2018; Altieri et al. 2016; Ouedraogo 2017).
- One possible synergy between SLCF and climate change mitigation is the simultaneous improvement in energy efficiency in refrigeration and air-conditioning equipment during the hydrofluorocarbon (HFC) phase-down, as recognised in the Kigali Amendment to the Montreal Protocol. The Kigali Amendment and related national and regional regulations are projected to reduce future radiative forcing from HFCs by about half in 2050 compared to a scenario without any HFC controls, and to reduce future global average warming in 2100 from a baseline of 0.3-0.5°C to less than 0.1°C, according to a recent scientific assessment of a wide literature (World Meteorological Organization (WMO) 2018). If ratified by signatories, the rapid phase-down of HFCs under the Kigali Amendment is possible because of extensive replacement of high-global-warming-potential (GWP) HFCs with commercially available low-GWP alternatives in refrigeration and air-conditioning equipment. Each country's choices of alternative refrigerants will likely be determined by energy efficiency, costs, and refrigerant toxicity and flammability. National and regional regulations will be needed to drive technological innovation and development (Polonara et al. 2017).

4.2.5.8 Efficient buildings, cooler in summer, warmer in winter

Countries in cold regions often focus more on building sector GHG emissions mitigation measures such as improving building envelopes and home appliances, and electrifying space heating and water heating.

Japan expects continued electrification of both residential and commercial buildings to 65% and 79%, respectively, by 2050 to reach 70-90% CO_2 reduction from 2013 levels (Kato and Kurosawa 2019). Similarly, China's 1.5C pathway also requires 58% to 70% electrification of buildings (Jiang et al. 2018;

Energy Transitions Commission and Rocky Mountain Institute 2019; China National Renewable Energy Centre 2019).

For the EU-28 to reach net carbon neutrality, complete substitution of fossil fuels with electricity (up to 65% share), district heating, and direct use of solar and ambient heat are needed for buildings, such as increased use of solar thermal and heat pumps for heating (Duscha, Vicki, Wachsmuth, Jakob, Eckstein, Johannes, Pfluger 2019)

For the UK and Canada, improved insulation to reduce energy demand and efficient building appliances and heating systems are important building strategies needed to reduce emissions to zero by 2050 (Vaillancourt et al. 2017; Roberts et al. 2018a; Chilvers et al. 2017).

For Ireland, achieving 80%-95% emissions reduction below 1990 levels by 2050 also requires changes in building energy technology and efficiency, including improving building envelopes, fuel switching for residential buildings, and replacing service-sector coal use with gas and renewables (Chiodi et al. 2013).

4.2.5.9 Electrifying transport

Electrification of transport as a key end-use in tandem with power sector decarbonisation is expected to be a key strategy for deep CO_2 mitigation in many countries. Passenger transport and light duty freight can already be electrified, but electrifying heavy-duty road transport and fuel switching in aviation and shipping are much more difficult and have not been addressed in most of the recent research.

In Germany, widespread electrification of private vehicles is expected by 2030 (Schmid and Knopf 2012) while for the EU-28, 50% overall transport electrification (excluding feedstock) and 75% electrification of road transport is needed to reach net carbon neutrality (Duscha, Vicki, Wachsmuth, Jakob, Eckstein, Johannes, Pfluger 2019). In addition, novel fuels such as hydrogen, synthetic hydrocarbons and sustainable biogenic fuels are needed to decarbonise aviation and water transport to achieve net carbon neutrality (Duscha, Vicki, Wachsmuth, Jakob, Eckstein, Johannes, Pfluger 2019).

In India, electrification, hydrogen, and biofuels are key to decarbonising the transport sector (Dhar et al. 2018; Mittal et al. 2018; Vishwanathan et al. 2018). Under a 1.5C scenario, nearly half of the light-duty passenger vehicle stock needs to be electrified (Parikh et al. 2018).

In China, 1.5C-compatible pathway requires 39% electrification in transport (Jiang et al. 2018; China National Renewable Energy Centre 2019).

Similarly, in Canada, electrification of 59% of light-duty trucks and 23% of heavy-duty trucks are needed as part of overall strategy to reduce CO_2 emissions by 80% by 2050. In addition, hydrogen is expected to play a major role by accounting for nearly one-third of light-duty trucks, 68% of heavy-duty trucks, and 33% of rail by 2050 (Hammond et al. 2020).

4.2.5.10 Urban form meets information technology

Beyond technological measures, some densely populated countries including Germany, Japan, and India are exploring using information technology/internet-of-things to support mode-shifting and reduce mobility demand through broader behaviour and lifestyle changes (Aggarwal 2017; (Ashina et al. 2012); Canzler and Wittowsky 2016; Dhar et al. 2018; Vishwanathan et al. 2018).

In Japan, accelerated mitigation pathways consider the use of information technology and Internet of Things (IOT) to transform human behaviour and transition to a sharing economy (Ashina et al. 2012; Oshiro et al. 2017, 2018).

In Germany, one study points to including electromobility information and communication technologies in the transport sector as key (Canzler and Wittowsky 2016) while another emphasised shifting from road to rail transport, and reduced distances travelled as other possible transport strategies (Schmid and Knopf 2012).

India's transport sector strategies also include use of information technology and the internet, a transition to a sharing economy, and increasing infrastructure investment (Dhar et al. 2018; Vishwanathan et al. 2018). Behaviour and lifestyle change along with stakeholder integration in decision-making are considered key to implementing new transport policies (Aggarwal 2017; Dhar et al. 2018).

4.2.5.11 Net zero energy buildings

An increasing number of countries have set up Net Zero Energy Building targets (Table 4.6) (Höhne, Niklas et al. 2020). Roadmaps have been developed to support these targets in developed countries, focusing on energy efficiency and improved insulation and design, renewable and smart technologies (Mata et al. 2020).

EU, Japan and U.S. (public buildings only) have set targets for shifting new buildings to 100% near-zero energy buildings by 2030, with earlier targets for public buildings. Scotland has a similar target for 2050 (Höhne, Niklas et al. 2020).Technologies identified as needed for achieving near-zero energy buildings vary by region, but include energy-efficient envelope components, natural ventilation, passive cooling and heating, high performance building systems, air heat recovery, smart and information and communication technologies, and changing future heating and cooling supply fuel mixes towards solar, geothermal, and biomass (Mata et al. 2020) (Feng W. et al. 2020).

Subnational regions in Spain, U.S., Germany, and Mexico have set local commitments to achieving net zero carbon new buildings by 2050, with California having the most ambitious aspirational target of zero net energy buildings for all new buildings by 2030 (Höhne, Niklas et al. 2020)

EU is targeting retrofitting 3% of existing public buildings to be zero-energy buildings, with emphasis on greater thermal insulation of building envelopes (Höhne, Niklas et al. 2020; Mata et al. 2020)

Twenty seven countries have developed roadmap documents for NZEBs, but most roadmaps have focused on developed countries in Europe, North America, and Asia-Pacific (Mata et al. 2020).

China's roadmaps have emphasised insulation of building envelope, heat recovery systems in combination with renewable energy, including solar, shallow geothermal, and air source heat pumps (Mata et al. 2020).

Table 4.6 Targets by countries, regions, cities and businesses on decarbonising the building sector

	Countries	Subnational Regions	Cities	Businesses
Shift to 100 per cent (near-) zero energy buildings for new buildings	3	6	>28	>44
Fully decarbonise the building sector	1	6	>28	>44
Phase out fossil fuels (for example, gas) for residential heating	1	-	>3	
Increase the rate of zero-energy renovations	1 (public buildings)			

Source: (Höhne et al. 2020) (supplementary information). See also https://newclimate.org/ambitiousactions

4.2.5.12 Industrial energy efficiency

Industrial energy efficiency improvements are considered in nearly all countries but for countries where industry is expected to continue to be a key sector, new and emerging technologies that require significant R&D investment, such as hydrogen and CCS, will also be needed to achieve ambitious targets.

In China, non-conventional electrical and renewable technologies, including low-grade renewable heat, biomass use for high-temperature heat in steel and cement sectors, and additional electrification in glass, food and beverage, and paper and pulp industries, are needed to achieve 60% reduction in national CO_2 emission by 2050 (Khanna et al. 2019; Zhou et al. 2019). Increased recycled steel for electric arc furnaces and direct electrolysis or hydrogen-based direct reduction of iron and CCS utilisation in clinker and steel-making are also needed to achieve 1.5°C compatible pathway (China National Renewable Energy Centre 2019; Jiang et al. 2018).

In India, renewable energy and CCS are needed for the industrial sector to achieve 1.5°C and 2°C compatible pathways in 2050 (Vishwanathan and Garg 2020)

In EU-28, net carbon neutrality can only be reached with 92% reduction in industrial emissions relative to 1990, through electrification, efficiency improvement and new technologies such as hydrogen-based direct reduction of steel, low carbon cement, recycling (Duscha, Vicki, Wachsmuth, Jakob, Eckstein, Johannes, Pfluger 2019).

Both China and EU see 50% of industry electrification by 2050 as needed to meet 1.5C and net carbon neutrality pathways (Jiang et al. 2018; Capros et al. 2019).

Aggressive adoption of technology solutions for power sector decarbonisation coupled with end-use efficiency improvements and low-carbon electrification of buildings, industry and transport provides a pathway for accelerated mitigation in many key countries, but will still be insufficient to meet zero emission/1.5°C goals for all countries. Although not included in a majority of the studies related to pathways and national modelling analysis, energy demand reduction through deeper efficiency and other measures such as lifestyle changes and system solutions that go beyond components, as well as the co-benefits of the reduction of short-lived pollutants, needs to be evaluated for inclusion in future zero emission/1.5°C pathways.

4.2.5.13 Lowering demand, downscaling economies

Studies have identified technological and policy pathways to well below 2˚C and 1.5˚C targets, and to help achieve net zero CO_2 and GHG targets at national scale, that in aggregate are crucial to keeping global temperature below agreed limits. However, most of the literature focuses on supply-side options, including negative emissions technologies (CCS and others) that are not fully commercialised. Costs to research, deploy, and scale up these technologies are often high; higher carbon prices are a key policy to meet these costs. Recent studies have addressed lowering demand through energy conversion efficiency improvements, but few studies have considered demand reduction through efficiency (Grubler et al. 2018) and the related supply implications and mitigation measures.

Five main drivers of long-term energy demand reduction that can meet the 1.5˚C target include quality of life, urbanisation, novel energy services, diversification of end-user roles, and information innovation (Grubler et al. 2018). A low-energy-demand scenario requires fundamental societal and institutional transformation from current patterns of consumption, including: decentralised services and increased granularity (small-scale, low-cost technologies to provide decentralised services), increased use value from services (multi-use vs. single use), sharing economies, digitalisation, and rapid transformation driven by end-user demand. This approach to transformation differs from the status quo and current climate change policies in emphasising energy end-use and services first, with downstream effects driving intermediate and upstream structural change.

Radical low carbon innovation involves systemic, cultural, and policy changes and acceptance of uncertainty in the beginning stages. However, the current dominant analytical perspectives are grounded in neoclassical economics and social psychology, and focus primarily on marginal changes rather than radical transformations (Geels et al. 2018). Some literature is beginning to focus on mitigation through behaviour and lifestyle changes, but specific policy measures for supporting such changes and their contribution to emission reductions remain unclear (see also Section 4.4.2 and Chapter 5).

4.2.5.14 System analysis solutions are only beginning to be recognised in current literature on deep mitigation pathways, and rarely included in existing national policies or strategies

Most models and studies fail to address system impacts of widespread new technology deployment, for example: 1) material and resources needed for hydrogen production or additional emissions and energy required to transport hydrogen; or 2) materials, resources, grid integration, and generation capacity expansion limits of a largely decarbonised power sector and electrified transport sector. These impacts could limit regional and national scale-ups.

Systemic solutions are also not being sufficiently discussed, such as low-carbon materials; light-weighting of buildings, transport, and industrial equipment; promoting circular economy, recyclability and reusability, and addressing the food-energy-water nexus. These solutions reduce demand in multiple sectors, improve overall supply chain efficiency, and require cross-sector policies. Using fewer building materials could reduce the need for cement, steel, and other materials and thus the need for production and freight transport. Concrete can also be produced from low carbon cement, or designed to absorb CO_2 from the atmosphere (Falo-Sanjuan et al. 2019). Few regions have developed comprehensive policies or strategies for a circular economy, with the exception of the EU and China, and policies in the EU have only emerged within the last decade. While China's circular economy policies emphasises industrial production, water, pollution and scaling-up in response to rapid economic growth and industrialisation, EU's strategy is focused more narrowly on waste and resources and overall resource efficiency to increase economic competitiveness (McDowall et al. 2017).

Increased bioenergy consumption is considered in many 1.5˚C and 2˚C scenarios. System thinking is needed to evaluate bioenergy's viability because increased demand could affect land and water availability, food prices, and trade (Sharmina et al. 2016). To adequately address the energy-water-food nexus, policies and models must consider interconnections, synergies, and trade-offs among and within sectors, which is currently not the norm.

A systems approach is also needed to support technological innovation. This includes recognising unintended consequences of political support mechanisms for technology adoption and restructuring current incentives to realise multi-sector benefits. It also entails assimilating knowledge from multiple sources as a basis for policy and decision-making (Hoolohan et al. 2018).

Current literature does not explicitly consider systematic, physical drivers of inertia, such as capital and infrastructure needed to support accelerated mitigation (Pfeiffer et al. 2018). This makes it difficult to understand what is needed to successfully shift from current limited mitigation actions to significant transformations needed to rapidly achieve deep mitigation.

4.2.5.15 Ambitious targets to reduce short-lived climate forcers, including methane

Recent research shows that temperature increases are likely to exceed 1.5°C during the 2030s and 2°C by mid-century unless both CO_2 and short-lived climate forcers (SLCFs) are reduced (Shindell et al. 2017; Rogelj et al. 2018a). Because of their short lifetimes (days to a decade and a half), SLCFs can provide fast mitigation, potentially avoiding warming of up to 0.6 ºC at 2050 and up to 1.2 ºC at 2100 (Ramanathan and Xu 2010; Xu and Ramanathan 2017). In Asia especially, co-benefits of drastic CO_2 and air pollution mitigation measures reduce emissions of methane, black carbon, sulphur dioxide, nitrogen oxide, and fine particulate matter by approximately 23%, 63%, 73%, 27%, and 65% respectively in 2050 as compared to 2010 levels. Including the co-benefits of reduction of climate forcing adds significantly to the benefits reducing air pollutants (Hanaoka and Masui 2018).

To achieve net zero GHG emissions implies consideration of targets for non-CO_2 gases. While methane emissions have grown less rapidly than CO_2 and F-gases since 1990 (Chapter 2), the literature urges action to bring methane back to a pathway more in line with the Paris goals (Nisbet et al. 2020). Measures to reduce methane emissions from anthropogenic sources are considered intractable – where they sustain livelihoods – but also becoming more feasible, as studies report the options for mitigation in agriculture without undermining food security (Wollenberg et al. 2016; Frank et al. 2017; Nisbet et al. 2020). Ambitious reductions in reducing methane are complementary to, rather than substitutes for, reductions in CO_2 (Nisbet et al. 2020).

Rapid SLCF reductions, specifically of methane, black carbon, and tropospheric ozone have immediate co-benefits including meeting sustainable development goals for reducing health burdens of household air pollution and reversing health- and crop-damaging tropospheric ozone (Jacobson 2002, 2010). SLCF mitigation measures can have regional impacts, including avoiding premature deaths in Asia and Africa and warming in central and Northern Asia, southern Africa, and the Mediterranean (Shindell et al. 2012). Reducing outdoor air pollution could avoid 2.4 million premature deaths and 52 million tonnes of crop losses for four major staples (Haines et al. 2017). Existing research emphasises climate and agriculture benefits of methane mitigation measures with relatively small human health benefits (Shindell et al. 2012). Research also predicts that black carbon mitigation could substantially benefit global climate and human health, but there is more uncertainty about these outcomes than about some other predictions (Shindell et al. 2012). Other benefits to SLCF reduction include reducing warming in the critical near-term, which will slow amplifying feedbacks, reduce the risk of non-linear changes, and reduce long-term cumulative climate impacts—like sea-level rise—and mitigation costs (Rogelj et al. 2018a; Xu and Ramanathan 2017; Hu et al. 2017; Shindell et al. 2012; UNEP and WMO 2011).

4.3 Development pathways and mitigation options

4.3.1 Framing of development pathways

4.3.1.1 What are development pathways?

The term development pathway is defined in various ways in the literature (see Table 4.7 below), but invariably these definitions refer to the evolution over time of a society's defining features. A society's development pathway can be described, analysed, and explained from a variety of perspectives, capturing a range of possible features, trends, processes, and mechanisms. It can be examined in terms of specific quantitative indicators, such as population, urbanisation level, life expectancy, literacy rate, GDP, carbon dioxide emission rate, average surface temperature, etc. Alternately, it can be described with reference to trends and shifts in broad socio-political or cultural features, such as democratisation, liberalisation, colonisation, globalisation, consumerism, etc. Or, it can be described in a way that highlights and details a particular domain of interest; for example, as an "economic pathway", "technological pathway", "demographic pathway", or others. Any such focused description of a pathway is more limited, by definition, than the general and encompassing notion of a development pathway.

Being representations of societal evolution over time, development pathways can be discussed retrospectively and interpreted in a historical light, or explored prospectively by anticipating and assessing possible future pathways. Development pathways, and prospective development pathways in particular, can reflect societal objectives, as in "low-emission development pathways", "climate-resilient development pathways", "sustainable development pathways", "inclusive development pathway", and as such can embed normative assumptions or preferences. A national development plan (see Section 4.3.2) is a representation of a possible development pathway for a given society.

One approach for exploring shifts in future development pathways is through scenarios. Some examples of scenario exercises in the literature are provided in Table 4.7.

Table 4.7 Development pathways at global, national and local scale

Scale	Process and publication	Description of development pathways
Global	IPCC Special Report on Emission Scenarios (Nakicenovic et al. 2000)	Four different narrative storylines describing relationships between driving forces and the evolution of emission scenarios over the 21st century.
Global	Shared Socioeconomic Pathways (Riahi et al. 2017; O'Neill et al. 2017)	Five narratives describing alternative socio-economic developments, including sustainable development, regional rivalry, inequality, fossil-fuelled development, and middle-of-the-road development, using alternative long-term projections of demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources.
Global	(Rao et al. 2019)	Alternative development pathways that explore several drivers of rising or falling inequality.
Global	Futures of Work (World Economic Forum 2018)	Eight possible visions of the future of work in the year 2030, based on different combinations of three core variables: the rate of technological change and its impact on business models, the evolution of learning among the current and

		future workforce, and the magnitude of talent mobility across geographies— all of which are likely to strongly influence the nature of work in the future,
National	Mt Fleur Scenarios (Galer 2004)	Four socio-political scenarios intended to explore possible futures of a newly post-apartheid South Africa, which included three dark prophecies and one bright vision which reportedly influenced the new leadership.
National	Mitigation Action Plans and Scenarios (MAPS) (Winkler et al. 2017; Raubenheimer et al. 2015)	Mitigation and development-focused scenarios modelling including socio-economic implications for Brazil, Chile, Peru, and Colombia, linked sectoral and economy modelling combined with intensive stakeholder engagement.
National	Deep Decarbonisation Pathways (Bataille et al. 2016a; Waisman et al. 2019)	Mitigation-focused scenarios for sixteen countries from each country's perspective, carried out by local institutes using national models. The common method is a tool for decision-makers in each context to debate differing concrete visions for deep decarbonisation, seek consensus on near-term policy packages, with aim to contribute to long-term global decarbonisation.
Local	New Lenses on Future Cities (Shell Global 2014)	Six city archetypes used to create scenarios to help understand how cities could evolve through more sustainable urbanisation processes and become more efficient, and have coped with major development challenges in the past.

While a particular choice of how to characterise a development pathway is made in light of the specific features one is interested in examining, it is also influenced by our explicit and implicit priorities, values, disciplinary backgrounds, and political world views. The process of defining and describing a society's development pathway in fact contributes to the ongoing process of understanding, explaining and defining the historical and contemporary meaning and significance of a society. Narratives of development are thus important in shaping a society's development pathways. Different framings of development pathways influence society's understanding of the conceivable spectrum of its future options and prospects, and include framings such as economic growth, shifts in industrial structure, technological innovation, reframing stories of development (from growth to well-being, see Chapter 5) and making development more sustainable (see Chapters 1 and 17).

Scenario exercises are structured undertakings to explore alternative future development pathways, often drawing on stakeholder input and accepting the deep and irreducible uncertainty inherent in societal development into the future (Kahane 2019; Schweizer and Kriegler 2012; Raskin and Swart 2020).

It helps improve understanding of constraints, trade-offs, and choices. "Scenario analysis offers a structured approach for illuminating the vast range of possibilities. A scenario is a story, told in words and numbers, describing the way events might unfold. If constructed with rigor and imagination, scenarios help us to explore where we might be headed, but more, offering guidance on how to act now to direct the flow of events toward a desirable future" (Raskin et al. 2002).

Shifting development paths to increased sustainability (SDPS) is complex (see Cross-Chapter Box 4) and scenarios are useful to clarify societal objectives, understand constraints, and explore future shifts.

Scenario exercises are effective when they enable multi-dimensional assessment, and accommodate divergent normative viewpoints (Kowarsch et al. 2017). They are valuable for the quantitative and qualitative insights they can provide, and also for the role they can play in providing a forum and process by which diverse and even mutual antagonistic stakeholders can come together, build trust, improve understanding, and ultimately converge in their objectives.

4.3.1.2 Shifting development pathways

Development pathways evolve as the result of the countless decisions and actions at all levels of societal structure, as well due to the emergent dynamics within and between institutions, cultural norms, socio-technological systems, and the biogeophysical environment. Society can choose to make decisions and take actions with the shared intention of influencing the future development pathway toward specific agreed objectives.

At the global scale, salient examples of such objectives include the Paris Agreement and the SDGs. Policies aimed at meeting those objectives embody the deliberate attempt of societies to influence their future development pathway. At the national and local scales, related objectives may apply, such as those guiding a country's Nationally Determined Contribution (see section 4.2) and Low Emission Development Strategy, or efforts that are consistent with it at the sub-national scale (Hsu et al. 2017). The SDGs provide a lens on diverse national and local development objectives.

Humankind currently faces multiple sustainability challenges that together present global society with the challenge of assessing, deliberating, and attempting to bring about a viable, positive future development pathway. Ecological sustainability challenges include reducing GHG emissions, protecting the ozone, controlling pollutants such as aerosols and persistent organics, managing nitrogen and phosphorous cycles, etc. (Steffen et al. 2015). Socioeconomic sustainability challenges include conflict, persistent poverty and deprivation, various forms of pervasive and systemic discrimination and deprivation, and socially corrosive inequality. The shared prioritising of these challenges is reflected in the global adoption of the SDGs and their underlying indicators (United Nations 2018).

The interactions among the 17 SDGs have been systematically studied and found to be manifold and complex (Pradhan et al. 2017; Nilsson et al. 2016; Weitz et al. 2018). Moreover, addressing them implies changes to deep, interconnected, structural features of global society, such as to our physical infrastructure (e.g., energy, water, industrial, urban infrastructure), our societal institutions (e.g., educational, public health, economic, innovation, and political institutions), and our behavioural and cultural tendencies (e.g., consumption patterns, conventional biases, discriminatory interpersonal and intergroup dynamics, and inequitable power structures). These observations suggest three implications: first, that addressing each SDG in isolation, or as independent technical challenges, is unlikely to be effective. And, second, that incremental, marginal changes is similarly unlikely to be effective. In contrast, effectively addressing the SDGs is likely to mean significant disruption of long-standing trends and transformative progress to shift development pathways to meet all the SDGs, including climate action, beyond incremental changes targeted at addressing mitigation objectives in isolation. Mitigation conceived as incremental change is not enough, involving approaches that broaden the set of levers and enablers of transformational change. And thirdly, transformation change has implications for equity, including just transitions (see section 4.5).

Section 4.4 elaborates mechanisms through which societies can develop and implement policies to substantially shift development pathways toward securing shared societal objectives. Such policies entail establishing favourable enabling conditions: governance and institutions, behaviour, innovation, policy and finance. The first three categories tend to refer to *ultimate drivers*, the latter three to more *proximate drivers* (Raskin 2000). These, in turn, are fluid and evolve over time, and are amenable to intentional change, to greater or lesser degrees and over longer or shorter time scales, based on a range of different measures and processes. Bringing about intentional changes in these ultimate drivers implies taking action to put in in place the *enabling conditions* that can facilitate change in a positive direction (see section 4.4).

In sum, development pathways unfold over time in response to complex dynamics among various drivers and diverse actors with varying interests and motivations (*high agreement, robust evidence*). The way countries develop determines their capacity to accelerate mitigation and achieve other sustainable development objectives simultaneously (*medium-robust evidence, medium agreement*). Meeting ambitious mitigation and development goals cannot be achieved through incremental change (*robust evidence, medium agreement*). Despite this complexity, it is possible to shift development pathways by designing and implementing policies and enhancing enabling conditions, with the aim of making societally preferred outcomes more likely and avoiding societally undesirable outcomes (*medium evidence, medium agreement*).

4.3.2 Implications of development pathways for mitigation and adaptation

4.3.2.1 Countries have different development priorities

At the global level, the Sustainable Development Goals (SDGs) adopted by all the United Nations Member States in 2015 are delineated with a view to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030. The 17 SDGs are integrated and imply that development must balance social, economic and environmental sustainability.

While all countries share the totality of the SDGs, development priorities hic et nunc differ across countries and over time. These priorities are strongly linked to local contexts, and depend on which dimension of the improvement in the well-being of people—understood as the central objective—is considered the most urgent.

Development priorities are reflected in the decisions that actors within societies make, such as policy choices by governments and parliaments at all level, votes over competing policy platforms by citizens, or selection of issues that non-state actors push for. An increasing amount of national development plans are also being produced, that provide a sense how countries foresee the sequencing of development priorities over time.

The observation of these decisions and plans show that national priorities arise in response to multiple objectives ranging from poverty eradication to providing energy access, addressing concerns of inequality, providing education, improving health, cleaning air and water, sustaining growth and providing jobs, among others.

For example, eradicating poverty and reducing inequality is a key development priority across many countries, such as Brazil (Grottera et al. 2017a), Indonesia (Irfany and Klasen 2017), India (GoI, 2015), South Africa (Winkler 2018) and other low- and middle-income countries (Dorband et al. 2019). Reducing inequality relates not only to income, but also to other dimensions such as in access to energy services (Tait 2017). Similarly, the development priorities of many poor countries and communities with low capacities to adapt, has been focused more on reducing poverty, providing basic infrastructure, education and improving health, rather than on mitigation (Chimhowu et al. 2019).

This section discusses how development choices impact on emissions and on the capacity to mitigate. It also discusses the conditions under which addressing development priorities such as poverty and inequality can in turn improve the prospects of mitigation and adaptation. The literature assesses the social impacts across countries (Markkanen and Anger-Kraavi 2019; Roy et al. 2018). Section 4.3.2.2 discusses national development plans, section 4.3.2.3 discusses the implications of development pathways for emissions and mitigative capacity. On this basis, section 4.3.2.4 discusses the conditions under which mitigation can be integrated into mitigation plans. Finally, 4.3.2.5 points to the need for improved tools to pave and assess development pathways..

4.3.2.2 National development priorities are reflected in an increasing number of development plans

There is evidence that Governments are increasingly resorting to development of national plans to build institutions, resources, risk/shock management capabilities to achieve national development. The number of countries with a national development plan has more than doubled, from about 62 in 2006 (Bank 2007) to 134 plans published between 2012 and 2018. The comeback of planning may be linked to increased consideration given to sustainability, which is by construction forward-looking and far ranging, and therefore requires state and civil society to prepare and implement plans at all levels of governance. The development and formulation of national plans can be viewed as an organised, conscious and continual attempt to select the best available alternatives to achieve specific goals or as a process of ongoing social deliberation with constant (re)negotiation of goals, policies and actions across communities and citizenries so that choices made are technically desirable and politically feasible.

A systematic assessment of 107 national development plans and 10 country case studies provides useful insights regarding the type and content of the plans (Chimhowu et al. 2019). Over time, some regions such as Russia and Eastern European States moved away from the practice of developing national development plans, while other countries such as India, China or Malaysia continued this practice even in the wake of liberalisation. Various initiatives such as the World Summit for Children in 1990; the Heavily Indebted Poor Country initiative that started offering debt relief in exchange for commitments by beneficiary states to invest in health, education, nutrition and poverty reduction in 1996; and push towards Comprehensive Development Frameworks seem to have catalysed the development of national actions plans across countries to estimate, measure and track investments and progress.

The most recent development plans tend to differ from the ones established before. Complexity science has over the years argued for new forms of planning based on contingency, behaviour change, adaptation and constant learning (Colander and Kupers 2016; Ramalingam 2013), and new plans have increasingly focused on increasing resilience of individuals, organisations and systems (Hummelbrunner and Jones). Also, development plans are increasingly focusing on mobilising action across multiple actors and multiple dimensions to enhance resilience and improve the ability to undertake stronger mitigation actions, following rising interest in government failure, rent seeking and other aspects of the liberal critique of state driven development (Chimhowu et al. 2019). Finally, alongside short-term (typically 5 year) plans with operational purpose, countries have also expressed visions of their development pathways over longer time horizons, via, e.g., Voluntary National Reviews submitted in the context of the UN High Level Political Forum on Sustainable Development.

Development plans tie in multiple development priorities that evolve and broaden over time as societies develop, as exemplified inter alia by the history of development plans in India (Box 4.2). Similarly, China's 13th 5 Year Plan focuses on objectives of addressing poverty, improving health, education and public well-being but also on modernisation of agriculture, industry and infrastructure, new forms of urbanisation and a clear intent of focusing on innovation and new drivers of development (Central Compilation & Translation Press 2016).

Box 4.2 India's national development plan

India's initial national development plans focused on improving the living standards of its people, increasing national income and food self-sufficiency. Accordingly, there was a thrust towards enhancing productivity of the agricultural and industrial sectors. While the main focus was on maintaining high economic growth and industrial productivity, poverty eradication, employment and inclusive growth remained important priorities. The 12th Five Year Plan (2012-17) for the first time brought in a focus on sustainability and mentioned the need for faster, sustainable and inclusive growth. With the 13th Plan (2017-2022), the scope has been broadened again, as the Plan seeks to create a "New India" by 2022. Accordingly, the Strategy for New India @ 75 focuses on bringing innovation, technology, enterprise and efficient management together at the core of policy formulation and implementation (Government of India 2018). Development is envisaged as a mass movement wherein every individual experiences benefits in terms of better living standards. India's latest development Plan also has a strong focus on achieving broad-based economic growth to ensure balanced development across all regions and states and across sectors. There is a thrust on embracing new technologies while fostering innovation and upskilling, modernisation of agriculture, improving regional and inter-personal equity, and bridging the gap between public and private sector performance, by focusing on efficient delivery of public services, rooting out corruption and black economy, formalising the economy and expanding the tax base, improving the ease of doing business, nursing the stressed commercial banking sector back to a healthy state, and stopping leakages through direct benefit transfers, among other measures (Govt. of India 2018; Government of India 2018).

4.3.2.3 Development pathways shape emissions and capacities to mitigate

Analysis in the mitigation literature often frames mitigation policy as having development co-benefits, the main objective being climate stabilisation. This misses the point that development drives emissions, and not vice versa, and it is the overall development approach and policies that determine mitigation pathways (Munasinghe 2007). It is increasingly clear that politically, however, climate change must be understood as a development problem (Winkler et al. 2015). In fact, there is a vast body of literature supporting the fact that development pathways have direct and – just as importantly – indirect implications for GHG emissions (IPCC 2000; Winkler 2017b), through multiple channels, such as the nature of economic activity, spatial patterns of development, of patterns of inequality.

Economic structure: Chapter 2 outlines that overall, affluence (GDP per capita), economic growth and population have remained the main upward drivers of CO_2 emissions from fossil-fuel combustion in the past decade, with energy efficiency the main countervailing force (section 2.4) (Wang and Feng 2017; Lin and Liu 2015). At country level, however, the picture is more contrasted. (Sumabat et al. 2016) indicate that economic growth had a negative impact on CO_2 emissions in Philippines. (Baek and Gweisah 2013) found that CO_2 emissions tended to drop monotonously as incomes increased. Lantz and Feng (2006) also indicate that per capita GDP is not related to CO_2 emissions in Canada. sChen et al. (2018a) indicated that CO_2 emissions in China industry significantly reduced due to improvement in energy intensity. Other studies indicate an emerging consensus that the relationship between CO_2 emissions and economic indicators depends on the level of development of countries (Nguyen and Kakinaka 2019; Sharma 2011). And absolute decoupling of economic growth and GHG emissions has been found to occur in some countries (Le Quéré et al. 2019).

A major component of the development pathway of a country is precisely the nature of the economic activities on which the country relies (e.g., agriculture and mining, heavy industry, services, high-tech products, etc.) as well as the way it articulates its economy with the rest of the World (e.g., export-led growth vs. import substitution strategies). As a result, the development pathway ultimately drives the underlying structure of the economy, and thus to a large degree the relationship between activity and

GHG emissions. For example, both India and China show signs of relative decoupling between GDP and emissions because of structural change (Chen et al. 2018a). Looking ahead, choices about the nature of economic activities are expected to have significant implications for emissions. For example, a development pathway that focuses on enhancing economic growth based on accelerated growth in manufacturing is likely to lead to very different challenges for mitigation compared to one that focuses on services-led growth. (Quéré et al. 2018) find that choices about whether or not to export offshore oil in Brazil will have significant implications for the country GHG emissions. Similarly, in China, transforming industrial structure towards tertiary sectors (Kwok et al. 2018) and restructuring exports towards higher value-added products (Wu et al. 2019) are expected to have significant implications for GHG emissions.

Spatial patterns of development: Chapter 2 outlines that rapid urbanisation in developing and transition countries leads to increased CO_2 emissions, the substantial migration of rural populations to urban areas in these countries being the main factor leading to increased levels of income and expenditure of new urban dwellers which in turn leads to increased personal carbon footprints and overall emissions (section 2.4). Urbanisation, and more broadly spatial patterns of development, are in turned driven to a large part by development choices, such as, inter alia, spatial provision of infrastructure and services, choices regarding the agriculture and forestry sector, land-use policies, support to regional / local development, among others (World Bank 2009). For example, (Dorin 2017) points out that if agriculture sectors in Africa and India follow the same development path that developed countries have followed in the past, namely increased labour productivity through enlargement and robotisation of farms, then unprecedented emigrations of rural workers towards cities or foreign countries will ensue, with large-scale social, economic and environmental consequences. Looking ahead, a development pathway that encourages concentrated influx of people to large urban centres will lead to very different energy and infrastructure consumption patterns than a pathway that prioritises the development of smaller, self-contained towns and cities.

Degree of inequality: Chapter 2 notes that while eradicating extreme poverty and providing universal access to modern energy services to poor populations across the globe has negligible implications for emissions growth, existing studies on the role of poverty and inequality as drivers of GHG emissions provide limited evidence that under certain contexts greater inequality can lead to a deterioration in environmental quality and may be associated with higher GHG emissions (section 2.4). In fact, factors affecting household consumption based emissions include household size, age, education attainment, employment status, urban vs rural location and housing stock (Druckman and Jackson 2015). There is evidence to indicate that at the household level, the increase in emissions from additional consumption of the lower income households could be larger than the reduction in emissions from the drop in consumption from the high income households (Sager 2019). Accordingly, as countries seek to fulfil the objective of reducing inequality, there are possibilities of higher increase in emissions (Sager 2019).

Since reducing inequality, as noted above, is amongst a major development priority in many countries, a large body of literature focuses on the compatibility of climate change mitigation and reduction in economic inequality (Baek and Gweisah 2013; Berthe and Elie 2015; Grunewald et al. 2017; Hao et al. 2016; Wiedenhofer et al. 2017; Auffhammer and Wolfram 2014). However, the use of narrow approaches or simple methods of studying the relationships of income inequality and emissions by looking at correlations, may miss important linkages. For example, the influence of inequality on social values such as status and civic mindedness and non-political interests that shape environmental policy can influence overall consumption and its environmental impacts (Berthe and Elie 2015).

[*One paragraph to be added showing the difference between mitigation costs in IP 1.5—SP and the other IP1.5-xx. IP1.5-SP is based on SSP1, whereas all the other IP1.5-xx are based on SSP2.*

Differences between IP1.5-SP and other IP1.5 thus illustrates how a shift in development pathway [here from SSP2 to SSP1] does impact on the costs associated with reaching the same climate target.]

[*One paragraph to be added in final draft showing how development pathways impact on degree of adaptation to climate change and on adaptative capacity based on final draft of WGII report, notably Chapter 18.*]

In sum, development pathways can lead to different emission levels and different capacities and opportunities to mitigate (*medium evidence, high agreement*). Thus, focusing on shifting development pathways can lead to larger systemic sustainability benefits.

4.3.2.4 Integrating mitigation considerations requires non-marginal shifts in development pathways

Concerns about mitigation are already being introduced in national development plans, as there is evidence that development strategies and pathways can be carefully designed so as to align towards multiple priorities and achieve greater synergistic benefits. For example, India's solar programme is a key element in its NDC that can not only provide energy security and contribute to mitigation, but can simultaneously contribute to economic growth, improved energy access and additional employment opportunities, if policies and measures are carefully planned and implemented. Similarly, South Africa National Development Plan (2011) does integrate transition to low-carbon as part of the country development objectives (Box 4.3).

Box 4.3 South Africa's National Development Plan

South Africa adopted its first National Development Plan (NDP) in 2011 (NPC 2011), the same year in which the country adopted climate policy (RSA 2011) and hosted COP17 in Durban. Chapter 5 of the NDP address environmental sustainability in the context of development planning, and specifically "an equitable transition to a low-carbon economy" (NPC 2011). The chapter refers explicitly to the need for a just transition, protecting the poor from impacts and any transitional costs from emissions-intensive to low-carbon. The plan proposes several mitigation measures, including a carbon budgeting approach, reference to Treasury's carbon tax, and the integrated resource plan for electricity. The NDP refers to coal in several chapters, in some places suggesting additional investment (including new rail lines to transport coal and coal to liquids), in others decommissioning coal-fired power "Procuring at least 20 000MW of renewable electricity by 2030, importing electricity from the region, decommissioning 11 000MW of ageing coal-fired power stations and stepping up investments in energy-efficiency" (NPC 2011: p.46). Reference to environmental sustainability is not limited to chapter 5 – the introductory vision statement includes acknowledgement "that each and every one of us is intimately and inextricably of this earth with its beauty and life-giving sources; that our lives on earth are both enriched and complicated by what we have contributed to its condition" (NPC 2011: p. 21); and the overview of the plan includes a section on climate change, addressing both mitigation and adaptation.

Looking ahead, given that different development pathways can lead to different levels of GHG emissions and to different capacities and opportunities to mitigate, there is increasing research on how to make development pathways more sustainable. A strong body of literature focusing on the "new normal" as a system with higher quality growth and focusing on "innovative development pathways" is emerging in recent times. These studies are increasingly seeking answers to questions like what innovation is needed to follow development pathways that reduce inequality and GHG emissions (Zou et al. 2016). There is much discussion on the need for a new approach and frameworks that move towards systems thinking and provide a perspective on global innovation of development pathways (Zou et al. 2016).

Literature suggests that if development pathways are to be changed to address the climate change problem, choices that would need to be made about development pathways would not be marginal (Stern and Professor 2009), and would require a new social contract to address a complex set of inter-linkages across sectors, classes and the whole economy (Winkler 2017b). The necessary transformational changes can be positive if it is rooted in the development aspirations of the economy and society in which it takes place (Dubash 2012; Jones et al. 2013), but it can also lead to carbon colonialism if the transformations are imposed by Northern donors or perceived as such.

Accordingly, influencing a societies' development pathways draws upon a broader range of policies and other efforts than narrowly influencing mitigation pathways, to be able to achieve the multiple objectives of reducing poverty, inequality and GHG emissions. The implications for employment, education, mobility, housing and many other development aspects must be integrated and new ways of looking at development pathways which are low carbon must be considered (Bataille et al. 2016b)(Waisman et al. 2019). For instance, job creation and education are important elements that could play a key role in reducing inequality and poverty in developing countries like South Africa and India (Winkler et al. 2015; Rao and Min 2018) these also open up broader opportunities for mitigation.

4.3.2.5 New tools are needed to pave and assess development pathways

Relative to the literature on mitigation pathways described in 4.2.5 and in 4.3.3, the literature on development pathways is limited. The climate research community has developed the Shared Socio-economic pathways (SSPs) that link several socio-economic drivers including equity in relation to welfare, resources, institutions, governance and climate mitigation policies in order to reflect many of the key development directions (O'Neill et al. 2014). In most modelling exercises however, development remains treated as an exogenous input. In addition, models may capture only some dimensions of development that are relevant for mitigation options, thereby not capturing distributional aspects and not allowing to check consistency with broader developmental goals (Valadkhani et al. 2016). Quantitative tools for assessing mitigation pathways could be more helpful if they could provide information on a broader range of development indicators, and moreover could model substantively different alternative development paths, thereby providing information on which levers might shift development in a more sustainable direction.

Doing so requires new ways of thinking with interdisciplinary research and use of alternative frameworks and methods suited for understanding of change agents, determinants of change and adaptive management among other issues (Winkler 2018). This includes, inter alia, being able to examine enabling conditions for shifting development pathways (see 4.4.1); re-evaluating the neo-classical assumptions within most models, both on the functioning of markets and on the behaviour of agents, to better address obstacles on the demand side, obstacles on the supply side and market distortions (Ekholm et al. 2013; Staub-Kaminski et al. 2014; Grubb et al. 2015) improving representation of issues related with uncertainty, innovation, inertia and irreversibility within the larger development contexts including energy access and security ; improving the representation of social and human capital, and of social, technological and governance innovations (Pedde et al. 2019).

Tools have been developed in that direction, for example in the Mitigation Action Plans and Scenarios (MAPS) community (La Rovere et al. 2014b), but need to be further mainstreamed in the analysis. Back-casting is the preferred modelling approach for assessment aiming to align national development goals with global climate targets like CO_2 stabilisation. Back-casting is a normative approach where modellers construct desirable futures and specify upfront targets and then find out possible pathways to attain these targets (IPCC et al. 2001). In backcasting, the long-term national development objectives remain the key benchmarks guiding the model dynamics and the global climate goal is interfaced to realise the co-benefits. The model then delineates the roadmap of national actions that achieve the national goals and deliver optimal full costs and benefits of low carbon development including the costs of adaptation and impacts from residual climate change. Back-casting modelling exercises show that aligning development and climate actions result in much lower 'social cost of carbon' (Shukla et al. 2008). The back-casting does not aim to produce blueprints. It indicates the relative feasibility and the social, environmental, and political implications of different development and climate futures on the assumption of a clear relationship between goal setting and policy planning (Dreborg 1996). Back-casting exercises are well suited for preparing local specific roadmaps like for the cities (Gomi et al. 2011, 2010).

4.3.3 Implications of mitigation for national development objectives

4.3.3.1 Introduction

Section 4.3.2 has outlined the diversity of development objectives that countries are pursuing, given national circumstances. This section examines how accelerated mitigation may impact the realisation of these objectives in the short- and medium-term. It focuses on three objectives discussed in the literature, sustaining economic growth (4.3.3.2), providing employment (4.3.3.3), and alleviating poverty and ensuring equity (4.3.3.4). The present section complements similar review performed at global level in section 3.6.

In the literature, the impacts of mitigation are typically assessed relative to a reference scenario, either "business as usual" with no mitigation, or increasingly "with current policies" with some mitigation already undertaken. "With current policies", however, can differ across studies depending on modellers' assumptions, and by definition evolves over time. In addition, accelerated mitigation pathways differ markedly from the reference, making the comparison with the reference less relevant. Given these conceptual difficulties, we report in this section both deviations from reference scenario and absolute numbers.

4.3.3.2 Mitigation and economic growth in the near- and mid-term

A significant part of the literature assesses the impacts of mitigation on GDP, consistent with policymakers' interest in this variable. Three caveats, however, should be made upfront. First, computable equilibrium models, on which these assessments are mostly based, capture all the direct links from mitigation to GDP, but generally do not capture indirect links such as the economic benefits derived from increased air quality. These limitations are discussed below. Second, an expanding literature criticises GDP as a proper indicator of welfare. To our knowledge, however, the impacts of mitigation are seldom measured against alternative metrics in the literature. The mechanisms linking mitigation to GDP outlined below would remain valid even with alternative indicators. Third, another stream of literature criticises the pursuit of economic growth as a goal, advocating a range of alternative instead. In the language of the present chapter, these alternatives constitute alternative development paths, the discussion of which can be found in section 4.3.1.

Most country-level mitigation modelling studies in which GDP is an endogenous variable report negative impacts of mitigation on GDP in 2030 and 2050, relative to the reference (*robust evidence, high agreement*) (Nong et al. 2017) for Australia, (Chen et al. 2013) for Brazil, (Mu et al. 2018a; Cui et al. 2019; Zhao et al. 2018; Li et al. 2017; Dong et al. 2018; Dai et al. 2016) for China, (Álvarez-Espinosa et al. 2018) for Colombia, (Fragkos et al. 2017) for the EU, (Mittal et al. 2018) for India, (Fujimori et al. 2019) for Japan, (Veysey et al. 2014) for Mexico, (Pereira et al. 2016) for Portugal, (Alton et al. 2014)(van Heerden et al. 2016) for South Africa, (Chunark et al. 2017) for Thailand, (Acar and Yeldan 2016) for Turkey, (Roberts et al. 2018b) for the UK, (Chen and Hafstead 2019)(Zhang et al. 2017) for the USA, (Nong 2018) for Vietnam) (Figure 4.4a). In all reviewed studies, however, GDP continues to grow even with mitigation (Figure 4.4b).

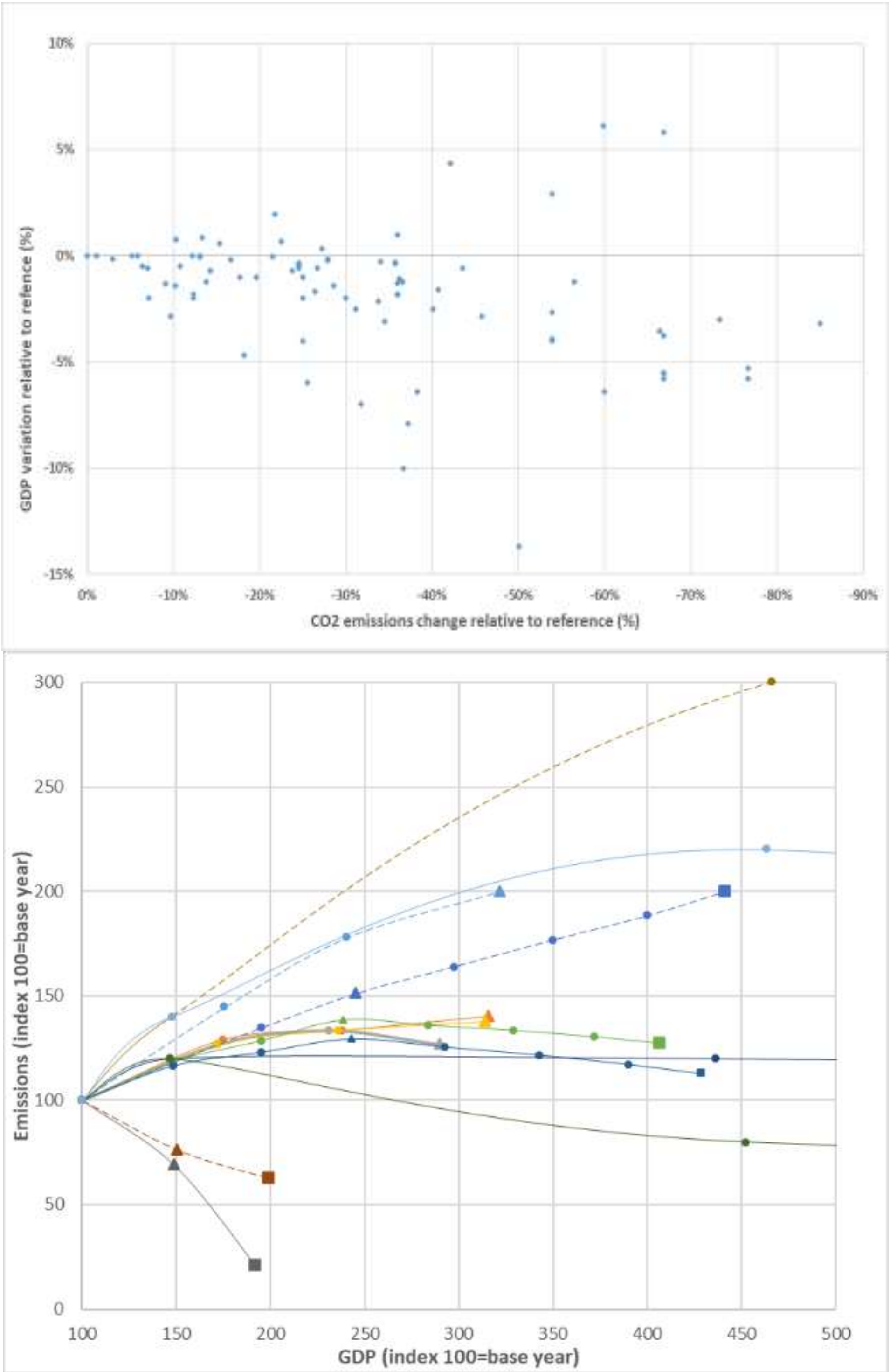


Figure 4.4 GDP against emissions in country-level modelling studies, in variations relative to reference (panel a) and in absolute terms (panel b, index 100 = model base year).

Each point represents one simulation by one model for one country. In panel b, each line refers to a different scenario, points with triangle marker refer to year 2030 simulations, points with square marker refer to year 2050. [*To be further elaborated with data extracted from AR6 database of national scenarios.*]

Two major mechanisms interplay to explain the impact of mitigation on GDP. First, the price of GHG-intensive goods and services increases as a result of the carbon constraint, translating into higher factor costs for firms and higher costs of final goods and services for households. Second, additional investment required for mitigation partially crowds out productive investment elsewhere (Fujimori et al. 2019), except in Keynesian models in which increased public investment actually boosts GDP (Pollitt et al. 2015; Bulavskaya and Reynès 2018; Landa Rivera et al. 2016). Magnitude and duration of GDP loss depend on the stringency of the carbon constraint, the degree of substitutability with less-GHG-intensive goods and services, assumptions about costs of low-carbon technologies and their evolution over time (e.g., (Cui et al. 2019; Duan et al. 2018; van Meijl et al. 2018) and decisions by trading partners, which influence competitiveness impacts for firms (Alton et al. 2014; Fragkos et al. 2017) {*high confidence*}.

In the near-term, presence of long-lived emissions intensive capital stock, labour market rigidities (Devarajan et al. 2011) or other rigidities may increase impacts of mitigation on GDP. In the mid-term, on the other hand, physical and human capital, technology, institutions, skills or location of households and activities are more flexible. Future skills and job creation goals can be achieved through development of renewable energy, particularly in the high-skill labour market (Hartley et al. 2019). In addition, cumulative mechanisms such as induced technical change or learning by doing on low-emissions technologies and process may reduce the impacts of mitigation on GDP.

Table 4.8 Country-level modelling studies finding positive short-term outcome of mitigation on GDP relative to baseline

[More studies to be added in FGD]

Reference	Country/region	Explanation for positive outcome of mitigation on GDP
(Antimiani et al. 2016)	European Union	GDP increases relative to reference only in the scenario with global cooperation on mitigation
(Willenbockel et al. 2017)	Kenya	The mitigation scenario introduces cheaper (geothermal) power generation units than in BAU (in which thermal increases). Electricity prices actually decrease.
(Siagian et al. 2017)	Indonesia	Coal sector with low productivity is forced into BAU. Mitigation redirects investment towards sectors with higher productivity.
(Blazquez et al. 2017)	Saudi Arabia	Renewable energy penetration assumed to free oil that would have been sold at publicly subsidised price on the domestic market to be sold internationally at market price
(Wei et al. 2019)	China	Analyse impacts of feed-in tariffs to renewables, find positive short-run impacts on GDP; public spending boost activity in the RE sector. New capital being built at faster rate than in reference increases activity more than activity decreases due to lower public spending elsewhere.

(Gupta et al. 2019)	India	Investment is fixed share of GDP, so additional investment in low-carbon technology has an economic stimulus effect
(Huang et al. 2019)	China	Power generation plan in the baseline is assumed not cost minimising

Country-level studies find that the negative impacts of mitigation on GDP can be reduced if pre-existing economic or institutional barriers are targeted in complement to the imposition of the carbon constraint (*robust evidence*, *high agreement*). For example, if the carbon constraint takes the form of a carbon tax or of permits that are auctioned, the way the proceeds from the tax (or the revenues from the sales of permits) are used is critical for the overall macroeconomic impacts (Chen et al. 2013). Figure 4.5 shows that depending on the choice of accompanying policies, the same level of carbon constraint can yield very different outcomes for GDP. The potential for mitigating GDP implications of mitigation through fiscal reform is discussed in 4.4.1.6 below.

More generally, mitigation costs can be reduced by proper policy design if the economy is considered to be on the efficiency frontier (Grubb 2014), defined as the set of configurations within which the quality of the environment and economic activity cannot be simultaneously improved given current technologies. Most of the studies which find that GDP increases with mitigation in the near-term precisely assume that the economy is initially not on the frontier. Making the economy more efficient—i.e., lifting the constraints that maintain the economy in an interior position—creates opportunities to simultaneously improve economic activity and reduce emissions. Table 4.8 describes the underlying assumptions in each study.

It may be noted that none of the study assessed above integrates the benefits of mitigation in terms of reduced impacts of climate change. This is not surprising since these studies are at national or regional scale, whereas reduced impacts depend on global emissions. Discussion on reduced impacts is provided in section 3.6.2 and in the Cross-Working Group Box "Estimating Global Economic Impacts from Climate Change and the Social Cost of Carbon" in WGII Chapter 16.

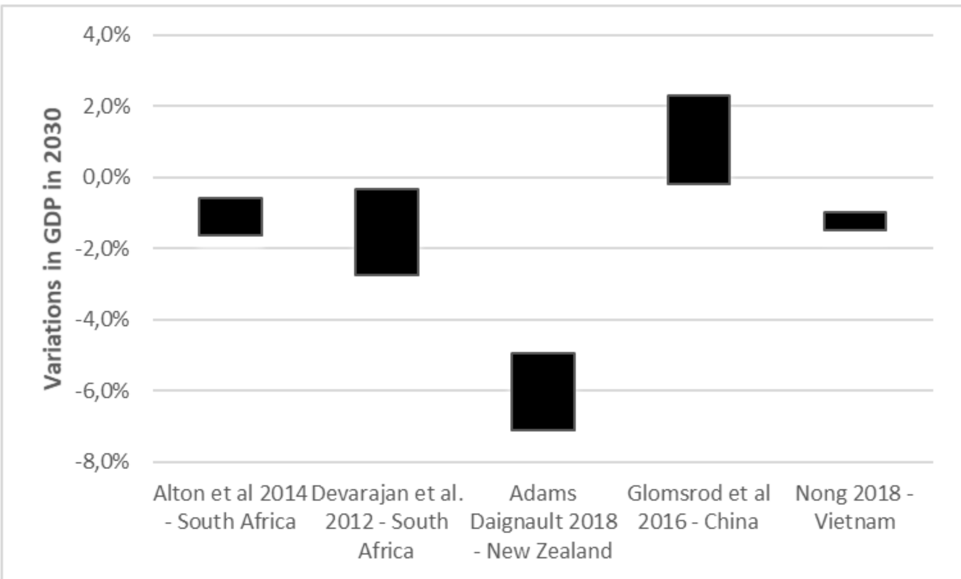


Figure 4.5 Range of variations in GDP relative to reference in 2030 associated with introduction of carbon constraint, depending on modality of policy implementation.

Note: stringency of carbon constraint is not comparable across the five studies shown in the Figure [*More studies to be added*]

4.3.3.3 Mitigation and employment in the short- and medium-term

Numerous studies have analysed the potential impact of carbon pricing on labour markets. (OECD 2017a) and (Chateau et al. 2018) find that the implementation of green policies globally (defined broadly as policies that internalise environmental externalities through taxes and other tools, shifting profitability from polluting to green sectors) need not harm total employment, and that the broad skill composition (low-, high- and medium-skilled jobs) of emerging and contracting sectors is very similar, with the largest shares of job creation and destruction at the lowest skill level. To smoothen the labour market transition, they conclude that it may be important to reduce labour taxes, to provide education and training programs, and to compensate vulnerable households.

At the sectoral level, however, the changes are more substantial – sectors that are carbon-dependent (producing carbon or intensive users of carbon) (Huang et al. 2019) do less well and this is also true for countries that are dominated by such sectors (Arndt et al. 2013). Among worker categories, low-skilled workers tend to suffer wage losses as they are more likely to have to reallocate, something that can come at a cost in the form of a wage cut (assuming that workers who relocate are initially less productive than those who already work in the sector). The results for alternative carbon revenue recycling schemes point to trade-offs: a reduction in labour taxes often leads to the most positive employment outcomes while lump-sum (uniform per-capita) transfers to households irrespective of income yield a more egalitarian outcome.

The results from country-level studies using CGE models tend be similar to those at global level. Aggregate employment impacts are small and may be positive especially if labour taxes are cut (for Ethiopia and Turkey; see (Telaye et al. 2019), and (Kolsuz and Yeldan 2017; Fragkos et al. 2017), for the EU, (Mu et al. 2018b) for China respectively). On the other hand, sectoral reallocations away from fossil-dependent sectors may be substantial (for South Africa; see (Alton et al. 2014), for China see (Huang et al. 2019)). Targeting of investment to labour-intensive green sectors may generate the strongest employment gains (for France; see (Perrier and Quirion 2018; van Meijl et al. 2018), for the Netherlands, (Patrizio et al. 2018) for the USA); and the changes in skill requirements between emerging and declining sectors are quite similar, involving smaller transitions than during the IT revolution (for the US, see (Bowen et al. 2018)).

In sum, the literature suggests that, employment effect of mitigation policies tend to be limited on aggregate, but can be significant at sectoral level (*limited evidence, medium agreement*) and that cutting labour taxes may limit adverse effects on employment (*limited evidence, limited agreement*). Labour market impacts, including job losses in certain sectors, can be mitigated by equipping workers for job changes via education and training, and by reducing labour taxes to boost overall labour demand (Stiglitz et al. 2017).

Like most of the literature on climate change, the above studies do not address gender aspects. These may be significant since the employment shares for men and women vary across sectors and countries. For example, in many developing countries, sectors in which women play a relatively important role – the collection of water and fuel wood (which, like other services produced by households for own consumption are not part of GDP) and agricultural production – may be negatively affected by climate change (Sen Roy and Roy 2018).

4.3.3.4 Mitigation and equity in the near- and mid-term

Climate mitigation may exacerbate socio-economic pressures on poorer households (Jakob et al. 2014). First, the price increase in energy-intensive goods and services—including food (Hasegawa et al.

2018)—associated with mitigation may affect poorer households disproportionally (Bento 2013), and increase the number of energy-poor (Berry 2019). Second, the mitigation may disproportionally affect low-skilled workers (see previous section). Distributional issues have been identified not only with explicit price measures (carbon tax, emission permits system, subsidy removal), but also with emissions standards (Davis and Knittel 2019), efficiency standards (Bruegge et al. 2019), or subsidies for renewables (Borenstein and Davis 2016).

Distributional implications, however, are context specific. In an analysis of the distributional impact of carbon pricing based on household expenditure data for 87 low- and middle-income countries, (Dorband et al. 2019) find that, in countries with a per-capita income of up to USD15,000 per capita (PPP adjusted), carbon pricing has a progressive impact on income distribution and that there may be an inversely U-shaped relationship between energy expenditure shares and per-capita income, rendering carbon pricing regressive in high-income countries, i.e., in countries where the capacity to pursue compensatory policies tends to be relatively strong.

The literature finds that the detailed design of mitigation policies is critical for their distributional impacts (*robust evidence, high agreement*). For example, Vogt-Schilb et al. (2019) suggest to turn to cash transfer programs, established as some of the most efficient tools for poverty reduction in developing countries. In an analysis of Latin America and the Caribbean, they find that allocation of 30 percent of carbon revenues would suffice to compensate poor and vulnerable households on average, leaving the rest for other uses. This policy tool is not only available in countries with relatively high per-capita incomes: in Sub-Saharan Africa, where per-capita incomes are relatively low, cash transfer programs have been implemented in almost all countries ((Beegle et al. 2018), p. 57), and are found central to the success of energy subsidy reforms (Rentschler and Bazilian 2017).

Distributional concerns related to climate mitigation are also prevalent in developed countries, as demonstrated, for instance, by France's recent yellow-vest movement, which was ignited by an increase in carbon taxes. In that particular case, no compensation mechanism had been put in place when the tax was set up in 2014. It has been shown ex post that transfer schemes considering income levels and location could have protected or even improved the purchasing power of the bottom half of the population (Bureau et al. 2019). CGE analysis of the previous attempt at introducing a carbon tax in France suggests that reducing labour taxes coupled with targeted transfers could have been superior by limiting the macroeconomic burden associated with the tax (Combet et al. 2010; Combet and Hourcade 2017). Policymakers may also consider protecting vulnerable households via direct tax reductions or reduced consumption taxes on goods serving basic needs (Baranzini et al. 2017).

4.3.4 Articulation between accelerating mitigation and shifting development pathways

4.3.4.1 Introduction

The previous two sections have considered the implications of development pathways for mitigation, and vice versa. This section considers the articulation of accelerating mitigation and shifting development pathways, i.e., how mitigation objectives – such as those included in the Paris Agreement – can be considered within the context of shift development pathways. To address the challenge of widespread and rapid transformations implied by goals such as these, it is useful to consider potential societal responses as falling along a continuum. At one end are measures focused directly and specifically on reducing GHG emissions *per se*, and on the other are measures, policies, processes, and dynamics that more broadly influence and shape the overall development pathway. The former are often referred to as mitigation measures, and are aimed at affecting the mitigation pathway by determining proximate drivers of emissions. The latter may be referred to as development measures and are aimed at affecting the development pathways so as to achieve societal objectives, and thus also can affect both proximate and ultimate drivers of emissions.

This section will review the ways in which actors can – and indeed continually are – making decisions and taking actions that affect the evolving societal development pathway, and the ways in which those decisions and actions can influence – positively or negatively – the pace and scale of mitigation as well as prospects of meeting other societal objectives. This section moreover finds that approaches based on a more comprehensive consideration of development measures, as opposed to mitigation measures alone, opens up wider and more effective options for meeting mitigation and other development objectives (see Chapter 13 on policies, institutions and related measures).

4.3.4.2 Shifting development paths to increase sustainability and broaden mitigation options

Mitigation conceived as incremental change is not enough, involving approaches that broaden the set of levers and enablers of transformational change. Given the observation (see section 4.2) that current and pledged mitigation efforts are insufficient relative to mitigation goals of the Paris Agreement, decision-makers might usefully consider a broader palette of policies and measures as part of an overall strategy to meet climate goals and other sustainable development goals (see 4.3.2; Table 4.9). Mitigation measures (narrowly defined) aim at influencing the proximate drivers of emissions, and conventional climate policy instruments include, for example, emissions taxes or permits, price incentives such as feed-in tariffs for low-carbon electricity generation, and fuel economy standards, and building codes. Increasingly, however, mitigation objectives are being explicitly envisioned as being inseparable from broader developmental goals, which can be facilitated by policy coherence and integration with broader objectives and policies sectorally and societally. This is supported by other observations that mitigation measures alone will not achieve the long-term goals of the Paris Agreement (IPCC 2018a; Rogelj et al. 2016; UNEP 2018; Méjean et al. 2015). An approach of shifting development pathways to increased sustainability (SDPS) broadens the scope for mitigation. To meet all the SDGs, shifts in development pathways cannot be incremental or marginal (4.3.1). An approach of SDPs helps manage trade-offs between mitigation and other SDGs.

Figure 4.6 illustrates shifting development pathways to increased sustainability.

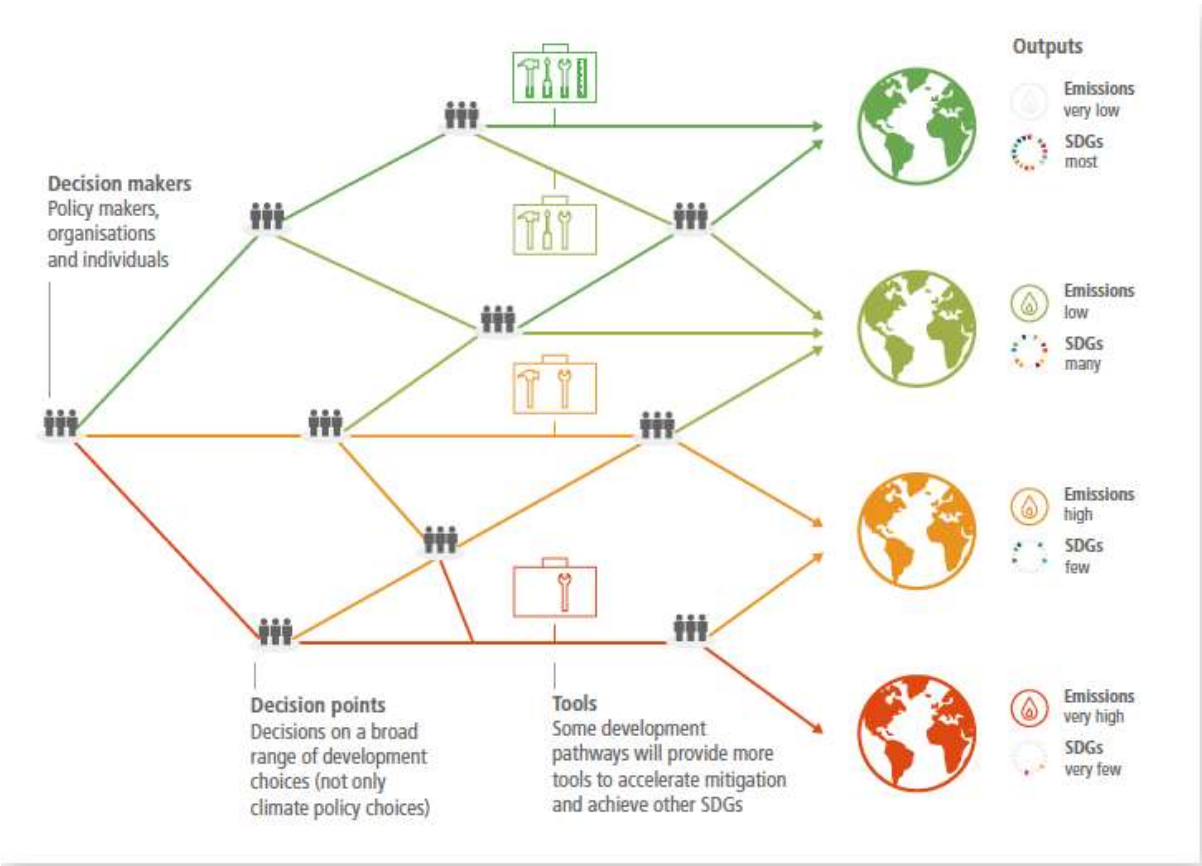


Figure 4.6 Shifting development pathways to increased sustainability: Choices by a wide range of actors at key decision points on development pathways can provide more tools to accelerate mitigation and achieve other Sustainable Development Goals

Figure 4.6 shows how choices made by a wide range of decision-makers influence which of many possible development pathways a society follows. There are many decision points, many of which are well outside the scope of conventional climate policy, which nonetheless influence how broad set of tools are available. With a broader set of enablers and levers in a toolbox, it becomes feasible to accelerate mitigation and achieve other SDGs. Some choices lead to pathways that more effectively manage trade-offs and achieve other Sustainable Development Goals (see section 4.4.1).

The approach of SDPS is explored across several other chapters of the Working Group III report, in the following cross-chapter box.

Cross-Chapter Box 4 Shifting development paths to increase sustainability and broaden mitigation options

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1. What do we mean by development pathways?

In the present report, development pathways refer to patterns of development resulting from multiple decisions and choices made by many actors in the national and global contexts. Each society whether in the Global North or the Global South follows its own pattern of development (Figure 1.6). Development pathways can also be described at smaller scales (e.g., for regions or cities). By extension, the concept can also be applied to sectoral systems (e.g., the development pathway of the agricultural sector or of industrial systems).

2. Why do development pathways matter in a report about mitigation?

2a. Past development pathways determine both GHG emissions and the set of opportunities to reduce emissions

Development pathways drive GHG emissions for a large part (2.4, 2.5 and 2.6). For example, different social choices and policy packages with regard to land use and associated rents will result in human settlements with different spatial patterns, different types of housing markets and cultures, and different degrees of inclusiveness, and thus different demand for transport and associated GHG emissions (8.3.1, 10.2.1).

There is compelling evidence to show that continuing along existing development pathways is unlikely to achieve rapid and deep emission reductions. For example, investments in long-lived infrastructure, including energy supply systems, could lock-in high emissions pathways and risk making deep decarbonisation and sustainable policies more difficult and expensive.

Development pathways also determine the set of tools available to mitigate climate change (Figure 4.6). For example, the capacity of households to move closer to their workplace, in response to, e.g., a price signal on carbon and thus on gasoline, depends on rents, which themselves depend on the spatial patterns of development of human settlements (8.3.1). Said differently, mitigation costs depend on past development choices. Similarly, development pathways determine the enablers and levers available for adaptation (WGII, Chapter 18) and for achieving other SDGs.

In the absence of shifts in development pathways, conventional mitigation policy instruments (e.g., carbon tax, emission quotas, technological norms, etc.) may not be able to limit emissions to a degree sufficient to meet deep mitigation objectives. Or they may only be able to do so at very high economic and social costs.

Policies to shift development pathways, on the contrary, make mitigation policies more effective. For example, policies that prioritise non-car transit, or limit rents close to work places would make it easier for households to relocate in response to a price signal on transport, and thus makes the same degree of mitigation achievable at lower economic and social cost.

2b. Shifting development pathways broadens the scope for synergies between development objectives and mitigation

Second, societies pursue a variety of development objectives, of which protecting the Earth's climate is part. The SDGs provide a global mapping of these goals. Absent climate mitigation, our collective ability to achieve the SDGs in 2030 and to sustain them beyond 2030 is likely to be compromised, even if adaptation measures are put in place (WGII).

There are many instances in which reducing GHG emissions and moving towards the achievement of other development objectives can go hand in hand, in the near-, mid- and long-term (3.7, 6.7.7, 7.6.5, 8.2, 9.8, 10.1.1, 11.5.3, 17.3) (Figures 3.40, 12.1). For example, transitions from coal-based power to lower-emissions electricity generation technologies and from Internal Combustion Engine to lower-carbon transport has large mitigation potential and direct benefits for health through reduction in local air pollution (Box 6.2, 10.4.1). Energy efficiency in buildings and energy poverty alleviation through improved access to clean fuels also delivers significant health benefits (9.8.1).

Careful design of mitigation policies is critical to achieving these synergies (13.8). Integrated policies can support the creation of synergies between climate change goals and other SDGs. Policy design can also manage trade-offs, for example through policy measures as part of just transitions ()(17.4).

However, even with good policy design, decisions about mitigation actions, and the timing and scale thereof, may entail trade-offs with the achievement of other national development objectives in the near-, mid- and long-term. In the near-term, for example, regulations may ban vehicles from city centres to reduce congestion and local air pollution, but reduce mobility and choice. Increasing green spaces within cities without caps on housing prices may involve trade-offs with affordable housing and push low income residents outside the city (8.2.2). In the mid- and long-term, large-scale deployment of biomass energy raises concerns about food security and biodiversity conservation (3.7.1, 3.7.5, 7.4.4, 12.5.2, 12.5.3). Conflicts between mitigation and other development objectives can act as an impediment to climate action (13.8) and be amplified by vested interests.

Prioritising is one way to manage trade-offs, addressing some national development objectives earlier than others.

Another way is to adopt policy packages aimed at shifting development pathways towards sustainability as they expand the range of tools available to simultaneously achieve multiple development objectives, including mitigation.

In the city example of section 2a, a carbon tax alone would run counter to other development objectives if it made suburban households locked into high emissions transport modes poorer or if it restricted mobility choices, in particular for low- and middle-income households. Policy packages combining affordable housing and provision of safe low-carbon mobility could both facilitate equitable access to housing (a major development objective in many countries) and make it easier to mitigate by shifting the urban development pathway.

Similarly, a fundamental shift in the service provision that helps reduce energy demand (Chapter 5), driven by targeted policies, investment and enabling sufficiency and behaviour change, would reduce reliance on land-based mitigation technologies, hence limiting pressure on water and food resources and the achievement of associated SDGs. Some studies assume Western European lifestyle as a reference for the global North and an improvement in the living standard for the Global South to reduce energy demand and emissions (e.g., (Grubler et al. 2018)), while others explore a transformative change in the global North to achieve a decent living standard for all (Millward-Hopkins et al. 2020; Bertram et al. 2018) (3.7.8).

3. What does shifting development pathways towards sustainability entail?

Shifting development pathways towards sustainability implies making transformative changes that disrupt existing developmental trends. Such choices would not be marginal (Stern and Professor 2009), but include technological, systemic and socio-behavioural changes (Chapter 5).

These include creating new infrastructure, sustainable supply chains, institutional capacities for evidence-based and integrated decision-making, financial alignment towards low-carbon socially responsible investments, just transitions and shifts in behaviour and norms to support shifts away from fossil-fuel consumption (Green and Denniss 2018). Adopting multi-level governance modes, tackling corruption where it inhibits shifts to sustainability, and improving social and political trust are also key for aligning and supporting long-term environmentally just policies and processes.

Shifting development pathways entails fundamental changes in energy, urban, building, industrial, transport, and land-based systems. It also requires changes in behaviour and social practices. Overcoming inertia and locked-in practices may face considerable opposition (5.4.5) (Geels et al. 2017). The durability of carbon intensive transport modes and electricity generating infrastructures increase the risk of lock-in to high emissions pathways, as these comprise not just consumer practices, but sunk costs in infrastructure, supporting institutions and rules, as well as interest groups that benefit from and aim to protect the status-quo (Seto et al. 2016; Mattioli et al. 2020).

4. How to shift development pathways?

Shifting development paths is complex. If history is any guide, practices that can easily supplant existing systems and are clearly profitable move fastest (Griliches 1957). Changes that involve 'dissimilar, unfamiliar and more complex science-based components' take more time, acceptance and legitimation and involve complex social learning (Conley and Udry 2010), even when they promise large gains (Pezzoni et al. 2019).

Yet despite the complexities of the interactions that result in patterns of development, history also shows that societies can influence the direction of development pathways based on choices made by decision-makers, citizens, the private sector and social stakeholders. For example, fundamentally different responses to the first oil shock shifted then-comparable economies on to different energy sector development and economic pathways in the 1970s and 80s (Sathaye et al. 2009). More recent examples have shown evidence of voluntary transitions for e.g., advanced lighting in Sweden, improved cook-stoves in China, liquefied petroleum gas stoves in Indonesia or ethanol vehicles in Brazil (Sovacool 2016).

There is no one-size-fits-all recipe for shifting development pathways. However, the following insights can be drawn from past experience (4.4.1).

Shifts in development pathways result from both sustained political interventions and bottom-up changes in public opinion. No single sector or policy action is enough to achieve this. Coordinated policy mixes would need to coordinate multiple actors – i.e., individuals, groups and collectives, corporate actors, institutions and infrastructure actors – to deepen decarbonisation and shift pathways towards sustainability (Pettifor 2020). Shifts in one country may spill over to other countries. Collective action by individuals as part of formal social movements or informal lifestyle changes underpins system change (5.2.3, 5.4.1, 5.4.5.3, 13.5)

Sectoral transitions that aspire to shift development pathways often have multiple objectives, and deploy a diverse mix or package of policies and institutional measures (Figure 13.6). Context specific governance conditions can significantly enable or disable sectoral transitions, and play a determinative role in whether a sectoral transition leads to a shift in development pathway.

Literature suggests that through equitable resource distribution, high levels of human development can be provided at moderate energy and carbon levels by changing consumption patterns and redirecting systems in the direction of more sustainable resource use, suggesting that a special effort can be made in the near term for those on higher incomes who account for a disproportionate fraction of global emissions (Millward-Hopkins et al. 2020) (5.2.2).

The necessary transformational changes are likely to be more acceptable if rooted in the development aspirations of the economy and society within which they take place (Jones et al. 2013; Dubash 2012) and may enable a new social contract to address a complex set of inter-linkages across sectors, classes and the whole economy (Fleurbaey et al. 2018).

Taking advantage of windows of opportunity and disruptions to mindsets and socio-technical systems could advance deeper transformations. These might include the globally declining costs of renewables (Fig.1.7, 2.2.5, Box 16.2), emerging social norms for climate mitigation (Green and Denniss 2018), or the COVID-19 pandemic, all of which might be harnessed to centre political action on protecting human and planetary health (Büchs et al. 2020), but if not handled carefully could also risk to undermine the support for transformation.

5. How can shifts in development pathways be implemented by actors in different contexts?

Shifting development pathways to increased sustainability is a shared aspiration. Yet since countries differ in starting points (e.g., social, economic, cultural, political) and history, they have different urgent needs in terms of facilitating the economic, social, and environmental dimensions of sustainable development and, therefore, give different priorities (4.3.2, 17.4). The appropriate set of policies to shift development pathways thus depends on national circumstances and capacities.

In some developed countries and communities, affluence leads to high levels of consumption and emissions across sectors (Wiedmann et al. 2020; Mazur and Rosa 1974). For some countries, reducing consumption can reduce emissions without compromising on wellbeing. However, some developing countries still face the challenge of escaping "middle-income traps" (Agénor and Canuto 2015), as labour-saving technological change and globalisation have limited options to develop via the manufacturing sector (Altenburg et al. 2017). In least developed countries, infrastructure, industry, and public services are still being established, posing both a challenge to financial support to deploy technologies, and large opportunities to support accelerating low-to-zero carbon options (especially in terms of efficient and sufficient provision, (Millward-Hopkins et al. 2020)). Availability of capital, or lack thereof, is a critical discriminant across countries and requires international cooperation (15.2.2).

Shifting development pathways towards sustainability needs to be supported by global partnerships to strengthen suitable capacity, technological innovation (16.6), and financial flows (14.4.1, 15.2.4). The international community can play a particularly key role by helping ensure the necessary broad participation in climate-mitigation efforts, including by countries at different development levels, through sustained support for policies and partnerships that support shifting development pathways towards sustainability while promoting equity and being mindful of different transition capacities (4.3.2, 16.5, 16.6, 14.4, 17.4).

4.3.4.3 Expanding the range of policies and other mitigative options

'Traditional' policy instruments to induce climate mitigation have been focused on demand side or supply side, and include five basic categories: direct regulation; market-based (or economic) instruments; information policies; and other approaches including information provision and transparency, government provision of public goods or services; and facilitation of voluntary actions. Policies may be formulated into packages, seeking to achieve multiple objectives (see Chapter 13).

Shifting development pathways, on the other hand, entails policy approaches that include a broader range of instruments and initiatives, and impact more fundamentally on the actors, institutions and structures of societies and the dynamics among them. Consequently, focusing on shifting development pathways can establish supportive enabling conditions and alter the underlying drivers of emissions, opening up a wider range of mitigation opportunities and potential in the process of achieving development goals.

As shown in Figure 4.6, an approach of shifting development pathways can provide 'toolbox' containing a broad set of enablers and levers. Choices made by a range of decision makers at key points lead to worlds with a broader toolbox, and then it becomes feasible to accelerate mitigation and achieve other SDGs. Such development pathways can provide greater mitigative capacity, as they affect the ultimate drivers of emissions (and development generally), such as: the systemic and cultural determinants of consumption patterns, the political systems and power structures that govern decision making, the institutions and incentives that guide and constrain socio-technical innovation, and the norms and information platforms that shape knowledge and discourse, and culture, values and needs (Raskin et al. 2002). These ultimate drivers determine the mitigative capacity of a society, with capacity building assessed in AR5 (IPCC 2014a) and as part of strengthening the global response (IPCC 2019). While the evolution of these drivers is subject to varied influences and complex interactions, there are policy measures by which decision-makers might influence enabling conditions. Table 4.9 provides some examples of policy measures that can affect these drivers or high-level enabling conditions, the latter shown in the row headings.

Table 4.9 Enabling conditions and examples of policies and measures that can help shift development pathways

Enabling conditions	Examples of policy measures
Behaviour	• Progressive taxation • Ecological tax reform • Regulation of advertisement • Investment in public transit • Eco-labelling
Governance and institutions	• Campaign finance laws • Regulatory transparency • Commitment to multi-lateral environmental governance • Public investment in education and R&D • Public-service information initiatives • Public sector commitment to science-based decision-making
Innovation	• Investment in public education • Public sector R&D support • Fiscal incentives for private investments • International technology development and transfer initiatives
Finance and investment	• International investment treaties • Litigation and Liability regulations

	• Reform of subsidies and other incentives • Insurance sector and pension regulation • Green quantitative easing • Risk disclosure

Policies such as those listed in Table 4.9 are typically associated with broader objectives than greenhouse gas mitigation. They are generally conceived and implemented in the pursuit of overall societal development objectives, such as job creation, macro-economic stability, economic growth, and public health and welfare. However, they can have major influence on mitigative capacity, and hence can be seen as necessary tools if mitigation options are to be significantly broadened and accelerated (*medium evidence, medium agreement*).

Behaviour: Chapter 5 provides further detail on the impacts of large-scale, society-wide consumption patterns on mitigative capacity, and also the means by which past societal norms and preferences in consumption patterns can be influenced and evolve over time. Such changes result from policies aimed at meeting broader social objectives (e.g., that externalise social and environmental externalities), social movements that have catalytic or “tipping point” effects (e.g., student movements), and changes in institutions (e.g., educational curricula) (See Chapter 5).

Governance and institutions of decision-making can also strongly affect a society’s mitigative capacity (see 13.2). Policy measures can be taken to enhance institutional capacity, functional competence and technical expertise. Steps can also be taken to ensure democratic accountability and transparency. A major socio-economic transformation, such as the shift away from fossil fuel-based energy economy, can be expected to significantly disrupt the status quo, leading to a stranding of financial and capital assets and shifting of political-economic power. Ensuring the decision-making process is not unduly influenced by actors with much to lose is key to managing a transformation.

Innovation: socio-technical innovation applies to many domains, even when applied to a specific well-defined technology. For example, expanding the deployment of photovoltaics can draw upon policies that support specific technical innovations (e.g., to improve photovoltaics efficiency), or innovations in regulatory and market regimes (e.g., net-metering), to innovations in social organisation (e.g., community-ownership). More fundamentally, innovation regimes can be led and guided by markets driven by monetizable profits (as much of private sector led technological innovation of patentable intellectual property), or prioritise social returns (e.g., innovation structures such as innovation prizes, public sector innovation, investments in human capital, and socially-beneficial intellectual property regimes). Innovation in knowledge and discourse can be buttressed with more factual rigor with respect to the underlying challenges of climate change, both among the general public as well as among decision-makers.

Finance and investment: Chapter 15 includes a wide range of policy options for the finance sector aimed at redirecting investments from unsustainable to more sustainable options.

4.4 How to shift development pathways and accelerate the pace and scale of mitigation

4.4.1 Approaches, enabling conditions and examples

4.4.1.1 Framing the problem

What have we learned so far? As highlighted above, despite 30 years of UNFCCC and growing contributions by non-state actors, the emissions gap keeps growing (Section 4.2.2 and 4.2.3). Mitigation conceived as incremental change is not enough. Meeting ambitious mitigation goals entails rapid, non-marginal changes in production and consumption patterns (4.2.4 and 4.2.5). Taking another approach, we have seen in section 4.3 that shifting development pathways broadens the scope for mitigation (4.3.4) and offers more opportunities than mitigation alone to combine mitigation with the realisation of other SDGs (4.3.3, 4.3.2). Again incremental change is not enough, as meeting the diversity of SDGs implies non-marginal changes in development patterns (4.3.1).

A practical way forward is to combine shifting development pathways and accelerating mitigation (*medium evidence, medium-high agreement*). This means introducing multi-objective policy packages and sequences with climate and development components that both target mitigation directly and create the conditions for shifts in development pathways that will help accelerate further mitigation down the line, and meet other development objectives. Since development pathways result from a myriad of decisions from multiple actors (4.3.1), coordination across countries and with non-state actors is essential. To support this process, the literature points out the importance of good institutions and governance, and of channelling adequate private and public resources, the latter involving enlarging currently limited domestic fiscal space. The literature also points to the need to foster innovation—in technologies, but also in terms of institutions for instance—and behaviour change.

The academic literature does not provide a handbook on how to accomplish the above. However, analysis of past experience as well as understanding of how societies function yield insights that the present section aims at presenting.

Human history has seen multiple transformation of economies due to path-breaking innovations (Michaelowa et al. 2018), like the transformation of the energy system from traditional biomass to fossil fuels or from steam to electricity (Fouquet 2010, 2016a; Sovacool 2016). As a result, Fouquet (2016b) and Smil (2016) stress that even the most rapid global transformations have taken several decades. Enabling transformational change implies to create now the conditions that lead to that transformation (Díaz et al. 2019). The starting point is that there is no single factor determining such a transformation. Rather a range of enabling conditions can combine in a co-evolutionary process. Amongst the conditions that have been cited in the literature are higher levels of innovation, multilevel governance, transformative policy regimes or profound behavioural transformation (IPCC, 2018; Geels et al., 2018; Kriegler et al., 2017d; Rockström et al., 2017).

To present the insights from the literature on how to shift development pathways and accelerate the scale and pace of mitigation, this chapter uses broad categories the set of enabling conditions identified in the IPCC Special Report on Global Warming of 1.5°C, namely policy, governance and institutional capacity, finance, behaviour and lifestyles and innovation and technology (de Coninck et al. 2018b). As Figure 4.7 illustrates, *public policies* are required to foster both accelerating mitigation and shifting development pathways. Public policies play a special role here, since they are also vital to guide and provide the other enabling conditions (cf. Table 4.9, chapter 13). Improved governance and enhanced institutional capacity facilitate the adoption of policies that accelerate mitigation and shift development pathways, with the potential to achieve multiple mitigation and development objectives. Finance is required both to accelerate mitigation and to shift development pathways. As discussed in section 4.2.5, accelerated mitigation pathways encompass both rapid deployment of new technologies such as CCS or electric vehicles, as well as changes in consumption patterns: rapid deployment of mitigation *technology* and *behaviour change* are thus two enabling conditions to accelerated mitigation. Arguably, the latter also facilitates shifting development pathways. Finally, shifting development pathways towards sustainability can by itself be considered an enabling condition for accelerated mitigation, since it does open the scope for mitigation.

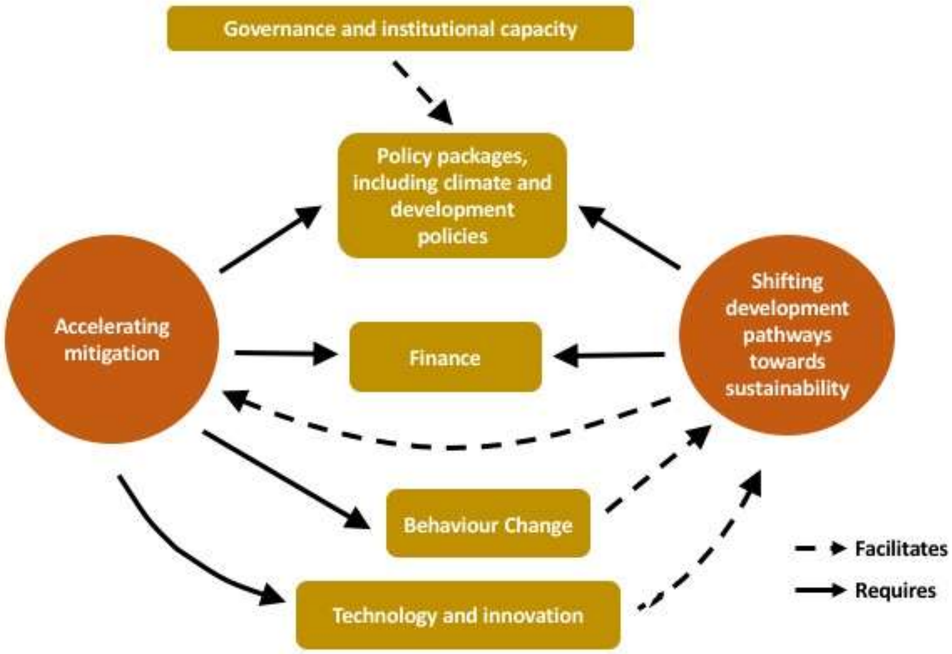

Figure 4.7 Enabling conditions for accelerating mitigation and shifting development pathways towards sustainability

Each of these categories is discussed at length in other Chapters of this Report, namely Ch.5 (behaviour change), 13 (policies, governance and institutional capacity), 15 (Finance) and 16 (Innovation). The purpose of the discussion below is to draw operational implications from these chapters for action, taking into account the focus of the present Chapter on action at the national level in the near- and mid-term, and the special emphasis on shifting development pathways in addition to accelerated mitigation.

The rest of the section is organised as follows. Policy packages that combine climate and development policies are first discussed (4.4.1.2). The next sections are dedicated to the conditions that facilitate shifts in development pathways and accelerated mitigation, namely governance and institutions (4.4.1.3), financial resources (4.4.1.4), behaviour change (4.4.1.5) and innovation (4.4.1.6). Four examples of how climate and development policies can be combined to shift pathways and accelerate mitigation are then presented (4.4.1.7, 4.4.1.8, 4.4.1.9 and 4.4.1.10). Section 4.4.2 focuses specifically on how shifts in development pathways can deliver both mitigation and adaptation. Finally, 4.4.3 discusses risks and uncertainties associated with combining shifting development pathways and accelerating mitigation.

4.4.1.2 Policy packages that include climate and development policies

Although many transformations in the past have been driven by the emergence and diffusion of an innovative technology, policy intervention was frequent, especially in the more rapid ones (Grubb et al.

2020; Michaelowa et al. 2018). Likewise, it is not expected that spontaneous behaviour change or market evolution alone can yield the type of transformations outlined in the accelerated mitigation pathways described in section 4.2.5, or in the shifts in development pathways described in 4.3.4. On the contrary, stringent temperature targets imply bold policies in the short term (Rockström et al. 2017; Kriegler et al. 2018) to enforce effective existing policy instruments and regulations, as well as to reform or remove harmful existing policies and subsidies (Díaz et al. 2019).

Policy integration is an essential component of shifting development pathways, addressing multiple objectives and exploring mitigation and adaptation synergies (*robust evidence, high agreement*). A shift in development pathways that includes accelerated mitigation, may best be achieved through integrated actions that comprise policies, both fiscal and other, in support of the broader SDG agenda (13.8, 13.9). Sectoral transitions that aspire to shift development pathways often have multiple objectives, and deploy a diverse mix or package of policies and institutional measures. For effectiveness, these should be based on country-specific priorities, including the impact of mitigation on employment and income distribution, and the need to ensure political support for mitigation.

Because low-carbon transitions are political processes, analyses are needed *of* policy as well as *for* policy (see 13.6.1 and 13.6.2). Political scientists have developed a number of theoretical models that both *explain* policy-making processes and provide useful insights for *influencing* those processes. Successful policy draws on a mix of methods and tools, which provide complementary insights (chapter 1). For example, theories of *policy networks* see policymaking as a deeply political process involving negotiations, compromises and the building of coalitions with stakeholders (Meckling et al. 2015). Similarly, policy implementation is considered in the socio-technical transition literature as a process also of improvisation, experimentation, and learning-by-doing, which can accelerate transitions (Geels et al. 2017). Scenarios are useful information for policymaking under uncertainty. Scenarios include narratives of futures (Raskin and Swart 2020; O'Neill et al. 2017), and global and national modelling can provide rigour in quantitative scenarios (O'Neill et al. 2016; Schwanitz 2013). Case studies of successes and failures in sustainable development and mitigation offer equally important insights. Robust decision-making techniques, risk-opportunity assessment, and participatory processes can aid the development and acceptance of decisions under uncertainty {1,13}

These considerations reinforce the argument that single policy instruments are not sufficient (*robust evidence, high agreement*). Policymakers might rather mobilise a range of policies, such as financial instruments (taxes, subsidies, grants, loans), regulatory instruments (standards, laws, performance targets) and processual instruments (demonstration projects, network management, public debates, consultations, foresight exercises, roadmaps) (Voß et al. 2007). Policies can be designed to focus on limiting or phasing out high-carbon technology. The appropriate mix is likely to vary between countries and domains, depending on political cultures and stakeholder configurations (Rogge and Reichardt 2016), but is likely to include a combination of: a) standards, nudges and information to encourage low-carbon technology adoption and behavioural change; b) economic incentives to reward low carbon investments; c) supply-side policy instruments including for fossil fuel production (to complement demand-side climate policies) (SEI et al. 2020; Green and Denniss 2018; Lazarus and van Asselt 2018) and d) innovation support and strategic investment to encourage systemic change (Grubb 2014). These approaches can be mutually reinforcing: for example, carbon pricing can incentivise low carbon innovation, while targeted support for emerging niche technologies can make them more competitive encourage their diffusion and ultimately facilitate a higher level of carbon pricing. Even in Germany, the success of a "demand-pull" instrument such as the feed-in tariffs only worked as well as it did because it formed part of a broader policy mix including "supply-push" mechanisms such as subsidies for research and "systemic measures" such as collaborative research projects and systems of knowledge exchange (Rogge et al. 2015).

4.4.1.3 Governance and institutional capacity

Governance for climate mitigation and shifting development pathways is enhanced when tailored to national and local contexts. Improved institutions and governance enable ambitious climate action and help bridge implementation gaps (*medium evidence high agreement*). If history is any guide, practices that can easily supplant existing systems and are clearly profitable move fastest (Griliches 1957). Changes that involve 'dissimilar, unfamiliar and more complex science-based components' take more time, acceptance and legitimation and involve complex social learning (Conley and Udry 2010), even when they promise large gains (Pezzoni et al. 2019). These processes involve a broad range of stakeholders, decision-maker actors and multiple regional and temporal scales. They necessitate a credible and trusted process for reconciling perspectives and balancing potential side-effects, managing winners and losers and adopting compensatory measures to ensure an inclusive just transition (Newell et al 2012; Miller and Richter 2014; Gambhir et al. 2018; Diffenbaugh and Burke 2019). Such processes are designed to manage the risk of inequitable or non-representative power dynamics (Helsinki Design Lab 2014; Kahane 2019; Boulle et al. 2015). More generally, stakeholder processes can be subject to regulatory capture by special interests. Information asymmetry between government and business may shape the results of consultative processes. Managing such risks requires sufficiently strong and competent institutions. Focused national climate institutions to address these challenges are more likely to emerge, persist and be effective when they are consistent with a framing of climate change that has broad national political support (*medium evidence, medium agreement*) (13.2, 13.5).

Innovative governance approaches can help meet these challenges (Clark et al. 2018; Díaz et al. 2019). *Enabling multilevel governance*—i.e., better alignment across governance scales—and coordination of international organisations and national governments can help accelerate a transition to sustainable development and deep decarbonisation (Tait and Euston-Brown 2017; Ringel, 2017; Cheshmehzangi, 2016; Revi, 2017; Michaelowa and Michaelowa 2017). *Participatory and inclusive governance*—partnerships between state and non-state actors—, and concerted effort across different stakeholders are crucial in supporting acceleration (Roberts 2016; Hering et al. 2014)(Figueres et al. 2017); Leal Filho et al. 2018; (Lee et al. 2018; Clark et al. 2018; Burch et al. 2014). So does *partnerships through transnational climate governance initiatives*, which coordinate nation-states and non-state actors on an international scale (Hsu et al. 2018). Although they are unlikely to close the gap of the insufficient mitigation effort of national governments (Michaelowa and Michaelowa 2017) (see section 4.2.3), they help building confidence in governments concerning climate policy and push for more ambitious national goals (UNEP 2018b).

Meeting these challenges also requires enhanced institutional capacity and enhanced institutional mechanisms to strengthen the coordination between multiple actors, improve complementarities and synergies between multiple objectives (Rasul 2016) (Ringel 2017) (Liu et al. 2018) and pursue climate action and other development objectives in an integrated and coherent way (Rogelj et al. 2018b; Von Stechow et al. 2016; McCollum et al. 2018; Fuso Nerini et al. 2019), (Roy et al. 2018) particularly in developing countries (Adenle et al. 2017) (Rosenbloom 2017). Institutional capacities to be strengthened include vertical collaboration and interaction within Nation-States and horizontal collaboration (e.g., transnational city networks) for the development and implementation of plans, regulations and policies. More specifically capacities include: capacity for knowledge harnessing and integration (from multiple perspectives); capacity for integrated policy design and implementation (Scott 2017); capacity for long-term planning (Lecocq et al. 2020) capacity for monitoring, and review process; capacity for coordinating multi-actor processes to create synergies and avoid trade-offs. As a result, institutions that enable and improve human capacities and capabilities are a major driver of transformation. To this extent, promoting education, health care and social safety, also are instrumental to undertake climate change mitigation and cope with environmental problems (Sachs et al. 2019; Winkler et al. 2007).

4.4.1.4 Channelling financial resources

Accelerated mitigation and shifting development pathways necessitates both re-directing existing financial flows from high- to low-emissions technologies and systems and to provide additional resources (*robust evidence, high agreement*). An example are changes in investments from fossil fuels to renewable energy, with pressures to disinvest in the former and increasing levels of 'green finance' (6, 15). Some renewable energy technologies have become competitive (section 4.2, chapter 2), so that public support is needed the extent that the low-emissions options have higher costs per unit of service provided than high-emission development pathways. Chapter 12 provides an overview of mitigation costs, and Chapter 15 an overview of the shifts in stocks and flows along several pathways. Lack of financial resources, on the other hand, is identified as a major barrier to the implementation of accelerated mitigation and of shifts in development pathways. Providing financial resources has two major components. One relates to private capital. The other to public finance.

There is substantial amount of research on the redirection of financial flows towards low-carbon investment, as detailed in Chapter 15. Financial systems are an indispensable element of a systemic transition (Fankhauser, Sahni, Savvas, & Ward, 2016; Naidoo 2020). Policy frameworks can re-direct financial resources towards low-emission assets and services (UNEP 2015), mainstreaming climate finance within financial and banking system regulation, and reducing transaction costs for bankable mitigation technology projects (Mundaca et al. 2013; Brunner and Enting 2014)(Yeo 2019). Shifts in the financial system to finance climate mitigation and other SDGs can be achieved by aligning incentives and investments with multiple objectives (UNEP Inquiry 2016).

Different approaches have been developed to improve such alignment, from national credit policies to directly green mainstream financial regulations (e.g., through modifications in the Basel rules for banks). For all approaches, an essential precondition is to assess and monitor the contribution of financial flows to climate and sustainability goals, with better metrics that clearly link with financial activity (Chenet et al. 2019).

Enabling the alignment of investment decision-making with achieving climate and broader sustainability goals includes acknowledging and disclosure of both climate-change related risk and of risks associated with mitigation in financial portfolios. Reliable information on financial exposure to these risks and opportunities will facilitate financing the transition. However, current disclosures remain far from the scale the markets need to channel investment to sustainable and resilient solutions (Clark et al. 2018; Masson-Delmotte et al. 2018; UNEP - Finance Initiative 2020)(Task Force on Climate-Related Financial Disclosures 2019).

Disclosure helps address behavioural biases and improve pricing and market efficiency, but is not enough (Ameli et al. 2020). In addition, climate targets can be translated into investment roadmaps and financing needs for financial institutions, both at national and international level. Financing needs are usable for financial institutions, to inform portfolio allocation decisions and financing priorities (Chenet et al. 2019). At the international level, for example, technology roadmaps for key sectors can be translated into investment roadmaps and financing needs, as shown by existing experiences in energy and industrial sectors (Chenet et al. 2019; WBSCD 2018; International Energy Agency 2015)

The transition from traditional public climate finance interventions to the market-based support of climate mitigation (Bodnar et al. 2018) demands innovative forms of financial cooperation and innovative financing mechanisms to help de-risk low-emission investments and support new business models. These financial innovations may involve sub-national actors like cities and regional governments in raising finance to achieve their commitments (Cartwright 2015) (CCFLA 2017). Moreover, public-private partnerships have proved to be an important vehicle for financing investments to meet the Sustainable Development Goals, including economic instruments for financing conservation (Díaz et al., 2019; Sovacool 2013).

Early action is needed to overcome barriers and to adjust the existing incentive system to align national development strategies with climate and sustainable development goals in the medium-term. (Steckel et al. 2017) conclude that climate finance could become a central pillar of sustainable development by reconciling the global goal of cost-efficient mitigation with national policy priorities. Without a more rapid, scaled redeployment of financing, in development trajectories that hinder the realisation of the global goals will be locked in (Zadek and Robins 2016). Investment might be designed to avoid trading off the Paris goals against other SDGs, as well as those that simultaneously reduce poverty, inequality, and emissions (Fuso Nerini et al. 2019).

At the national level, it is also essential to create fiscal space for actions promoting the SDG agenda and thereby broadening the scope of mitigation (*medium evidence, medium agreement*). To do so, the pricing of carbon is favoured by leading economists as an efficient means of discouraging carbon emissions throughout an economy (both in consumption and production) at the same time as it encourages a switch to non-carbon energy sources and generates revenues for prioritised actions. Carbon pricing may be achieved in two ways: tax payments based on the level of emissions or cap-and-trade systems that limit total allowable emissions. With regard to levels, the High-Level Commission on Carbon Prices concluded that “the explicit carbon-price level consistent with achieving the Paris temperature target is at least USD40–80/tCO_2 by 2020 and USD50–100/tCO_2 by 2030, provided a supportive policy environment is in place” (CPLC 2017; Wall Street Journal 2019). Fiscal space may also stem from other sources than carbon taxes. Countries may explore the room to add to it via increases in other taxes and reduced spending in low-priority areas. Fiscal reforms are complex endeavours (see 4.4.1.8). For countries at lower income levels, foreign aid can make an important contribution to the same agenda (Kharas and Mcarthur 2019).

It may also be noted that, according to estimates at the global level, military spending amounted to USD1.748 trillion in 2012 (the last year with data), a figure that corresponded to 2.3 percent of GDP, 55 percent of government spending in education, and was 13 times the level of net ODA (World Bank 2020; SIPRI 2020). Given this, moderate reductions in military spending (which may involve conflict resolution and cross-country agreements on arms limitations) could free up considerable resources for the SDG agenda, both in the countries that reduce spending and in the form of ODA. The resolution of conflicts within and between countries before they become violent would also reduce the need for public and private spending repairing human and physical damage. The fact that civil wars are common in the countries that face the severest SDG challenges underscores the importance of this issue (Collier 2007, pp. 17-37).

International climate finance could support countries to introduce carbon pricing or remove fossil fuel subsidies, creating a fiscal space that may be used in support of the countries’ sustainable development objectives. It also encourages less carbon-intensive production and consumption (Wall Street Journal 2019; Farid et al. 2016; (World Bank 2014) CPLC 2017).

4.4.1.5 Changing behaviour and lifestyles

Changes in behaviour and lifestyles are important to move beyond mitigation as incremental change, and when supporting shifts to more sustainable development pathways will broadening the scope of mitigation (*medium evidence, medium agreement*). Global mitigation pathways in line with well below 2°C and 1.5°C temperature limits assume substantial behavioural and societal change and low-carbon lifestyles as critical enabling factors (Masson-Delmotte et al. 2018; Rogelj et al. 2018a) (see 4.2.5).

Behavioural changes within transition pathways offer Gigaton-scale CO_2 savings potential at the global level, and therefore represent a substantial overlooked strategy in traditional mitigation scenarios (5.3.3.2).

Reaching the Paris Agreement goals will likely rely in part on reduced consumption of high-emissions goods and services. Table 4.9 and Figure 4.3 from IPCC SR1.5 shows examples of mitigation and adaption actions relevant for 1.5ºC-consistent global mitigation pathways (de Coninck et al. 2018b).

Individual motivation and capacity are impacted by different factors that go beyond traditional social, demographic and economic predictors (5.4.1). However, it is unclear to what extent behavioural factors (i.e., cognitive, motivational and contextual aspects) are taken into account in policy design.(Luis Mundaca, Sonnenschein, Steg, Höhne, & Ürge-Vorsatz, 2019; Dubois et al. 2019). Transformative policies are much more likely to be successfully adopted and lead to long-term behavioural change if they are designed in accordance with principles of cognitive psychology (van der Linden et al. 2015). Actors in society, particularly individuals, do not respond in an economically "rational" manner based on perfect-information cost-benefit analyses, and compelling narratives can drive individuals to adopt new norms and policies (Shiller 2019)(Runge 1984). Rather, norms can be more quickly and more robustly shifted by proposing and framing policies designed with awareness of how framings interact with individual cognitive tendencies (van der Linden et al. 2015).

Economic policies can play a significant role in influencing people's decisions and behaviour. However, many drivers of human behaviour and values, work largely outside the market system. (Díaz et al. 2019; Winkler et al. 2015). Policymakers can design more effective policies to shift consumption patterns by using the deep understanding of decision-making offered by behavioural science (UNEP 2017b).

Climate actions are related to knowledge but even strongly to motivational factors (Hornsey et al. 2016) (Bolderdijk et al. 2013); (Boomsma and Steg 2014), which explains the gap between awareness and action (Ünal et al. 2018). Social influences, particularly from peers, affect people's engagement in climate action (Schelly 2014). Role models appear to have a solid basis in people's everyday preferences (WBGU 2011). Social norms can reinforce individuals' underlying motivations and be effective in encouraging sustainable consumption patterns, as many examples offered by behavioural science. Social networks also influence and spread behaviours. (Service et al. 2014) (Clayton et al. 2015)(Farrow et al. 2017)(Shah et al. 2019). These social influences can be addressed in climate policy.

However, behavioural change not embedded in structural change, will contribute little to climate change mitigation, suggesting that behavioural change is not only a function of individual agency but also depends on other enabling factors, such as infrastructures, institutions and social norms (see 5.4). Shifts towards public transport, for instance, involve new technologies (buses, trams), infrastructures (light rail, dedicated bus lanes), regulations (operational licenses, performance contracts), and institutions (new organisations, responsibilities, oversight) (see 5.4.1; 5.4.5).

Collective action by individuals as part of formal social movements or informal lifestyle movements underpins system change (*robust evidence, high agreement*) (5.4, 5.5). Organisations are comprised of individuals, but also become actors in their own right. Recent literature has considered the role of coalitions and social movements in energy democracy and energy transitions towards sustainability (Hess 2018). Other scholars have examined the role of women in redistributing power, both in the sense of energy transition and in terms of gender relations (Allen et al. 2019)(Routledge et al. 2018). It may also be noted that changes in economic structure will have gender implications given the fact that the roles of men and women vary across sectors. For example, in many developing countries, sectors in which women play a relatively important role, including agriculture and unpaid household services like collection of water and fuel wood, may be negatively affected by climate change (Roy 2018). Mitigation and broader sustainable development policies that facilitate active participation by stakeholders can build trust, forge new social contracts, and contribute to a positive cycle building climate governance capacity {5.2.3, 5.4.1, 5.4.5.3}.

Transformational strategies that align mitigation with subjective life satisfaction, and build societal support by positive discourses about economic, social, and cultural benefits of low-carbon innovations, promises far more success than targeting mitigation alone (WBGU 2011; Asensio and Delmas 2016; Geels et al. 2017). Given that present bias - being motivated by costs and benefits that take effect immediately than those delivered later- significantly shapes behaviour, schemes that bring forward distant costs into the present or that upfront incentives, have proved to be more effective (Zauberman et al. 2009)(van den Broek et al. 2017)(Safarzyńska 2018).

There is high confidence in the literature that the interactions between forces of agency, structure and meaning are driving a low-carbon transition (5.4). The twin goal of attaining wellbeing for all, and mitigating climate change shapes demand-side service-oriented solutions {*high confidence*} (5.2.1, 5.2.2, Table 5.1, Figure 5.5, Box 5.2).

4.4.1.6 Fostering Technological Innovation

As outlined in section 4.2.5, rapid, large-scale deployment of improved low-carbon technology is a critical component of accelerated mitigation pathways. As part of its key role in technological change, Research and Development (R&D) can make a crucial contribution to accelerated mitigation up to 2030 and beyond, among other things by focusing on closing technology gaps that stand in the way of decarbonising today's high emitting sectors, in support their future viability. Such sectors include shipping, trucking, aviation and heavy industries like steel, cement and chemicals. Government policies can play a key role by providing resources and favourable incentives (IEA 2020).

The direction of innovation matters (robust evidence, high agreement). The research community has called for more "responsible innovation," (Pandza and Ellwood 2013) "open innovation," (Rauter et al. 2019) "mission-oriented" (Mazzucato and Semieniuk 2017) innovation, "holistic innovation," (Chen et al. 2018b) "next-generation innovation policy," (Kuhlmann and Rip 2018) or "transformative innovation" (Schot and Steinmueller 2018) so that innovation patterns and processes are commensurate to our growing sustainability challenges. There is a growing recognition that new forms of innovation can be harnessed and coupled to climate objectives (Fagerberg et al. 2016; Wang et al. 2018). As such, innovation and sociotechnical change can be channelled to intensify mitigation via "deliberate acceleration" (Roberts et al. 2018a) and "coalition building" (Hess 2018). Deep decarbonisation in sectors with long lived capital stock (such as heavy industry, buildings, transport infrastructure) will entail simultaneous technology, policy and financing innovations (Bataille 2020).

In addition to individual technologies, system innovation is a core focus of the transitions literature (Grin et al. 2010; Markard et al. 2012; Geels et al. 2017). Accelerating low carbon transitions not only involves a shift of system elements but also underlying routines and rules, and hence transitions shift the directionality of innovation. They hence concern the development of a new paradigm or regime that is more focused on solving sustainability challenges that cannot be solved within the dominant regime they substitute. Several studies have pointed at the important possible contributions of grassroots innovators for the start-up of sustainability transitions (Seyfang and Smith 2007; Smith et al. 2016; Seyfang et al. 2014). In particular, a range of studies have shown that users can play a variety of roles in promoting system innovation: shielding, nurturing (including learning, networking and visioning) and empowering the niches in relation to the dominant system and regime (Schot et al. 2016; Randelli and Rocchi 2017; Meelen et al. 2019).

More broadly, it is increasingly clear that digital changes are becoming a key driving force in societal transformation (Tegmark 2017). Digitalisation is not only an "instrument" for resolving sustainability challenges, it is also a fundamental driver of disruptive, multiscalar change (Sachs et al. 2019) Information and communication technologies (ICT), artificial intelligence (AI), the internet of things (IOT), nanotechnologies, biotechnologies, robotics, are not usually categorised as climate technologies, but have a potential impact on GHG emissions (OECD 2017)).

4.4.1.7 Structural change provides a way to keep jobs and mitigate

Developing countries have experienced a period of rapid economic growth in the past two decades. Patterns of growth have differed markedly across regions, with newly emerging East Asian economies building on transition to manufacturing—as China has done in the past—while Latin American countries tend to transition directly from primary sector to services (Rodrik 2016), and African countries tend to rely on productivity improvements in the primary sectors (Diao et al. 2019). Yet many countries still face the challenge of getting out of the "middle-income trap" (Agénor and Canuto 2015), as labour-saving technological change and globalisation have limited options to develop via the manufacturing sector (Altenburg et al. 2017).

Looking ahead, several studies have illustrated how structural change towards sustainability could lead to reduced emissions intensity and higher mitigative capacity. In China, for example, the shift away from heavy industry (to light industry and services) has already been identified as the most important force limiting emissions growth (Guan et al. 2018), and as a major factor for future emissions (Kwok et al. 2018).

Overall, (Altenburg et al. 2017) argue that reallocation of capital and labour from low- to high-productivity sectors—i.e., structural change—remains a necessity, and that it is possible to combine it with reduced environmental footprint (including, but not limited to, mitigation). They argue that this dual challenge calls for structural transformation policies different from those implemented in the past, most importantly through a "systematic steering of investment behaviour in a socially agreed direction" and encompassing policy coordination (*limited evidence, medium agreement*).

In order to permit progress on their SDG agendas, it is essential that countries develop visions of their future decarbonised sectoral production structure, including its ability to generate growth in incomes, employment and foreign exchange earnings. as well as the related spatial distribution of production, employment, and housing. To this extent, governance and institutional capacity matter, such as availability of tools to support long-term planning. A sectoral structure that permits strong growth is essential given strong associations between growth in per-capita incomes and progress on most SDGs (including those related to poverty; health; education; and access to water, sanitation, electricity, and roads; but not income equality), in part due to the fact that higher incomes provide both households and governments with resources that at least in part would be used to promote SDGs (Gable et al. 2015).

The future viability of sectors will depend on the extent to which they can remain profitable while relying on renewable energy. The challenge to identify alternative sectors of growth is particularly acute for countries that today depend on oil and natural gas for most of their foreign exchange and government revenues (Mirzoev et al. 2020). In the context of measures to promote gender equality (SDG 5), it may also be important to take complementary actions to address the gender implications of changes in economic structure, which stem from the fact that the roles of men and women vary across sectors. For example, in many developing countries, sectors in which women play a relatively important role, including agriculture and unpaid household services like collection of water and fuel wood, may be negatively affected by climate change (Roy et al. 2018).

Given strong complementarities between policies discussed above, an integrated policy approach is crucial. For example, as suggested, the actions that influence the pace at which GHG emissions can be cut with political support may depend on taxation (including carbon taxes), investments in infrastructure, spending on R&D, changes in income distribution (influenced by transfers), and communication. In this light, it is important to consider the demands that alternative policy packages put on government policy-making efficiency and credibility as well as the roles of other enabling conditions. In fact, plans to undertake major reforms may provide governments with impetus to accelerate the enhancement of their capacities as part of the preparations (Karapin 2016; Jakob et al 2019; Withana & Sirini 2016)

4.4.1.8 Embedding carbon finance in broader fiscal reforms offers a way to mitigate and rethink the social contract

In many countries, fiscal systems are currently under stress to provide resources for the implementation of development priorities, such as, for example, providing universal health coverage and other social services (Meheus and McIntyre 2017) or sustainably funding pension systems in the context of aging populations (Asher and Bali 2017; Cruz-Martinez 2018). Overall, (Baum et al. 2017) argue that low-income countries are likely not to have the fiscal space to undertake the investment entailed in reaching the SDGs. To create additional fiscal space, major options include improving tax recovery, reducing subsidies and levying additional taxes.

Mitigation offers an opportunity to create additional fiscal space, and thus to serve the objectives outlined above, by creating a new source of revenue for the government via carbon taxation or emissions permit auctioning and by reducing existing expenditures via reduction in subsidies to fossil-fuel. The 1991 tax reform in Sweden is an early example in which environmental taxation (including, but not limited to, fossil fuel taxation) was introduced as part of a package primarily aimed at lowering the marginal tax rates (more than 80% at the time), at reducing other taxes, while keeping most of the welfare state. To do so, the tax base was broadened, including through environmental and carbon taxation (Sterner 2007). Once in place, the carbon tax rate was substantially ramped up over time, and its base broadened (Criqui et al. 2019).

The future potential for using carbon taxation as a way to provide space for fiscal reform has been highlighted in the so-called “green fiscal reform” literature (Vogt-Schilb et al. 2019). The potential is large, since only 13.1 percent of global GHG emissions were covered by carbon pricing schemes in 2019 (Watts et al. 2019) and since many countries price carbon negatively by subsidising fossil fuel use, thus generating effects that are the opposite of those that positive carbon prices hope to promote. In 2018, the global subsidy value amounted to $427 billion, i.e., some 10 times the payment for carbon use (Watts et al. 2019). However, the size of the potential for creating fiscal space varies strongly across countries given differences in terms of current carbon prices and fuel subsidies.

The limited adoption of and political support for carbon pricing may be explained by the fact that most of the gains occur in the future and depend on actions across the globe, making them seem abstract and unpredictable, whereas the costs in the form of higher carbon prices are immediate (Karapin 2016). Furthermore, the links between carbon pricing and emissions may not be clear to the public who, in addition, may not trust that the government will use budgetary savings according to stated plans. The latter may be due to various factors, including a history of limited government commitment and corruption (Maestre-Andrés et al 2019 ; Withana & Sirini 2016; Chadwick 2017).

The literature reports limited systematic evidence based on *ex post* analysis of the performance of carbon pricing–carbon taxes and greenhouse gas (GHG) emissions trading systems (ETSs) (Haites 2018). Performance assessment is complicated by the effect of other policies and exogenous factors. (Haites 2018) suggests that since 2008, other policies have probably contributed more to emission reductions than carbon taxes, and most tax rates are too low to achieve mitigation objectives. Emissions under ETSs have declined, with the exception of four systems without emissions caps (ibid). Every jurisdiction with an ETS and/or carbon tax also has other policies that affect its GHG emissions.

To help policymakers overcome obstacles, research has reviewed the international experience from carbon pricing reforms. Elimination of fossil fuel subsidies, equivalent to the elimination of negative carbon prices, have been more successful when they have included complementary and transparent measures that enjoy popular support, accompanied by a strong communications component that explains the measures and stresses their benefits (Rentschler and Bazilian 2017; Withana & Sirini 2016; Maestre-Andrés et al 2019).

Part of the losses (and related calls for compensation or exemptions) due to carbon pricing are related to the fact that it hurts the competitiveness of sectors that face imports from countries with lower carbon prices, leading to "carbon leakage" if carbon-intensive production (and related jobs) migrates from countries with relatively high carbon prices. Research confirms that a border carbon tax (or adjustment), set on the basis of the carbon content of the import, including a downward adjustment on the basis of any carbon payments (taxes or other) already made before entry, could reduce carbon leakage while also raising additional revenue and encouraging carbon pricing in the exporting country (Withana & Sirini 2016; Cosbey et al 2019).

The timing of carbon pricing reforms is also important: they are more likely to succeed if they exploit windows of opportunity provided by events that raise awareness of the costs of carbon emissions (like bouts of elevated local air pollution or reports about the role of emissions in causing global warming), as well as momentum from climate actions by other countries and international climate agreements (Karapin 2016; Jakob et al 2019). It is also important to consider the level of international prices of carbon energy: when they are low, consumer resistance would be smaller since prices will remain relatively low, though the tax may become more visible when energy prices increase again. As part of ongoing efforts to accelerate mitigation, such tax hikes may be crucial to avoid a slow-down in the shift to renewable energy sources (Rentschler and Bazilian 2017; Withana & Sirini 2016). In countries that exports carbon energy, carbon taxation may run into additional resistance from producers.

There is also considerable literature providing insights on the political and social acceptability of carbon taxes, suggesting for example that political support may be boosted if the revenue is recycled to the tax payers or earmarked for areas with positive environmental effects (e.g., (Bachus et al. 2019) for Belgium, and (Beiser-McGrath and Bernauer 2019) for Germany and the USA), as well as on the difficulties associated with political vagaries (and economic consequences thereof) associated with the introduction of such instruments (Pereira et al. 2016). Similarly, "best practice" have been drawn from past experience on fossil-fuel subsidy reforms (Sovacool 2017; Rentschler and Bazilian 2017). Specific policies, however, depend on societal objectives, endowments, structure of production, employment, and trade, and institutional structure (including the functioning of markets and government capacity) (Kettner et al. 2019). As noted in Section 4.3.3, macroeconomic analysis finds that the overall economic implications of carbon pricing differ markedly depending on the way the proceeds from carbon pricing are used, and thus on the way the fiscal system is reformed, with potential for double dividend if the proceeds from the tax are used to repeal the most distortive taxes in the economy.

In the context of this section on development pathways, it is worth emphasising that potential revenues drawn from the climate mitigation component of the fiscal reform varies strongly with the context, and may not be sufficient to address the other objectives pursued. Even if the carbon price is high, the revenue it generates may be moderate as a share of GDP and eventually it will be zero if emissions are eliminated. For example, (Jakob et al. 2016) find that the carbon pricing revenues that most countries in Sub-Saharan Africa could expect to generate only would meet a small part of their infrastructure spending needs. In Sweden, the country with the highest carbon tax rate in the world, the tax has not been a significant part of total tax revenues. Moreover, emissions from sectors covered by the tax have shrunk and, as a result, the revenues from the tax, as a share of GDP, have also declined, from a peak of 0.93 percent in 2004, when the rate was USD109 per metric ton of CO_2, to 0.48 per cent in 2018, when the rate had reached USD132 (Jonsson, Samuel, Anders Ydstedt 2020; Statistics Sweden 2020). This means that governments that want to avoid a decline in the GDP share for total tax revenues over time would have to raise the intake from other taxes. However, it is here important to note that domestic tax hikes are likely to involve trade-offs since, at the same time as the spending they fund may provide various benefits, they may also reduce the capacity of households and the private sector to consume and invest, something that may reduce growth over time and reduced resources for spending in support of human development (Lofgren et al. 2013). It is also worth emphasising that restructuring of the fiscal system amount to changes in the social contract of the society (Combet and Hourcade 2017, 2014), and thus represents a major economic and social decision.

4.4.1.9 Combining housing policies with carbon taxation can deliver both housing and mitigation in the transport sector

The spatial distribution of households and firms—across both urban and rural areas—is a central characteristic of development pathways. Patterns of urbanisation, territorial development, and regional integration have wide-ranging implications for economic, social and environmental objectives. (World Bank 2009). Notably, choices regarding spatial forms of development have large-scale implications for demand for transportation, and associated GHG emissions.

Exclusionary mechanisms such as decreasing accessibility and affordability of inner-urban neighbourhoods is a major cause of suburbanisation of low- to middle-income households (e.g., (Hochstenbach and Musterd 2018). Suburbanisation, in turn, is associated with higher transportation demand (Bento et al. 2005) and higher carbon footprints for households (Jones and Kammen 2014). Similarly, other studies find significant positive link between housing prices and energy demand (Lampin et al. 2013).

Reducing emissions from transport in cities through traditional climate policy instruments (e.g., through a carbon tax) is more difficult when inner-urban neighbourhoods are less accessible and less affordable, because exclusionary mechanisms act as a countervailing force to the rising transportation costs induced by the climate policy, pushing households outwards rather than inwards. Said differently, the costs of mitigating intra-city transportation emissions are higher when inner-urban housing prices are higher (Lampin et al. 2013).

This suggests that policies making inner-urban neighbourhoods more accessible and more affordable can open up broader opportunities for suburban households to relocate in the face of increasing transportation costs. This is particularly important for low- and middle-income households, who spend a greater portion of their income on housing and transportation, and are more likely to be locked into locations that are distant from their jobs. Making inner-urban neighbourhoods more accessible and more affordable has the potential to reduce both the social costs—e.g., households feeling helpless in front of rising fuel prices—and the economic costs of mitigation policies—as a lower price of carbon is likely to achieve the same amount of emission reductions since households have more capacities to adjust.

Making inner-cities neighbourhoods more accessible and more affordable for the low- or middle-income people in cities in which rents in inner-areas are too high is a complex endeavour (Benner and Karner 2016). At the same time, it is already a policy objective in its own right in many, independent of the climate mitigation motivation, for a range of social, health and economic reasons. Revenues derived from climate policies could provide additional resources to support such programs, as some climate policy already have provisions to use their revenues towards low-income groups (Karner and

Marcantonio 2018). The mitigation benefits of keeping inner-cities more accessible and affordable for low- and middle-income households often remains out of, or is only emerging in the debates surrounding the planning of fast-developing cities in many developing countries (Grant 2015; IADB 2012; Khosla and Bhardwaj 2019). Finally, from a political economy perspective, it is also interesting to note that (Bergquist et al. 2020) find higher support for climate policy packages in the U.S. when affordable housing programs are included.

In addition, investment in infrastructure is critical to the development of decarbonised economic structures that generate growth, employment, and universal access to a wide range of services that are central to the SDG agenda: transportation, water, sanitation, electricity, flood protection, and irrigation. For low- and middle-income countries, annual costs of reaching these goals by 2030 and putting their economies on a path toward decarbonisation may range between 2 and 8 percent of GDP, with the level depending on spending efficiency. Notably, these costs need not exceed those of more polluting alternatives. For transportation, this involves a shift toward more public transportation (rail and bus), and decarbonised electricity for vehicles, combined with land-use policies that densify cities and reduce distances between homes and jobs. By influencing the spatial distribution of households and firms and the organisation of transportation, infrastructure has a strong bearing on GHG emissions and the costs of providing services to different populations. Depending on country context, the private sector may play a particularly important role in the financing of infrastructure (Rozenberg and Fay 2019) (World Bank 2009)(Klein 2015).

Many investments in infrastructure and sectoral capital stocks have long lifetimes. Given this, it may be important to make sure that today's investments be fully decarbonised at the start or that they later can be converted to zero carbon. Today's investments in electric vehicles in settings where electricity is produced with fossil fuels is an example of convertible investments -- they will be decarbonised once electricity production has switched to renewable energies. For capital stocks that cannot be decarbonised, countries may face costs of decommissioning well before the end of their useful lifetimes, especially when it is needed to respect country commitments to future full decarbonisation.

4.4.1.10 Changing economic, social and spatial patterns of development of the agriculture sector provide the basis for sustained reductions in emissions from deforestation

A growing literature addresses the complex interactions between development paths, climate mitigation, and enabling conditions to promote mitigation capacity without undermining development opportunities. As the energy and AFOLU sectors are the largest sources of GHG emissions, emphasis is often given to the roles of these two sectors. The literature assesses co-benefits of sectoral policies that lead to decarbonisation pathways and simultaneously promote economic development, improve living standards, reduce inequality, and create job opportunities (Bataille et al. 2016b, 2018; Pye et al. 2016; Maroun and Schaeffer 2012; Richter et al. 2018; La Rovere et al. 2018; Waisman et al. 2019)

While this may be particularly challenging in developing countries, given large populations still lacking basic needs, previous development paths show that finding synergies in development and climate objectives in the AFOLU sector is possible. One example is Brazil, which has arguably shifted its development pathway to reduce emissions and make progress towards several SDGs, though progress is not linear. Over the past two decades, Brazil had made remarkable progress in implementing a sequence of policies across multiple sectors. This policy package simultaneously increased minimum wages of low income families, achieved universal energy access, and raised the quality of life and well-being for the large majority of the population (Bezerra et al. 2017; Grottera et al. 2018, 2017b; La Rovere et al. 2018). This led to significant social benefits, reduction of income inequality and poverty eradication (Bezerra et al. 2017; Grottera et al. 2017b), reflected in a decrease of the Gini coefficient and a rise in the human development index (La Rovere 2017).

Regulatory instruments were used to limit deforestation rates, together with implemented economic instruments that provided benefits to those protecting local ecosystems and enhancing land-based carbon sinks (Soterroni et al. 2019, 2018; Bustamante et al. 2018; Nunes et al. 2017). In parallel, public policies reinforced environmental regulation and command-and-control instruments to limit deforestation rates and implemented market-based mechanisms to provide benefits to those protecting local ecosystems and enhancing land-based carbon sinks (Sunderlin et al. 2014; Hein et al. 2018; Simonet et al. 2019; Nunes et al. 2017). The private sector, aligned with public policies and civil society, implemented the Amazon Soy Moratorium, a voluntary agreement that bans trading of soybeans from cropland associated with cleared Amazon rainforest and blacklists farmers using slave labour. This was achieved without undermining production of soybean commodities (Soterroni et al. 2019). As a result, between 2005 and 2012, the country halved its GHG emissions and reduced the rate of deforestation by 78 per cent (INPE 2019a,b). This example shows that development delivering well-being can be accompanied by significant mitigation. A long-term and strategic vision was important in guiding enabling policies and mechanisms.

In more recent years, some of these shifts in Brazil's development pathways were undone. Political changes have redefined development priorities, with higher priority being given to agricultural development than climate change mitigation. The current administration has reduced the power of environmental agencies and forestry protection laws (including the forest code), while allowing the expansion of cropland to protected Amazon rainforest areas (Ferrante and Fearnside 2019; Rochedo et al. 2018). As a result, in 2020, the deforestation exceeded 11,000 km^2, and reached the highest rate in the last 12 years (INPE 2020) [*update consolidated numbers from 2020 in FGD*]. The literature cautions that, if current policies and trends continued, the Amazon may reach an irreversible tipping point beyond which it will be impossible to remediate lost ecosystems and restore carbon sinks and indigenous people knowledge (Nobre 2019; Lovejoy and Nobre 2018; INPE 2019a). Further, fossil fuel subsidies and other fiscal support of increased exploitation of oil resources may create carbon lock-ins that inhibit further low-carbon investments (Lefèvre et al. 2018).

Brazil's progress in mitigation depended significantly on reduced deforestation in the past. If deforestation rates keep on rising, mitigation efforts would need to shift to the energy sector. However, according to Rochedo et al. (2018), mitigation costs in the energy sector in Brazil are three times the costs of reducing deforestation and increasing land-based carbon sinks. Further mitigation strategies may depend on CCS in Brazil as elsewhere (Nogueira de Oliveira et al. 2016; Herreras Martínez et al. 2015), though the economic feasibility of deployment is not yet clear (4.2.5).

4.4.2 Links to adaptation

Mitigation actions are strongly linked to adaptation. These connections can come about because mitigation actions can be adaptive (e.g., some agroforestry projects) but also through policy choices (e.g., climate finance is allocated among adaptation or mitigation projects) and even biophysical links (e.g., climate trajectories can influence the viability of adaptation projects. As development pathways shape the levers and enablers available to a society, a broader set of enabling conditions also helps with adaptation (*medium evidence, high agreement*).

Previous assessments have consistently recognised this linkage. The Paris Agreement includes mitigation and adaptation as key areas of action, through "nationally determined contributions" (NDCs) and communicating adaptation actions and plans. The Agreement and recognises that adaptation is a global challenge faced by all with local, subnational, national, regional and international dimensions. IPCCs Fifth Assessment Report (IPCC 2014b) emphasised that sustainable development is helpful in going beyond a narrow focus on separate mitigation and adaptation options and their specific co-benefits. The IPCC special report on climate change and land addresses greenhouse gas emissions from land-based ecosystems with a focus on the vulnerability of land-based systems to climate change. The report identifies the potential of changes to land use and land management practices to mitigate and adapt to climate change, and to generate co-benefits that help meet other sustainable development goals (Add reference to SRCCL).

A substantial literature detailing trade-offs and synergies between mitigation and adaptation exists and is summarised in the IPCC special report on Global Warming of 1.5°C including energy system transitions; land and ecosystem transitions (including addressing food system efficiency, sustainable agricultural intensification, ecosystem restoration); urban and infrastructure system transitions (including land use planning, transport systems, and improved infrastructure for delivering and using power); industrial system transitions (including energy efficiency, bio-based and circularity, electrification and hydrogen, and industrial Carbon Capture, Utilisation and Storage (CCUS); and carbon dioxide removal (including bioenergy with CCS, afforestation and reforestation, soil carbon sequestration, and enhanced weathering.) (IPCC 2018: supplementary information Table 4.SM.5.1). Careful design of policies to shift development pathways towards sustainability can increase synergies and manage trade-offs between mitigation and adaptation (*robust evidence, medium agreement*).

This section examines how development pathways can build greater adaptive and mitigative capacity, and then turns to several examples of mitigation actions with and implications for adaptation where there is a notable link to development pathways and policy choices. These examples are in the areas of agriculture, blue carbon and terrestrial ecosystem restoration.

4.4.2.1 Development pathways can build greater capacity for both adaptation and mitigation

Shifting development pathways is critical to achieving mitigation goals. Previous assessments have reflected on making development more sustainable (Sathaye et al. 2007; Fleurbaey et al. 2014b; IPCC et al. 2001) Since AR5, other assessments have highlighted how ecosystem functions can support sustainable development and are critical to meeting the goals of the Paris Agreement (IPBES 2019). The special report (IPCC SR15) found that sustainable development pathways to 1.5 °C broadly support and often enable transformations; that the implementation of mitigation options often leads to synergies but not reductions at the pace and scale required; and that "sustainable development has the potential to significantly reduce systemic vulnerability, enhance adaptive capacity, and promote livelihood security for poor and disadvantaged populations {*high confidence}*" (IPCC 2018b: 5.3.1). With careful management, shifting development pathways can build greater adaptive and mitigative capacity, as further confirmed in recent literature (Schramski et al. 2018; Harvey et al. 2014; Ebi et al. 2014; Rosenbloom et al. 2018; Antwi-Agyei et al. 2015; Singh 2018; IPBES 2019). The literature points to the challenge of careful design of specific measures, and overall shifting development pathways to achieve both mitigation and adaptation goals.

Governance and Institutional capacity

Governance and institutional capacity enable adaptation in a similar manner to mitigation. Within this general synergy, one difference in relation to adaptation relates to scale. Cities and sub-national governments tend to focus on adaptation, whereas institutions for managing mitigation are typically established by national governments (see 13.8.2). The private sector has direct involvement in mitigation, being integral to reducing emissions as part of national efforts and participating in carbon markets and voluntary initiatives, whereas adaptation tends to fall under corporate social responsibility. Mitigation-focused initiatives from non-state actors tend to attain greater completion than adaptation-focused initiatives (NewClimate Institute et al. 2019).

Behaviour and lifestyles

On the level of individual entities, adaptation is reactive but mitigation is undertaken deliberately. Chapter 5 considers behavioural change, including the reconsideration of values and what is meant by well-being, and reflecting on a range of actors addressing both adaptation and mitigation (see Chapter 5). Climate change deniers and sceptics can be induced to undertake pro-environmental action if those actions are framed in terms of societal welfare, not climate change (Bain et al. 2012; Hornsey et al. 2016). Concrete initiatives to change behaviour and lifestyles include the Transition Town movement, which seeks to implement a just transition – both in relation to adaptation and mitigation – in specific localities – assessed in special report (Roy et al. 2018).

Finance

Most climate funding supports mitigation efforts, not adaptation efforts (Buchner et al. 2019) (Halimanjaya and Papyrakis 2012). Mitigation projects are often more attractive to private capital (Abadie et al. 2013; Buchner et al. 2019). Efforts to integrate adaptation and mitigation in climate change finance are limited (Locatelli et al. 2016) There is a perception that integration of mitigation and adaptation projects would lead to competition for limited finance dollars available for adaptation (Locatelli et al. 2016). Long-standing debates (Ayers and Huq 2009; Smith et al. 2011) whether development finance counts as adaptation funding remain unresolved.

Innovation and technologies

Systems transitions that address both adaptation and accelerating mitigation include the widespread adoption of new and possibly disruptive technologies and practices and enhanced climate-driven innovation (IPCC 2018b). The literature points to trade-offs that developing countries face in investing limited resources in research and development, though finding synergies in relation to agriculture (Adenle et al. 2015). Other studies point to difference in technology transfers for adaptation and mitigation (Biagini et al. 2014). Adaptation projects tend to use existing technologies whereas mitigation climate actions are more likely to rely on novel technologies. Innovations for mitigation are typically (but not exclusively) north to south technology transfers (Biagini et al. 2014) Indigenous knowledge can be a unique source for techniques for adaptation (Nyong et al. 2007) and may be favoured over externally generated knowledge (Tume et al. 2019).

Policy

Chapter 13 considers the implications of specific policy instruments and integrated policy packages. Adaptation-focused pathways might reduce inequality, if adequate support is available and well-distributed (Pelling and Garschagen 2019). Some studies suggest that cities might plan for possible synergies in adaptation and mitigation strategies, currently done independently (Grafakos et al. 2019). The literature suggests that cities might identify both mitigation and adaptation as co-benefits of interventions targeted at developmental goals (Dulal 2017).

4.4.2.2 Specific links between mitigation and adaptation

Development is a key factor leading to land degradation in many parts of the world (IPBES 2019). Shifting development to sustainable pathways can include restoration and protection of ecosystems, which can enhance capacity for both mitigation and adaptation actions (IPBES 2019).

In this section, we explore mitigation actions related to sustainable agriculture, coastal ecosystems (“blue carbon”), and restoration and protection of some terrestrial ecosystems. These mitigation actions are exemplary of trade-offs and synergies with adaptation, sensitivity to biophysical coupling, and linkages to development pathways. For other examples, see chapters 6 (Energy Systems), 7 (Agriculture, Forestry, and other Land Uses) 8 (Urban systems) 9 (Buildings), 10 (Transport) and 11 (Industry).

Sustainable Agriculture can benefit mitigation and adaptation

Conservation agriculture can yield mitigation co-benefits through improved fertiliser use or efficient use of machinery and fossil fuels (Cui et al. 2018; Harvey et al. 2014; Pradhan et al. 2018a) and can help build adaptive capacity (Smith et al. 2017; Pradhan et al. 2018a). Climate smart agriculture (CSA) ties mitigation to adaptation through its three pillars of increased productivity, mitigation, and adaptation (Lipper et al. 2014) although managing trade-offs among the three pillars involves taking care (Thornton et al. 2018a). The '4 per 1000' goal to increase soil carbon by 0.4% per year (Soussana et al. 2019) is compatible with the three pillars of CSA. Sustainable intensification also complements CSA (Campbell et al. 2014). Soil organic carbon may foster crop resilience to climate change (Aguilera et al. 2013).

Weindl et al estimate that mixed crop-livestock systems can avoid deforestation on 76 million ha globally, while reducing the costs of adaptation in agriculture by 0.3% of total production costs (Weindl et al. 2015). This example of providing a cost-effective mitigation co-benefits of adaptation action is supported by evidence from various regions (Thornton and Herrero 2015; Thornton et al. 2018b).

Agroforestry can sustain or increase food production in some systems, increasing farmers' resilience to climate change (Jones et al. 2012). A meta-analysis of European agroforestry systems suggests that agroforestry in the European context provides ecosystem services, some of which are adaptative and mitigative (erosion control, enhanced soil fertility), but does not enhance provisioning (Torralba et al. 2016)

Some sustainable agricultural practices have trade-offs, and their implementation can have negative effects on adaptation or other ecosystem services. Fast-growing tree monocultures or biofuel crops may enhance carbon stocks but reduce downstream water availability and decrease availability of agricultural land (Primer 2018; Dynamics 2019). Similarly, Agroforestry can, in some dry environments, increase competition with crops and pastures, decreasing productivity, and reduce catchment water yield (Schrobback et al. 2011).

Agricultural practices can adapt to climate change while decreasing CO_2 emissions on the farm field. However, if such a practice leads to lower yields, interconnections of the global agricultural system can lead to land use change elsewhere and a net increase in greenhouse gas emissions (Erb et al. 2016).

Implementation of sustainable agriculture can increase or decrease yields depending on context (Pretty et al. 2006).

There are multiple agricultural mitigation options that southeast Asian countries could use to meet NDCs that would have an important adaptive impact (Amjath-Babu et al. 2019).

Blue carbon and mitigation co-benefits of adaptation actions

The Paris Agreement recognised that mitigation co-benefits resulting from Parties' adaptation actions and/or economic diversification plans can contribute to mitigation outcomes (UNFCCC 2015: Article 4.7). Blue carbon refers to carbon stored in vegetated coastal ecosystems such as seagrasses, salt marshes, and mangroves (Wylie et al. 2016; Fennessy et al. 2019; Fourqurean et al. 2012; Tokoro et al. 2014). Restoring or protecting such coastal ecosystems increases carbon sinks, reduces coastal erosion and protects from storm surges, and otherwise mitigates impacts of sea level rise and extreme weather along the coast line (Alongi 2008; Siikamäki et al. 2012; Romañach et al. 2018). Restoration of tidal flow to coastal wetlands inhibits methane emissions which occur in fresh and brackish water (Kroeger et al. 2017)

On a per-area basis, carbon stocks in coastal ecosystems can be higher than terrestrial forests (Howard et al. 2017, (Crooks et al. 2018; McLeod et al. 2011; Bindoff et al. 2019) , and is discussed quantitatively in chapter 7 of this report. Restoration and protection of coastal ecosystems has been advocated as a climate solution at national scales (Bindoff et al. 2019, (Fargione et al.) Taillardat et al. 2018) and global scales (Howard et al. 2017). Relative to the scope of anthropogenic emissions, however, restoration/protection of these ecosystems has limited potential as a global-scale mitigation measure

(Gattuso et al. 2018; Bindoff et al. 2019). Also, methane emissions from ecosystems may partially reduce the benefit the carbon sequestration (Rosentreter et al. 2018) depending on the salinity (Poffenbarger et al. 2011; Kroeger et al. 2017).

While restoration or protection of coastal ecosystems may have limited global impact as a mitigation measure, it is an important adaptation and development measure with many important benefits, described as a 'no regrets' mitigation option in the Special Report on the Ocean and Cryosphere in a Changing Climate (Bindoff et al. 2019) Coastal habitat restoration projects can also provide significant social benefits in the form of job creation (through tourism and recreation opportunities) and habitat preservation (Edwards et al. 2013; Sutton-Grier et al. 2015; Sutton-Grier and Moore 2016; Kairo et al. 2018; Wylie et al. 2016; Bindoff et al. 2019).

Coastal ecosystem-based adaptation can be cost-effective, but suffers from the vulnerability that it may no longer be effective at higher levels of climate change (Alongi 2015; Bindoff et al. 2019)

Restoration and protection of terrestrial ecosystems

Restoration of terrestrial landscapes can be a direct outcome of development pathways, and can be critical to achieving a variety of sustainable development goals (SDGs 1, 2, 6, 8, 13, 15) (Lapola et al. 2018; Vergara et al. 2016) although it also presents risks and can have trade-offs with some SDGs. (Dooley and Kartha 2018; Cao et al. 2010). Landscape restoration is nearly always a mitigation action, and also provides adaptive capacity. It also represents a development pathway choice in a way that enhances adaptive and mitigative capacity via impact on farmer livelihoods. For example, afforestation of degraded areas can produce large synergies between mitigation and adaptation through their impact on farmer livelihoods (Rahn et al. 2014). A study of potential restoration of degraded lands in Latin America (Vergara et al. 2016) indicates substantial benefits for mitigation, adaptation, and economic development.

Preventing degradation of landscapes can support both mitigation and adaptation (Arneth et al. 2019). Restoration of forests and wetlands is associated with improved water filtration, ground water recharge and flood control (Ellison et al. 2017; Griscom et al. 2017). Afforestation/reforestation reduces flooding through decreased peak river flow, also improved water quality and groundwater recharge (Berry et al. 2014). Tree planting led to more resilient livestock by providing shade and shelter (Hayman et al. 2012).

While policy in Brazil has tended to focus on the Amazon as a carbon sink, the mitigation co-benefits of ecosystem-based adaptation actions have been highlighted in the literature (Gregorio et al. 2015) (Locatelli et al. 2011).

The literature reports trade-offs in addition to the synergies noted above. Some afforestation programs are of limited success, and may have adverse environmental consequences, including desertification and increased erosion which are mal-mitigative (Cao et al. 2010).

Reforestation for mitigation purposes can be more effective if done with adaptation in mind (Gray et al. 2011). Related, if climate change gets to a certain point, landscape restoration projects may fail (Dooley and Kartha 2018).

4.4.3 Risks and uncertainties

Shifting development pathways and accelerating mitigation are complex endeavours that carry risks. Some of these risks can be easily captured by quantitative models. Others are better understood via qualitative approaches, such as qualitative narrative storylines (told in words) and methods mixing qualitative and quantitative models (Kemp-Benedict 2012; Hanger-Kopp et al. 2019). The following outline key risks and relevant hedging strategies identified in the literature.

4.4.3.1 Actions by others not consistent with domestic efforts

The international context is a major source of uncertainty for national-level planning, especially for small- or medium-sized open economies, because the outcome of domestic choices may significantly depend on decisions made by other countries and actor, over which national governments have limited or no control (Lachapelle and Paterson 2013). Availability of foreign financial resources in countries with limited domestic savings (Baum et al. 2017) and availability of technology transfers (Glachant and Dechezleprêtre 2017) are some examples. Other external decisions with significant bearing on domestic action include mitigation policies in other countries (Dai et al. 2017), and especially in major trading partners, the lack of which can result in competitive disadvantage for sectors exposed to international competition (Alton et al. 2014). The international prices of the key commodities (notably energy), goods and services in a country trade balance are important, notably when shifting development pathway is based on structural change (e.g., (Willenbockel et al. 2017) for Ghana and Kenya).

Remedies include first devising policy packages that are, to the extent possible, robust to uncertainty regarding external decisions. For example, mitigation in the building sector is considered less problematic for competitiveness since the construction sector is less exposed to international competition. Remedies also include securing international cooperation to reduce the uncertainty that domestic decision-makers face about the international context. Securing mechanisms that allow international capital to flow, in a direction that supports shifting development pathways and accelerating mitigation is, in particular, critical here (Chapter 15). As outlined in Chapter 14, cooperation can generate large positive spill overs [*To be completed in Final Draft with reference to Ch.14*]. Third, cooperation is not limited to governments. As discussed in section 4.2.3, international cooperative initiatives among non-State actors (cities, economic branches, etc.) can also provide know-how, resources and stable cooperative frameworks that reduce uncertainty for individual actors.

4.4.3.2 Parts of complex policy packages fail

As outlined in the examples in section 4.4.1 above, shifting development pathways and accelerating mitigation are complex endeavours, on which there is limited experience and know-how from the past. An uncertainty is that parts of these policy packages may fail, that is under-deliver relative to the amount of mitigation and of transformations that was expected. For example, France has failed to meet its 2015-2018 carbon budget as housing retrofitting programs, in particular, have failed to deliver the expected amount of emission reductions (Haut Conseil pour le Climat 2019). There are two main options to tackle this risk. The first is to build in redundancy. The second is to anticipate that some parts of the policies will inevitably fail, and build-in monitoring and corrective mechanisms in a sequential decision-making process. To this regard, building institutions that can properly monitor, learn from and improve over time is critical (Nair and Howlett 2017).

4.4.3.3 New information becomes available

The science on climate change, its impacts and the opportunities to mitigate is continuously being updated. Even though decisions are no longer made "in a sea of uncertainty" (Lave 1991), we know that new information will come over time, that may have significant bearing on the design and objectives of policies to shift development pathways and accelerate mitigation. New information may come from climate sciences (e.g., updated GWP values or available carbon budgets (Quéré et al. 2018), impact sciences (e.g., on re-evaluation of climate impacts associated with given emission pathways (Ricke et al. 2018) or from mitigation sciences (e.g., on availability of given technologies (Lenzi et al. 2018; Giannousakis et al. 2020).

At the same time, economic and social systems are characterised by high degree of inertia, via long-lived capital stock or urban forms (Lecocq and Shalizi 2014), or more broadly mutually reinforcing physical, economic, and social constraints (Seto et al. 2016) that may lead to carbon lock-in (Erickson et al. 2015). Risks associated with long-lasting fossil-fuel power plants have been the object of particular attention. For example, (Pfeiffer et al. 2018) estimate that even if the current pipeline of power plants was cancelled, about 20% of the existing capacity might be stranded to remain compatible with 1.5°C or 2°C pathways—implying that additional capital accumulation would lead to higher sunk costs associated with stranded assets (Luderer et al. 2018; Johnson et al. 2015; Kriegler et al. 2018; Ansar et al. 2013).

In the presence of uncertainty and inertia (or irreversibilities), hedging strategies may be considered, that include selection of risk-hedging strategies and processes to adjust decisions as new information becomes available. The notion of hedging against risks is also prominent in the adaptation literature, as exemplified by the terminology of “climate resilient development” (Fankhauser and McDermott 2016) (WGII, Ch.18). There is also a growing literature on hedging strategies for individual actors (e.g., firms or investors) in the face of the uncertainties associated with mitigation (e.g., policy uncertainty or the associated carbon price uncertainty) (e.g., (Morris et al. 2018) or (Andersson et al. 2016)). On the other hand, there is often limited discussion of uncertainty and of its implication for hedging strategies in the accelerated mitigation pathway literature. Exceptions include (Capros et al. 2019), who elicit “no-regret” and “disruptive” mitigation options for the EU through a detailed sensitivity analysis, and (Watson et al. 2015) who discuss flexible strategies for the U.K. energy sector transition in the face of multiple uncertainties.

4.4.3.4 Black swans (e.g., COVID-19 crisis)

As the current COVID-19 crisis demonstrates, events happen that can derail the best-laid plans. The only point to note here is that events such as these one may also provide opportunities. Unexpected events beyond the range of human experience until then are called ‘black swan’ events, given the expectation that all swans are white. In the COVID-19 case, for example, due to their pivotal role in assuring the survival of many businesses, governments may be in a stronger position to make sure that the economic restructuring be done in ways that consider mitigation and adaptation. Also, lessons from the experience of conducting many activities on-line, which reduce emissions from travel, may leave an imprint on how some of these activities are carried out also in a post-COVID-19 world. Finally, the fact that the world during the pandemic has seen both local benefits from less air pollution and the ominous signs of natural disasters due to climate change may together contribute to increased support for mitigation.

4.4.3.5 Transformations run into opposition

As noted above, shifting development pathways and accelerating mitigation involve a broad range of stakeholders and decision-makers, at multiple geographical and temporal scales. They require a credible and trusted process for reconciling perspectives and balancing potential side-effects, managing winners and losers and implementing compensatory measures to ensure an inclusive just transition (Newell and Mulvaney 2013; Miller and Richter 2014; Gambhir et al. 2018; Diffenbaugh and Burke 2019). Such processes are designed to manage the risk of inequitable or non-representative power dynamics (Helsinki Design Lab 2014; Kahane 2019; Boulle et al. 2015). More generally, stakeholder processes can be subject to regulatory capture by special interests, or outright opposition from a variety of stakeholders. Information asymmetry between government and business may shape the results of consultative processes. Long experience of political management of change demonstrates that managing such risks is not easy, and requires sufficiently strong and competent institutions (Stiglitz 1998). The next section on Just Transition (4.5) addresses this issue.

4.5 Equity, including just transition

Equity is an ethical imperative, but it is also instrumentally an enabler of deeper ambition for accelerated mitigation (Hoegh-Guldberg et al. 2019). The literature supports a range of estimates of the net benefits – globally or nationally – of low-carbon transformation (3.6), and it identifies a number of difficulties in drawing definitive quantitative conclusions (e.g., comparisons of costs & benefits among different actors, the existence of non-economic impacts, comparison across time, uncertainty in magnitude). One of the most important of these dimensions is the distributional consequences of mitigation, as well as a range of equity considerations arising from the uncertainty in net benefits, as well as from the distribution of costs and benefits among winners and losers (Rendall 2019; Caney 2016; Lahn and Bradley 2016; Lenferna 2018a; Kartha et al. 2018b; Robiou Du Pont et al. 2017). For more on assessments of fairness in NDCs, see section 4.2.2.5.

While there is extensive literature on equity frameworks for national emissions allocations (Robiou du Pont and Meinshausen 2018; Climate Action Tracker 2017; CSO Equity Review 2018, 2015, 2017; Kemp-Benedict et al. 2018; Pye et al. 2020; Fyson et al. 2020; Holz et al. 2018; Pozo et al. 2020), such studies have tended to focus on allocation of a global carbon budget among countries based on quantified equity frameworks. The implicit normative choices made in these analysis have limitations (Kartha et al. 2018a). Ultimately, equity consequences depend on how costs and benefits are initially incurred and how they are shared as per social contracts (Combet and Hourcade 2017), national policy, and international agreements. The literature suggests a relation between the effectiveness of cooperative action and the perception of fairness of such arrangements. Winkler et al. (2018) demonstrate that countries have put forward a wide variety of indicators and approaches for explaining the fairness and ambition of their NDCs, reflecting the broader range of perspectives found in the moral philosophical literature cited above. (Mbeva and Pauw 2016) further find that adaptation and financing issues take on greater salience in the national perspectives reflected in the NDCs.

Topics of equity and fairness have begun to receive a greater amount of attention within the energy and climate literature, namely through the approaches of gender and race (Pearson et al. 2017; Lennon 2017; Allen et al. 2019), environmental justice (Mohai et al. 2009; Schlosberg, 2009), climate justice (Roberts & Parks, 2006; Routledge et al. 2018), and energy justice (Sovacool and Dworkin 2014). While such approaches frequently envision justice and equity as an ethical imperative, justice also possesses an instrumental value of enabling deeper and more socially acceptable mitigation efforts (Klinsky and Winkler 2018).

A more concrete focal point on these issues has been that of "just transition." Getting broad consensus for the transformational changes entailed in moving from a high-carbon to low-carbon economy means 'leaving no one behind', i.e., ensuring (sufficiently) equitable transition for the relevant affected individuals, workers, communities, sectors, regions and countries (Newell & Mulvaney, 2013; Jasanoff 2018). The concept of a "just transition" owes its origin to the US trade union movement in 1980s. The earliest version of a just transition was called the "Superfund for Workers" modelled on the 1980 Superfund program that designed federal funds for the clean-up of toxic substances from chemicals, mining and energy production (Stevis and Felli 2015). It was further taken up, for example, in the collaboration of the International Trade Union Confederation (ITUC), the International Labour Organization (ILO) and the UN Environmental Programme (UNEP) in promoting "green jobs" as integral elements of a just transition (ILO 2015; Rosemberg 2010). In recent years the concept of a "just transition" has gained increased traction, for example incorporated in the outcome of the Rio+20 Earth Summit and more recently recognised in the preamble of the Paris Agreement, which states "the imperative of a just transition of the workforce and the creation of decent work and quality jobs in accordance with nationally defined development priorities" (UNFCCC 2015c). Some heads of state and government signed a '*Solidarity and Just Transition Silesia Declaration* first introduced at COP24 in Poland (HoSG 2018).

The literature identifies targeted and proactive measures from governments, agencies, and authorities to ensure that any negative social, environmental or economic impacts of economy-wide transitions are minimised, whilst benefits are maximised for those disproportionally affected (Healy & Barry, 2017). While the precise definition varies by source, core elements tend to include: (1) investments in establishing low-emission and labour-intensive technologies and sectors (Mijn Cha et al. 2020); (2) research and early assessment of the social and employment impacts of climate policies (Green and Gambhir 2020; Mogomotsi et al. 2018); (3) social dialogue and democratic consultation of social partners and stakeholders (Smith 2017; Swilling and Annecke 2012); (4) the creation of decent jobs; active labour markets policies; and rights at work (UNFCCC 2016c; ILO 2015); (5) fairness in energy access and use (Carley and Konisky 2020); (6) economic diversification based on low carbon investments; (7) gender specific politics that promote equitable outcomes (Allwood 2020); (8) the fostering of international cooperation and coordinated multilateral actions (Lenferna 2018b; Newell and Simms 2020) and (8) redressing of past harms and perceived injustices (UNHRC 2020; Setzer and Vanhala 2019).

A just transition could therefore entail that the state intervene more actively in the eradication of poverty, regulating prosperity and creating jobs in "green" sectors, in part to compensate for soon-to-be abandoned fossil-fuel-based sectors , and that governments, polluting industries, corporations and those more able to pay higher associated taxes pay for transition costs, provide a welfare safety net and adequate compensation for people, communities, and regions that have been impacted by pollution, marginalised or negatively impacted by a transition from a high to low carbon economy and society (Muttitt and Kartha; Le Billon and Kristoffersen 2020; Kartha et al. 2018b).

The just transition concept has thus become an international focal point tying together social movements, trade unions, and other key stakeholders to ensure equity is better accounted for in low-carbon transitions and to seek to protect workers and communities (Pollin and Callaci 2019). It also forms a central pillar of the growing movement for a 'Green New Deal' — a roadmap for a broad spectrum of policies, programs, and legislation that aims to rapidly decarbonises the economy while significantly reducing economic inequality (Galvin and Healy 2020) (Galvin & Healy, 2020). The US Green New Deal Resolution (Ocasio-Cortez 2019) for example positions structural inequality, poverty mitigation, and a just transition at its centre. A European Green Deal was proposed in December 2019 (European Commission 2019), and it includes a $100 billion "Just Transition Mechanism" which aims to mitigate the social effects of transitioning away from jobs in fossil based industries. The literature examines the investments in green new deals and just transitions (Galvin 2020).

Concept alliances around a just transition in countries across the world take many forms (see Box 4.4).

Box 4.4 Selected organisations and movements supporting a just transition

Asian Pacific Forum on Women, Law and Development (Asia Pacific)
Blue Green Alliance (US)
Beyond Coal campaign (US)
Central Única dos Trabalhadores (Brazil)
Climate Action Network (global)
Climate Justice Alliance (US)
Cooperation Jackson (US)
Dejusticia (Colombia)
Deutscher Gewerkschaftsbund (German Trade Union Confederation) (Germany)
DiEM25 (pan-European)
European Union
European Trade Union Confederation (EU)
Grassroots Global Justice (US)
IndustriALL Global Union (global)
Indigenous Environmental Network (US)
International Labor Organization (global)
International Trade Union Confederation—-affiliated Just Transition Centre (Global) Just Transition Alliance (US)
Just Transition Centre (global)
Just Transition Fund (US)
Kentuckians for the Commonwealth (US)
Labor Network for Sustainability (US)
Latrobe Valley Authority (Australia)
Movement Generation (US)
NAACP (US)
National Union of Mineworkers of South Africa (South Africa)
Pan African Climate Justice Alliance (Africa)
Post Petroleum Transitions Roundtable (Mesa de Transición Post Petrolera) (Argentina)
Powering Past Coal Alliance (global)
Right to the city alliance (US)
Sierra Club (US)
Sunrise Movement (US)
The Leap Manifesto (Canada)
The Trade Unions for Energy Democracy Initiative (Global)
Trade Union Confederation of the Americas (TUCA) ITUC's regional branch (Americas)
Transitions Town Movement (UK)
Women's Environment and Development Organization (Global)
350.org (Global)

A just transition at national, regional and local scales can help to ensure that workers, communities, frontline communities and the energy-poor are not left behind in the transition. Moreover, a just transition necessitates that rapid decarbonisation doesn't perpetuate asymmetries between richer and poorer states and people (UNHRC, 2020)

As Table 4.8 and Figure 4.8 reveal, no fewer than 7 national commissions or task forces on a just transition existed as of 2020 as well as 7 other sets of national policies and a multitude of other actors, networks, and movements. For instance, the German phase out of coal subsidies involved a savings package for unemployed miners and subsidy reform packages introduced by Iran, Namibia, the Philippines, Turkey, and the United Kingdom provide similar compensating measures to affected groups (Sovacool 2017). Spain's just transition plan for coal miners includes early retirement, redundancy packages, silicosis compensation, retraining for green jobs, and priority job placement for former miners.

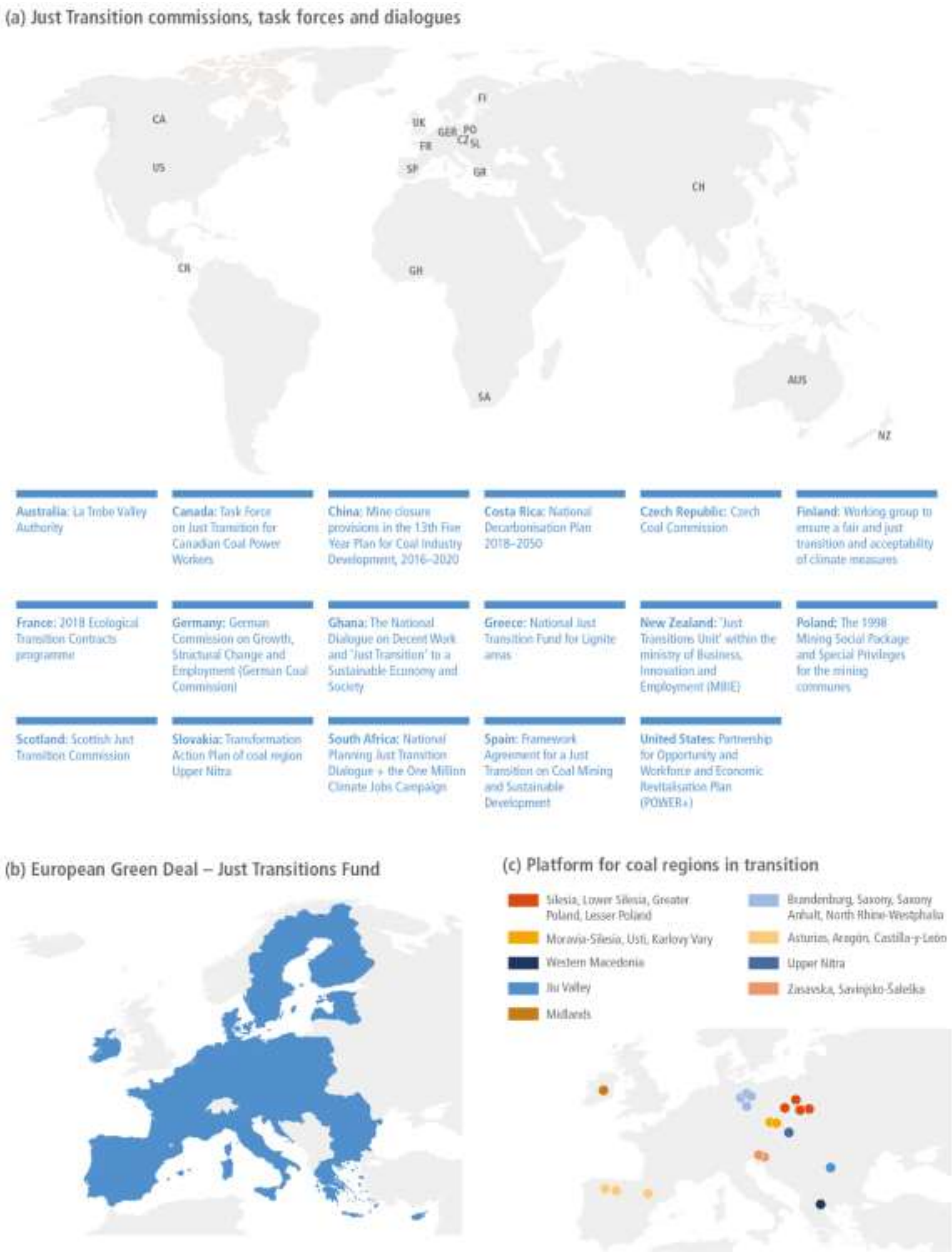

Figure 4.8 Just Transitions around the world, 2020

Panel A shows commissions, task forces, dialogues behind a just transition in many countries ((Snell 2018; Government of Canada 2019; Piggot et al. 2019; Harrison 2013; Government of Costa Rica 2019; Ng, S., Mabey, N. and Gaventa 2016; van Asselt and Moerenhout 2018; European Union 2019; Eueropean Union 2020; Galgoczi 2019; Finland 2020; Commission on Growth Structural Change and Employment 2019; Ministry of Employment and Labour Relations of Ghana 2018; Popp 2019; Galgóczi 2014; Adeoti et al. 2016; Gass and Echeverria 2017; Ministry of Business Innovation & Employment New Zealand 2019; Mendoza 2014; Szpor, A. and Ziółkowska 2018; Government of Scotland 2020; Bankwatch 2019; NPC (National Planning Commission) 2019; Strambo et al. 2019; Thalmann 2004; White House

2016; Schweitzer, M. and Tonn 2003; Mijn Cha et al. 2020; International Labor Organization 2018); **Panel B shows the funds related to the Just Transition within the European Union Green Deal, and Panel C shows the European Union's Platform for Coal Regions in Transition**.

Ensuring equity in turn entails a fundamental shifting of development pathways. Such shifts can be accomplished by a broad alliance of social actors supporting a just transition. Key enabling conditions include governance, behaviour and lifestyles, innovation, enhancing institutional capacities, policy and finance (see section 4.4.3 and (de Coninck et al. 2018b)). Shifting development pathways will open broader options, thereby accelerating mitigation and reducing climate impacts – another important dimension of equity, in that the poor who are least responsible for climate change are most vulnerable to its impacts (See WGII, Chapter 8).

4.6 Research gaps

- Literature on mitigation pathways at the national level remains skewed towards large emitters. Many low-income countries have very few or no studies at all (Lepault and Lecocq 2020) (section 4.2).
- Implementation gap between policies announced in plans and policies effectively undertaken warrants investigation (4.2).
- Ex ante and ex post analysis of mitigation action and of mitigation plans by non-state actors, and their relationship with mitigation action and plans by governments is limited (4.2.3)
- System analysis solutions are only beginning to be recognised in current literature on deep mitigation pathways, and rarely included in existing national policies or strategies (4.2.5).
- There is still a gap between the assessment of mitigation targets in the scientific literature and the development of practical roadmaps for policy implementation at national scale (4.2, 4.3).
- Literature on the implication of development choices for emissions and for capacity to mitigate is limited (4.3.2). More contributions from the research community working on development issues would be useful here.
- While the technology elements of accelerated mitigation pathways at national level are generally well documented, studies of economic and social implications of such pathways remain scare (4.3.3).
- Literature describing shifts in development pathways, and the conditions for such shifts (based on past experience or on models) remains scarce (4.3.4, 4.4.1). Studying shifts in development pathways requires new ways of thinking with interdisciplinary research and use of alternative frameworks and methods suited for understanding of change agents, determinants of change and adaptive management among other issues (Winkler 2018).
- Research gaps on specific enabling conditions, see Chapter 5 (behaviour change), 13 and 14 (policy, governance and institutional capacity), 15 (finance) and 16 (technology).
- Robust strategies to shift development pathways and accelerate mitigation in the context of large uncertainties (4.4.3).
- Experiences with just transition institutions worldwide warrant careful analysis (4.5).

Frequently asked questions

FAQ 4.1 What is to be done over and above countries existing pledges under the Paris Agreement to keep global warming well below 2 °C?

Accelerating mitigation is not enough; massive deep and rapid transformations are needed; Focusing on making transformative changes that disrupt existing developmental trends (Shifting development pathways) towards sustainability, i.e., involving substantial disruption to existing carbon intensive development trends, in particular to improve underlying enabling conditions for climate change mitigation; equity considerations and need for just transition matter; COVID-19 crisis does not fundamentally alter assessment, at least given current knowledge.

FAQ 4.2 What is to be done in the near term to accelerate mitigation and shifting development pathways?

Understand how to shift development pathways; including creating new infrastructure, sustainable supply chains, institutional capacities for evidence-based and integrated decision-making, financial alignment away from incumbent high-carbon technologies towards low-carbon socially responsible investments and shifts in behaviour and norms to support cleaner consumption; adopting multi-level governance modes, tackling corruption, and improving social and political trust are also key for aligning and supporting long-term environmentally just policies and processes; take a long-term perspective on near-term decisions and actions.

FAQ 4.3 What does 'shifting development pathways to increased sustainability' (SDPS) mean, and what is the concept of SDPS doing in a report on mitigation?

Development pathways determine GHG emissions. Mitigation conceived as incremental change is not enough. Mitigation policies grafted on to existing development pathways are unlikely to be able to achieve rapid and deep emission reductions. An approach of Shifting development pathways to increased sustainability (SDPS) is complementary to accelerating mitigation. SDPS can broaden opportunities by focusing on development pathways and considering how to shift them. Decision-makers might consider a broader toolbox of enablers and levers that is available in domains that have not traditionally been thought of as climate policy. The approach helps to think about change in systems and integrated policy packages. Putting in place more supportive enabling conditions can be done in the near-term – policy, institutional capacity, multi-level governance, finance and investment, innovation and technology, and drivers of behavioural change. Such shifts are the result of decisions by a wide range of actors – social movements, governments, non-state actors, businesses, intergovernmental organisations. SDPS is not an alternative to accelerating mitigation, it is complementary – both are needed to address the climate crisis.

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Supplementary Material

Table S4.10 Overview of methods used for projected emissions of NDCs and/or current policies (adapted from (Kuramochi et al. 2020a; den Elzen et al. 2019)**).**

Study	Policy cut-off[a]	Regions	Sectors	Emissions[b]/ GWP (if applicable)	Scenarios[c]	Policies	Methods[d]	References
Climate Action Tracker	11/2018	Global (33 countries in detail, covering x% of GHG emissions)	Energy, AFOLU	Kyoto gases/IPCC AR4	REF, CP, NDC	All policies (somewhat unclear)	Literature review (official, national, international sources), supplemented by additional bottom-up analysis (spreadsheet?)	(Climate Action Tracker 2019) method: https://climateactiontracker.org/methodology/
PBL Netherlands Environmental Assessment Agency	11/2018	Global (G20 countries with policy detail, NDCs for 78 countries, covering 91% of 2012 GHG emissions)	Energy, AFOLU	Kyoto gases/IPCC AR4	REF, CP, NDC	Expert-selected policies based on comprehensive policy inventory	CP: literature review (official, national, international sources), global IAM (IMAGE), ILM (GLOBIOM/G4M), NDC: FAIR model	(Kuramochi and et al. 2019) online tool: www.pbl.nl/indc
ADVANCE	4/2017 *	Global	Energy, AFOLU	Kyoto gases/IPCC AR4	REF, NDC	NDC: GHG targets	Set of global IAMs (AIM/CGE, IMAGE, IMACLIM, GCAM, GEM-E3, MESSAGE-GLOBIOM, POLES, REMIND, WITCH-GLOBIOM)	(Vrontisi et al. 2018; Luderer et al. 2018) online database : https://db1.ene.iiasa.ac.at/ADVANCEDB/

Study	Policy cut-off[a]	Regions	Sectors	Emissions[b]/ GWP (if applicable)	Scenarios [c]	Policies	Methods[d]	References
CD-LINKS global	12/2016	Global, with regional detail	Energy, AFOLU	Kyoto gases/IPCC AR4	REF, CP, NDC	CP: comprehensive policies; NDC: GHG targets, additional policies	Set of global IAMs (AIM/CGE, IMAGE, GEM-E3, MESSAGEix-GLOBIOM, POLES, REMIND-MAgPIE, WITCH-GLOBIOM)	(McCollum et al. 2018; Roelfsema et al. 2020) online database: https://db1.ene.iiasa.ac.at/CDLINKSDB/
GECO 2019 study (JRC)	03/2020	Global G20 countries with policy detail	Energy, AFOLU	Kyoto gases/IPCC SAR	REF, CP, NDC	Expert-selected policies based on comprehensive policy inventory	CP: literature review (official, national, international sources), global IAM (POLES), ILM (GLOBIOM/G4M)	(Keramidas et al. 2020)
NDC & INDC Factsheets (University of Melbourne)	11/2016	Global (195 countries)	Energy, AFOLU	Kyoto gases / IPCC AR4	NDC	NDC: Emissions pathways	literature review, IPCC scenario database	(Meinshausen and Alexander 2017) http://climatecollege.unimelb.edu.au/ndc-indc-factsheets
Kuramochi et al. (2020)	11/2020	Non-G20 countries: Chile, Colombia, Democratic	Energy, AFOLU	Kyoto gases/IPCC AR4	REF, CP, NDC	All policies (somewhat unclear)	Literature review (official, national, international sources), supplemented by additional	(Kuramochi et al. 2020b)

Study	Policy cut-off[a]	Regions	Sectors	Emissions[b]/ GWP (if applicable)	Scenarios[c]	Policies	Methods[d]	References
		Republic of the Congo (DRC), Iran, Kazakhstan, Morocco, the Philippines, Thailand, and Ukraine					bottom-up analysis (spreadsheet?)	
Keesler, Orifici and Blanco	11/2019	National (Argentina)	Energy, AFOLU	Kyoto gases/IPCC AR4	CP, NDC	CP: comprehensive policies; NDC: GHG target	National ESM	(Keesler et al. 2019)
Climateworks Australia	2018	National (Australia)	Energy, AFOLU	Kyoto gases/IPCC AR4	CP, NDC	CP: comprehensive policies; NDC: GHG target	National ESM	(ClimateWorks Australia 2018)
Commonwealth of Australia	2019	National (Australia)	Energy, AFOLU	Kyoto gases/IPCC AR4	CP, NDC	CP: comprehensive policies; NDC: GHG target	National ESM	(Commonwealth of Australia 2019)

Study	Policy cut-off[a]	Regions	Sectors	Emissions[b]/ GWP (if applicable)	Scenarios [c]	Policies	Methods[d]	References
Koberle et al. 2019; Rochedo et al. 2018	12/2016	National (Brazil)	Energy, AFOLU	Kyoto gases/IPCC AR4	CP, NDC	CP: comprehensive policies, NDC: GHG target	National ESM (BLUES)	(Koberle et al.; Rochedo et al. 2018)
(Fu et al. 2017; Fu 2018)	11/2017	National (China)	Energy	CO2/NA	CP, NDC	NDC	National ESM (China)	(Fu et al. 2017; Fu 2018)
(Li et al. 2019)	12/2018	National (China)	Energy	CO2/NA	CP, NDC	NDC: Emission peak by 2030, others?	National ESM (China TIMES)	(Li et al. 2019) Method: (Shi et al. 2016)
(Yang et al. 2018)	1/2017	National (China)	Energy	CO2/NA	REF, NDC	NDC: Emission peak, emission intensity	National ESM (China MAPLE), MACCs	(Yang et al. 2018)
China Renewable Energy Outlook	4/2017 *	National (China)	Energy	CO2/NA	CP	CP: stated policies and extrapolation of current policies	National ESM (CNREC scenario modeling tools)	(ERI/CNREC 2017)

Study	Policy cut-off[a]	Regions	Sectors	Emissions[b]/ GWP (if applicable)	Scenarios [c]	Policies	Methods[d]	References
European Commission (2018)	11/2018	Regional (EU)	Energy, AFOLU	Kyoto gases/IPCC AR4	CP, NDC	CP: comprehensive policies; NDC: GHG target	Modeling tools for EU analysis (PRIMES, GAINS, GLOBIOM/G4M, CAPRI, GEM-E3, E3ME)	(European Commission 2018) method: https://ec.europa.eu/clima/policies/strategies/analysis/models_en
Vrontisi et al. 2019	12/2016	Regional (EU)	Energy	Kyoto gases/IPCC AR4	CP, NDC	CP: comprehensive policies; NDC: GHG target	Regional ESM and CGE model (PRIMES, GEM-E3)	(Vrontisi et al. 2019)
Dusbash et al. 2018	2011-2015	National (India)	Energy	CO2/NA	CP, NDC	CP: comprehensive policies; NDC: GHG target	Set of 15 national ESM studies with a base-year of current policies pre-2015 and 2015	(Dubash et al. 2018)
Vishwanathan et al. 2019	12/2016	National (India)	Energy	CO2/NA	CP, NDC	CP: comprehensive policies, NDC	National ESM (AIM/Enduse 3.0)	(Vishwanathan et al. 2018; Vishwanathan and Garg)
Mathur et al. 2019	12/2016	National (India)	Energy	CO2/NA	CP, NDC	CP: comprehensi	National ESM (India MARKAL)	(Mathur and Shekhar)

Study	Policy cut-off[a]	Regions	Sectors	Emissions[b]/ GWP (if applicable)	Scenarios [c]	Policies	Methods[d]	References
						ve policies, NDC		
Oshiro et al. 2019	12/2016	National (Japan)	Energy, AFOLU	Kyoto gases/IPCC AR4	CP, NDC	CP, NDC	National ESM (AIM/Enduse, DNE21+)	(Oshiro et al. 2019)
JMIP/EMF35	3/2018	National (Japan)	Energy, AFOLU	CO2/NA, Kyoto gases/AR4	NDC	NDC: GHG target	National ESMs (AIM/Enduse[Japan], DNE21-Japan, IEEJ-Japan, TIMES-Japan)	(Sugiyama et al. 2020)
Safonov et al. (in review)	12/2016	National (Russia)	Energy	CO2/NA	CP, NDC	CP: comprehensive policies, NDC	National energy systems models (Russia-TIMES)	(Safonov et al.)
Rhodium Group (Pitt et al. 2019)	11/2019	National (USA)	Energy	Kyoto gases/IPCC AR4	CP, NDC	CP: comprehensive policies; NDC: GHG target	National ESM (USA)	(Pitt et al. 2019)
EIA Annual Energy Outlook 2019	6/2018 *	National (USA)	Energy	CO2	CP	CP: current laws and regulations	National ESM (NEMS)	(EIA 2019)

Study	Policy cut-off[a]	Regions	Sectors	Emissions[b]/ GWP (if applicable)	Scenarios [c]	Policies	Methods[d]	References
ENGAGE global	06/2020	Global, with regional detail	Energy, AFOLU	Kyoto gases/IPCC AR4	CP, NDC	CP: comprehensive policies; NDC: GHG targets, additional policies	Set of global IAMs (AIM/CGE, COFFEE, IMAGE, GEM-E3, MESSAGEix-GLOBIOM, POLES, REMIND-MAgPIE, TIAM-ECM, WITCH)	(Riahi and et al. 2020; Bertram et al. 2020)
ENGAGE national	03/2020	National (China, India, Japan, Korea, Thailand)	Energy, AFOLU	Kyoto gases/IPCC AR4	NDC	NDC: GHG targets	Set of national IAMs (AIM/Hub China, India, Japan, Korea, Thailand)	(Fujimori et al. 2020)
COMMIT	06/2020	Global with regional detail, National (Australia, Brazil, Canada, EU, India, Japan, Korea, Russia, USA)	Energy, AFOLU	CO2/NA, Kyoto gases/IPCC AR4	CP, NDC	CP: comprehensive policies; NDC: GHG targets, additional policies	Set of global and national ESMs/IAMs (global: AIM/CGE, COFFEE, IMAGE, MESSAGEix-GLOBIOM, POLES, PROMETHEUS, REMIND-MAgPIE, TIAM-Grantham, WITCH; national: AIM/CGE-Korea, AIM/Enduse-Japan, BLUES-Brazil, GCAM-Canada, GCAM-USA, MARKAL-India, PRIMES, RU-TIMES, TIMES-Australia)	(van Soest et al. 2020)

Study	Policy cut-off[a]	Regions	Sectors	Emissions[b]/ GWP (if applicable)	Scenarios [c]	Policies	Methods[d]	References
REMIND 2.1	06/2020	Global with regional detail	Energy, AFOLU	Kyoto gases/IPCC AR4	CP, NDC for SSP1/2/5, deep electrification	CP: comprehensive policies; NDC: GHG targets, additional policies	Global IAM (REMIND)	(Baumstark et al. 2020; Luderer et al. 2020)
PEP	08/2017	Global with regional detail	Energy, AFOLU	Kyoto gases/IPCC AR4	CP, NDC	CP: comprehensive policies; NDC: GHG targets, additional policies	Global IAM (REMIND-MAgPIE)	(Kriegler et al. 2018)
CEMICS	05/2017	Global with regional detail	Energy, AFOLU	Kyoto gases/IPCC AR4	CP, NDC	CP: ?; NDC: GHG targets	Global IAM (REMIND)	(Strefler et al. 2018)
TIAM-ECN ETH		National (Ethiopia)	Energy	Kyoto gases/IPCC AR4?	CP, NDC		National IAM embedded in global IAM (TIAM-ECN ETH)	(van der Zwaan et al. 2018)
TIAM-ECN KEN		National (Kenya)	Energy	CO2/NA	NDC		National IAM embedded in global IAM (TIAM-ECN KEN)	(Dalla Longa and van der Zwaan 2017)

Study	Policy cut-off[a]	Regions	Sectors	Emissions[b]/ GWP (if applicable)	Scenarios [c]	Policies	Methods[d]	References
TIAM-ECN MDG		National (Madagascar)	Energy	CO2/NA	NDC		National IAM embedded in global IAM (TIAM-ECN MDG)	(Nogueira et al. 2020)
TIMES_PT		National (Portugal)	Energy, AFOLU	Kyoto gases/IPCC AR4?	NDC (2 variants)		National ESM (TIMES_PT)	(Fortes et al. 2019)
Climate Equity Reference Calculator		Multi-national (91 countries and regions)	Energy, AFOLU	Kyoto gases/IPCC SAR	NDC		Literature review (NDC targets, emission inventories, exogenous emission pathways), spreadsheet calculation	(Holz et al. 2018)

Notes: [a] in case policy cut-off date is not explicitly specified in the publication or accompanying information, the study submission date minus six months is used as proxy; [b] CO2 = CO2 only, Kyoto = Kyoto GHGs; [c] REF = Reference or business-as-usual, CP = Current Policies, NDC = Nationally Determined Contribution; [d] IAM = Integrated Assessment Model, ESM = Energy Systems Model, ILM = Integrated Land Model, CGE = Computable General Equilibrium Model

Table S4.2 Comparison of 2030 emissions projections post-COVID compared to pre-COVID. The comparison is based on current policy scenario projections for all GHG emissions excluding LULUCF, unless otherwise noted.

Region	**Climate Action Tracker** (2020)	**IEA World Energy Outlook 2020** (IEA 2020) [a]	**Other studies**
World	-3.8% to -6.8%	-3.8% to -10%	-3 to -7% (UNEP 2020), -4% to -7% (Dafnomilis et al.), -3.9 to -9% (Vinca et al. 2020) [c]
Brazil	-5.2% to -4.4%	-2.4%	Not available
China	-6.0% to -0.5%	-1.2%	Not available
EU	-6.6% to -0.1%	N/A [b]	-0.2% (European Commission 2020) (NDC implementation scenario)
India	-11.8% to -8.5%	-18.6%	Not available
Japan	-13.2% to -5.5%	-3.3%	Not available
Russian Federation	-6.2% to -1.9%	-2.4%	Not available
USA	-9.8% to -5.1%	-9.6%	-6.4% to -5.1% (Larsen et al. 2020)

Notes: [a] Fossil fuel and industrial process emissions only. Stated Policies Scenario, energy CO_2 emissions, scenario "incorporates our assessment of all the policy ambitions and targets that have been legislated for or announced by governments around the world" (IEA 2020), and "assumes that significant risks to public health are brought under control over the course of 2021, allowing for a steady recovery in economic activity". [b] Comparison was not possible because WEO 2019 included the UK as part of the EU while WEO 2020 excluded the UK. [c] (Vinca et al. 2020) includes LULUCF emissions.

Supplementary Material Box S4.1. A fast-growing literature explores the implications of mitigation in the short- (up to 2030) and medium-run (up to 2050) by developing economy-wide scenarios. This literature is recent (75% published in 2015 or beyond) and very unevenly distributed geographically, with strong emphasis on China, and to a lesser degree India, the European Union and the U.S., while we could not find reference for more than half of the countries in the World (Figure 4.9) (high confidence).

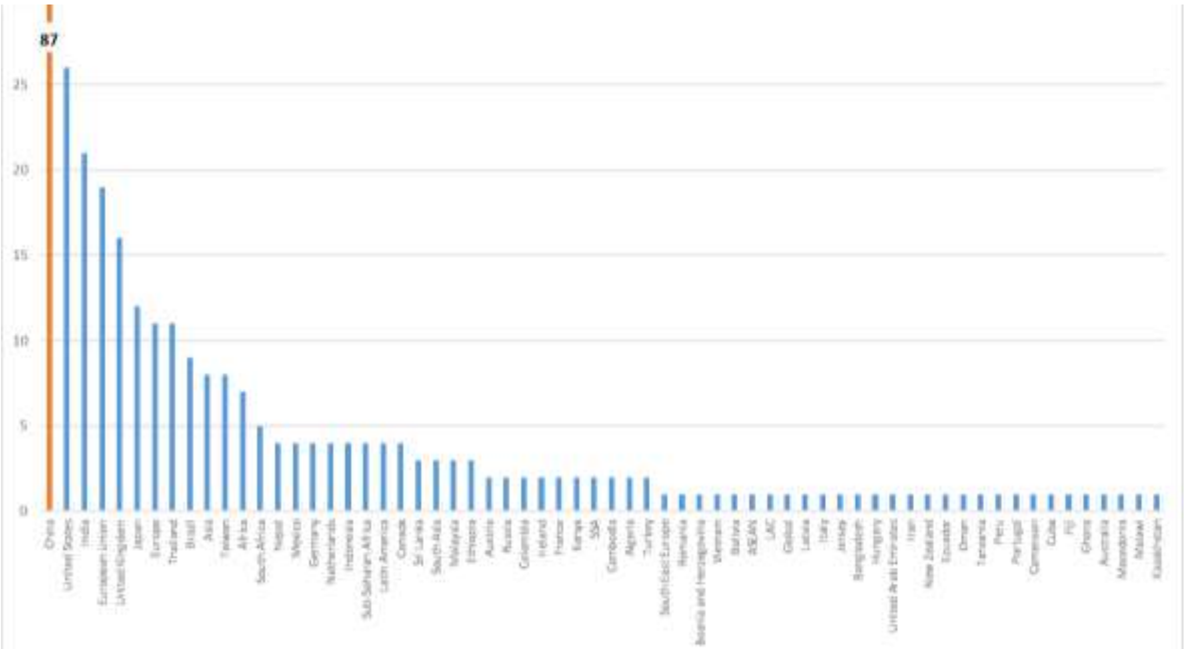

Figure 4.9 Regional distribution of peer-reviewed references on national-level mitigation pathways identified during chapter preparation. Source: Authors. Method: Systematic search in the Web of Science and Scopus databases looking for combinations of terms "mitigation" and [name of country or other Party to the UNFCCC] and [any year between 2020 and 2050] anywhere in title, keywords and abstracts. The search yielded [1205] references, which the authors narrowed down to [333] relevant papers through abstract and core text reading. Additional [xxx] relevant references identified from other sources.

Implications of mitigation on national development objectives are also analysed in a large body of grey literature, e.g., reports commissioned by governments in the context of the preparation and/or the evaluation of national mitigation plans. Some of this literature is dedicated to exploring NDCs (see 4.2.1 and 4.2.2) or to exploring mid-century pathways (4.2.4), with a large variety of climate objectives.

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