Chapter 2: Emissions Trends and Drivers

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Executive Summary

Global GHG emissions continued to rise and measured at 59±5.9 $GtCO_2eq$ in 2018 although the rate of growth has fallen compared to the previous decade *(high confidence)***. Still, emissions were higher than at any point in human history before** (*medium confidence*). Emissions in 2018 were 11% (5.9 $GtCO_2eq$) higher than in 2010 and 51% (20 $GtCO_2eq$) higher than 1990. Average annual GHG emissions for 2009-2018 were 56±5.6 $GtCO_2eq$ compared to 47±4.7 and 40±4.0 $GtCO_2eq$ for 2000-2009 and 1990-1999, respectively (*high confidence*). GHG emissions growth slowed since 2010: while average annual GHG emissions growth was 2.3% between 2000 and 2010, it was 1.3% for 2010-2018. Emissions of GHGs are weighed by Global Warming Potentials with a 100 year time horizon (GWP100) from the Sixth Assessment Report. GWP-100 is commonly used in wide parts of the literature on climate change mitigation and is required for emissions under the United Nations Framework Convention on Climate Change (UNFCCC). All metrics have limitations and uncertainties. {2.2.1, Table 2.5, Figure 2.4, Cross-Chapter Box 2, Annex B Section A.B.10}

Emission growth has been varied, but persistent across different gases (*high confidence*). In 2018, CO_2 emissions from fossil fuel and industry (FFI) were 38±3.0 Gt, CO_2 from agriculture, forestry and other land-use change (AFOLU) 5.4±2.7 Gt, CH_4 12±2.3 Gt CO_2eq, N_2O 2.5±1.5 $GtCO_2eq$ and fluorinated gases (f-gases) 1.8± 0.35 $GtCO_2eq$. While F-gas levels and CO_2 emissions from FFI have grown by 430% and 66% between 1990 and 2018, emissions increased by 25% and 28% for CH_4 and N_2O. The group of fluorinated gases have jointly grown much faster than all other GHGs, and makes a non-negligible contribution to global warming today. CO_2 remains the major driver of warming. {2.2.1, 2.2.2, Figure 2.4, Figure 2.3}

The global COVID-19 pandemic has led to a historic drop in CO_2 emissions from fossil fuel and industry (*medium confidence*). Preliminary data for 2020 suggest a decrease in FFI CO_2 emissions relative to 2019 of about 7% (2.7-13%) or about 3 $GtCO_2$, but emission growth has picked up with economic activity again since April 2020 after lock-down measures have been lifted or relaxed. Analysis from previous economic crises suggest a rebound in emissions in the absence of policy-induced structural shifts in the energy and other sectors. {2.2.2, Figure 2.5}

With continuing global CO_2 emission releases at current rates, the remaining carbon budget for keeping warming below 1.5°C will be exhausted before 2030 *(high confidence)*. Between 1850 and 2018 total cumulative CO_2 emissions FFI and AFOLU were 2400±390 $GtCO_2$. Of these, about 980±98 $GtCO_2$ were added to the atmosphere since 1990. 330±31 $GtCO_2$ were added since AR5 (2010). This is about the same size as the remaining carbon budget of 310±250 (390, 500) $GtCO_2$ for keeping global warming below 1.5°C and between 2-3 times smaller than the 960±250 (1140, 1390) $GtCO_2$ for keeping warming below 2°C with a probability of 67% (50%, 33%), respectively. At current rates of CO_2 emissions (43±4.1 Gt $CO_2\,yr^{-1}$), these remaining budgets will be exhausted in 7 (9,11) and 22 (27, 33) years, respectively. Even if global CO_2 emission decrease at 2% or 5% per year, the 1.5°C budget will be exhausted before 2030 highlighting the dependence of 1.5°C pathways on the availability of substantial CO_2 removal capacities. {2.2.2, Figure 2.6}

There is a growing number of countries that have achieved sustained GHG emission reductions since 1990 – individual countries at rates that are broadly consistent with climate change mitigation scenarios that limit warming to well below 2°C *(high confidence)*. There are at least 36 countries that have sustained territorial-based CO_2 and GHG emissions reductions for longer than 10 years. While total cumulative GHG reductions of these countries are small compared to recent global emissions growth, individual countries have cut their emissions by 50% from peak levels. Similarly, national GHG reduction rates in some years are in line with scenario pathways that limit warming well below 2°C at 66% probability (e.g. -4% average annual reductions), even outside of periods of economic decline. Overall, there are country cases emerging that highlight the feasibility of sustained emission reductions without sacrificing economic success. {2.2.3, Figure 2.11, Figure 2.12}

Consumption-based CO_2 emissions in the developed countries region are considerably higher than in other regions (*high confidence*). In developed countries consumption-based CO_2 emissions from fossil fuel combustion and industrial processes peaked at 16.8 $GtCO_2$ in 2007 with a subsequent 12% decline until 2015. With 41% of global CO_2 emissions in 2015, consumption-based CO_2 emissions in developed countries were highest across regions compared to 39% from Asia and Developing Pacific, 9% from African and Middle East, 6% from Latin American and Caribbean, and 6% from Eastern Europe and West-Central Asia, respectively. Asia and Developing Pacific has been a major contributor to consumption-based CO_2 emission growth since 2000 with an average growth rate of 6.4% per year. {2.3.2.1, Figure 2.16}

Many (43 out of 166) countries have decoupled consumption-based CO_2 emissions from economic growth in recent years (2010-2015) (*robust evidence, high agreement*)**.** A group of developed countries, such as some EU countries and the United States of America, and some developing countries, such as Cuba and Iran, have successfully achieved absolute decoupling of consumption-based CO_2 emissions and GDP growth (i.e., experienced GDP growth while their emissions have stabilised or declined). The decoupling has been achieved at various levels of per capita income and per capita emissions. The per capita emissions of decoupled economies range from 0.1 to 32 tonnes per capita. {2.3.3, Figure 2.17, Table 2.6}

International trade seems to be a moderate upward driver of global GHG emissions overall *(limited evidence, medium agreement),* **but improvements in carbon intensity have led to a net reduction in trade-related CO_2 emissions** (*robust evidence, high agreement*). Emissions driven by trade are small compared to other drivers and depend on which countries are participating in which part of the global supply chain and their relative carbon intensity. Until 2011, the growth of trade-related CO_2 emissions, which refers to emissions embodied in imported or exported products, was driven by an increase in trade volume outweighing gross emission savings from improvements in emissions intensity. After 2011, these two effects reversed, leading to a net reduction in trade-related CO_2 emissions. {2.3.4, 2.4}

There is a net CO_2 emission transfer from developing to developed countries via global supply chains (*robust evidence, high agreement*). The net emission transfer from developing to developed countries increased from 6.1% in 1995 and peaked in 2006 at 7.3%. Developed countries tend to be net CO_2 emission importers, whereas developing countries tend to be net emission exporters. This is caused by the international division of labour in the production of consumer goods, where emission-intensive processes are increasingly carried out in developing countries that tend to have less stringent environmental legislation, cheaper labour costs, cheaper raw materials, and increasing openness to trade. Most recently, CO_2 emission transfers between developing countries have been sharply increasing with the centre of trade activities shifting from Europe to Asia. {2.3.4, Figure 2.18}

Globally, affluence and population remained the strongest drivers of CO_2 emissions from fossil fuel combustion in the last decade *(robust evidence, high agreement)*. Trends since 1990 continued in the years 2010 to 2018 with affluence (GDP per capita) and population growth increasing emissions by 2.3% and 1% per year, respectively. This growth continuously outpaced a reduction in the use of energy per unit of GDP (-2.2% per year, globally). Energy demand has only decoupled from economic growth in relative terms, not in absolute amounts. A substantial decarbonisation of the energy system was only noticeable in North America, Europe and Eurasia, whereas globally the amount of CO_2 per unit of energy has practically remained unchanged over the last three decades. {2.4.1, Figure 2.20}

Developing countries have lower per-capita emissions but they remained major accelerators of global CO_2 emissions growth since 2010, mostly driven by increased consumption and investment

(robust evidence, high agreement). While energy intensity declined to a similar extent in OECD and non-OECD countries between 2010 and 2018, economic growth has been much stronger in non-OECD member countries. Very strong emissions growth in Eastern Asia has been slowing in recent years due to fewer coal power stations being added to the system. Developed economies reduced both territorial and consumption-based emissions mostly due to slower economic growth and fuel switching from coal to gas in North America as well as larger energy efficiency improvements and higher levels of fuel switching to renewables in Europe. However, the strong growth of renewable energy provision in some countries played a minor role in slowing down emissions growth at the global level. {2.4.1}

GHG emissions continued to rise across all sectors and subsectors; most rapidly in industry, energy supply and transport (*high confidence*). Compared to the previous decade (2000-2009), average annual greenhouse gas emissions for the period 2010-2018 grew by 36% (from 9.4 to 13 $GtCO_2eq$) in industry, 24% (16 to 20 $GtCO_2eq$) in energy supply and 19% (6.5 to 7.7 $GtCO_2eq$) in transport. Emissions growth was more modest in AFOLU (8.3%; 12 to 13 $GtCO_2eq$) and buildings (3.5%; 3.1 to 3.2 $GtCO_2eq$). {2.2.4, Figure 2.14}

GHG emissions remain highest in the energy sector, but accounting for indirect emissions raises the contribution of the buildings and industry sectors *(high confidence)*. In 2018, 34% (20 Gt CO_2eq) of the 59 $GtCO_2eq$ GHG emissions came from the energy sector, 23% (13 Gt CO_2eq) from industry, 23% (13 Gt CO_2eq) from AFOLU, 14% (8.3 Gt CO_2eq) from transport and 6% (3.4 Gt CO_2eq) from buildings. Allocating the CO_2 emissions from energy production to the sector of final energy use increased the share of the building and industry sector in total GHG emissions for the year 2018 by 11% and 10%, respectively. {2.2.4, 2.4.2, Figure 2.13, Figure 2.14}

GHG emissions growth has slowed in energy supply *(high confidence)*. Average annual growth in GHG emissions dropped from 3.2% for 2000-2010 to 1.4% in energy supply for 2000-2018. The slowing of growth was due to a reduction of coal power capacity additions in China, a structural shift to gas in the United States, and the increasing penetration of renewables in Europe. Despite these trends, large investments in fossil-fuel-based energy infrastructure has locked in technological pathways and institutional structures that will continue driving emissions in the future and impede the transitioning to renewables. More efforts are required to actively phase out all fossil fuels in the energy sector, rather than relying on fuel switching alone. {2.2.4, 2.4.2.1, Figure 2.14, Figure 2.21}

When indirect emissions from electricity and heat production are included, industry becomes the sector with the highest GHG emissions (*high confidence*). East Asia has been the main source and primary driver of global industry emissions growth since 1990, while industry emissions have declined in Europe and remained relatively steady in North America, Asia-Pacific Developed regions and Eurasia. The main driver has been a large rise in the global demand for basic materials, construction minerals and manufactured products, which in turn is driven by rising affluence and consumption, as well as a rapid rise in urban populations and associated infrastructure development. The industrial energy use as a fraction of GDP has steadily declined since 2010 in all regions. Without these improvements in energy intensity, industrial CO_2 emissions would have risen by more than 100% by 2017 since 1990s, instead of 56%. {2.2.4, 2.4.2.2, Figure 2.13, Figure 2.22}

GHG emissions of the buildings sector are mainly driven by a growing demand for building stock, floor space per capita and building energy services as countries develop and urbanise *(high confidence)*. Since 2010 GHG emissions in the buildings sector have declined from a high level in North America and Europe due to fuel switching and the expansion of renewables in the energy sector. In contrast GHG emissions have risen sharply in East Asia - where they have reached the highest level of all regions - and South Asia due to urbanisation and high levels indirect emissions from the electricity sector. {2.4.2.3, Figure 2.23}

Road transport for passengers and freight represent by far the largest component of transport sector emissions (73%) which continued to grow at a rate of about 2% per year over the last three decades *(high confidence)*. The high proportion of fossil fuels in total final energy used in transport (92%), insufficient improvements in transport energy efficiency and a global increase in passenger and freight travel activity levels mean that transport emissions kept increasing in all world regions. The adoption of electric vehicles is rapidly increasing in several regions departing from very low levels. While accounting for a small share of total GHG emissions, domestic and international aviation are growing faster than road transport emissions, with average annual growth rates of 3.0% and 2.1% respectively between 2010 and 2018. Energy efficiency improvements in aviation were considerably larger than in road transport, but outpaced by even larger increases in activity levels. {2.4.2.4, Figure 2.24}

GHG emissions from AFOLU continued to increase by 1% per year on average between 2010 and 2018 *(medium confidence)*. CO_2 emissions from land-use change and CH_4 emissions from enteric fermentation together account for almost 70% of the sector's emissions. Africa, Latin America and South East Asia had the largest CO_2 emissions from land use change, but substantial growth was only observed in Africa. CH_4 emissions from enteric fermentation were highest and strongly growing in Latin America, South Asia and Africa, reflecting rising consumption of animal-based diets in low- and middle-income countries. {2.4.2.5, Figure 2.25}

Eradicating extreme poverty and providing universal access to modern energy services to poor populations across the globe has negligible implications for emissions growth *(robust evidence, medium agreement)*. Existing studies on the role of poverty and inequality as drivers of GHG emissions provide limited evidence that in certain contexts greater inequality can lead to a deterioration in environmental quality and may be associated with higher GHG emissions (*limited evidence, medium agreement*). {2.4.3}

Rapid urbanisation in developing and transition countries leads to increased CO_2 emissions *(medium evidence, medium agreement)*. Migration from rural to urban areas in many developing countries remain associated with greater consumption and affluence as well as with a shift to fossil-fuel based energy services conducive to higher personal carbon footprints. {2.4.4}

Evidence of rapid energy transitions exists but at sub-global scales *(medium evidence, medium agreement)*. Most work on energy transitions pre-AR5 pointed out that past energy transitions occurred too slowly to keep warming well below 2°C, due to long infrastructure lifetimes and associated lock-in, risk aversion, and the time required by necessary global diffusion processes *(robust evidence, high agreement)*. Literature since AR5 identifies evidence and mechanisms by which future energy transitions may occur more quickly than those in the past, including technology transfer and cooperation, intentional policy and financial support, and harnessing synergies among technologies within a sustainable energy system perspective *(medium evidence, medium agreement)*. A fast low-carbon energy transition to meet stabilisation targets needs to be global and requires finance to facilitate low-carbon technology adoption in developing and particularly in least developed countries. {2.5.2, Table 2.8}

Multiple low-carbon technologies have shown rapid progress since AR5—in cost, performance, and adoption—enhancing the feasibility of rapid energy transitions (*robust evidence, high agreement*). The rapid historic cost decreases and deployment of modular technologies like solar, wind, and batteries have occurred much faster than expected by experts and by mitigation scenarios. The development of other low-carbon technologies such as bio- and fossil carbon capture has been slower than the growth rates anticipated in stabilisation scenarios. Emerging evidence since AR5 indicates that small scale (modular) technologies tend to improve faster and be adopted faster than large scale technologies *(medium evidence, high agreement.*) {2.5.3-.4, Figure 2.28, Figure 2.29}

Accelerating the rates of adoption of low carbon technologies is crucial for climate stabilisation *(medium agreement)***.** The magnitude of the scale-up challenge elevates the importance of urgency and persistence in fast technology development and adoption, ensuring participation of developing countries in an enhanced global flow of knowledge, skills, experience, equipment, and technology itself requires strong financial, institutional and capacity building support (*robust evidence, high agreement*). {2.5.4, Figure 2.30}

Robust incentives for investment in innovation, especially by national policy and international agreements are central to accelerating low-carbon technological change *(robust evidence, low agreement)*. Necessary policies involve instruments for technology push (e.g. scientific training, R&D) and demand pull (e.g. carbon pricing, adoption subsidies), as well as those promoting knowledge flows and especially technology transfer. {2.5, 2.8}

A rebalancing of the global distribution of income has decreased inequality between countries over the last decades accompanied by steady economic and GHG emissions growth *(robust evidence, high agreement)*. The impact of inequality on aggregate emissions depends on how quickly emissions increase as income rises. Emissions increase more slowly than income in most high and middle-income countries and at the same rate or faster in low-income countries (*low evidence, medium agreement*). {2.4.1., 2.7.2}

The top 10% emitters (the global wealthiest 10% on a per capita basis) contribute about 36-45% of global GHG emissions *(robust evidence, high agreement)*. Within countries, inequalities have increased for both income and GHG emissions. The top global 10% emitters live on all continents, with two thirds in rich OECD regions and one third in emerging economies *(robust evidence, medium agreement)*. Per capita consumption emissions in emerging economies are still far below the average in most OECD countries *(medium evidence, medium agreement)*. {2.6}

Carbon-intensive consumption patterns and lifestyles of wealthy consumers are emulated by middle and low-income segments of the population *(medium evidence, medium agreement)*. Increasing inequality within a country can create dilemmas of redistribution and social cohesion, and affect the willingness of rich and poor to accept mitigation and other policies to protect the environment *(medium evidence, medium agreement)*. {2.6.2}

Estimates of future CO_2 emissions from current energy infrastructures already exceed the remaining carbon budget for keeping warming below 1.5°C (*medium confidence*)**.** Based on assumed ranges for infrastructure lifetimes and utilisation, estimates of committed CO_2 emissions from *current* fossil fuel infrastructures of 715 (546-909) $GtCO_2$ and 658 (455-892) already exceed considerably the remaining carbon budget for keeping global warming well below 1.5°C with a 66% (50%) probability of 310 (390) ± 250 $GtCO_2$. Future CO_2 emissions from *current and planned* infrastructure are estimated at 846 (597-1126) $GtCO_2$. This is partially within the range of a carbon budget estimated at 960 (1140) ± 250 $GtCO_2$ for staying well below 2°C with an at least 66% (50%) probability. Hence, keeping warming well below 2°C will include early retirement of fossil energy infrastructures, carbon capture and utilisation or storage as well as direct CO_2 removal from the atmosphere. Complementary evidence from mitigation scenarios suggests that the fossil fuel infrastructure in the power sector has to be retired much earlier to keep warming well below 2°C as emissions from non-electric energy are much harder to reduce. For example, an earlier retirement of coal and gas power infrastructure by 23 (11-33) and 19 (11-16) year is typically observed in pathways that limit warming below 1.5°C. {2.7.2, 2.7.3, Figure 2.34, Figure 2.35, Table 2.9}.

Since the Paris Agreement a large number of coal power development plans have been cancelled (*medium confidence*)**.** Proposals to add new coal power capacity increased between 2009 and 2014 from about 910 to about 1250 GW in total, but dropped subsequently to about 410 GW by 2019. While a lot of plans to build coal power stations were scrapped, the total commissioned capacity did also drop from about 470 GW (~50% of the proposed capacity in 2009) for 2009-2014 to about 320 GW (~25% of the proposed capacity in 2015) for 2014-2019. {2.7.2, Table 2.10}

Every year, carbon committed from newly built energy infrastructure exceeds carbon emissions "saved" due to decommissioning of energy infrastructure d (*medium confidence*)**.** As a result, future CO_2 emissions from current energy infrastructure has failed to peak. This suggests that further inertia is added to the system, which makes a transformation towards carbon neutrality harder and may require additional stranding of assets for meeting the climate goals. {2.7.2}

Climate policies play an increasing role in emissions reductions taking place as a result of carbon pricing associated with carbon taxes or emissions trading. The literature is in broad agreement but the magnitude of the rate of reduction varies by the kind of data and methodology used, by country and by sector. (Robust evidence, high agreement). Countries with a lower carbon pricing gap (higher carbon price) tend to be more carbon efficient (medium confidence). {2.8.2.1}

Non-climate policies can also contribute to decreasing GHG emissions. Non-climate policies such as taxes and subsidies for clean transportation, support to renewable energy sources, electric vehicles and public transports have climate co-benefits by reducing GHG emissions in some contexts (Robust evidence, high agreement). Similarly, pollution control policies and legislations can have climate co-benefits when these go beyond end-of-pipe controls and complementarities between local pollution and global GHG emissions are considered in policy design (medium evidence, medium agreement). {2.8.2, 2.8.3}

2.1 Introduction

As demonstrated by the contribution of Working Group I to the Sixth Assessment Report of the IPCC (IPCC WGI), GHG concentrations in the atmosphere and the annual anthropogenic GHG emissions continue to grow and have reached a historic high driven mainly by continued fossil fuels use (Friedlingstein et al. 2019a; Jackson et al. 2019; Peters et al. 2019). Unsurprisingly, a large volume of new literature has emerged since AR5 on the trends and underlying drivers of anthropogenic GHG emissions. The mandate of this chapter is to provide a structured assessment of this new literature and establish the most important thematic links to other chapters in this report that present in-depth appraisals of GHG emissions trends and possibilities to curb them over the near and long term globally, in economic sectors mainly responsible for emissions, and by establishing policies and institutions to trigger systemic changes required for achieving the climate change goals enshrined in the Paris Agreement.

While AR5 has mostly assessed GHG emissions trends and drivers between 1970 and 2010, this assessment focusses on the period 1990-2018 with the main emphasis on changes since 2010.

Compared to Chapter 5 in the contribution of Working Group III to the Fifth Assessment (Blanco G. et al. 2014), the scope of the present chapter is broader. It provides the historical background of global progress in climate change mitigation for the rest of the report and serves as a starting point for the assessment of near- and medium- as well as long-term mitigation pathways in chapters 3 and 4, respectively. It also provides a systemic perspective on past emission trends in different sectors of the economy (chapters 6-12) and relates GHG emissions trends to past policies (Chapter 13) as well as observed technological developments (Chapter 16). There is also a greater thrust into the analysis of consumption-based sectoral emission trends compared to previous assessments. Similarly, greater focus has been placed on new literature on empirical evidence of behavioural choices and lifestyles closely linked to demand for goods and services particularly responsible for GHG emissions and the social aspects of mitigation (Chapter 5). Finally, a completely new section is devoted to assessing the literature on mitigation implications of existing and planned long-lived infrastructure and carbon lock-in. Figure 2.1 presents the road map of this chapter and the most important linkages to some other chapters in this report.

Figure 2.1 is a simplified illustration of the causal chain driving emissions along the black arrows. It also highlights the most important linkages to other chapters in this volume (blue lines). The logic of the figure is the following: the main topic of this chapter is trends of GHG emissions (discussed only in this chapter at such level of detail), hence they are at the top of the figure. The secondary theme of this chapter is drivers behind the trends, depicted in the second line of yellow-shaded boxes. Four categories of drivers are briefly introduced in these sections which highlight key issues and guide readers to chapters in which they can learn more details about those drivers. Finally, in addition to their own motivations and objectives, climate and non-climate policies shape aspirations and actions of actors in the main driver categories, hence shown in the row below.

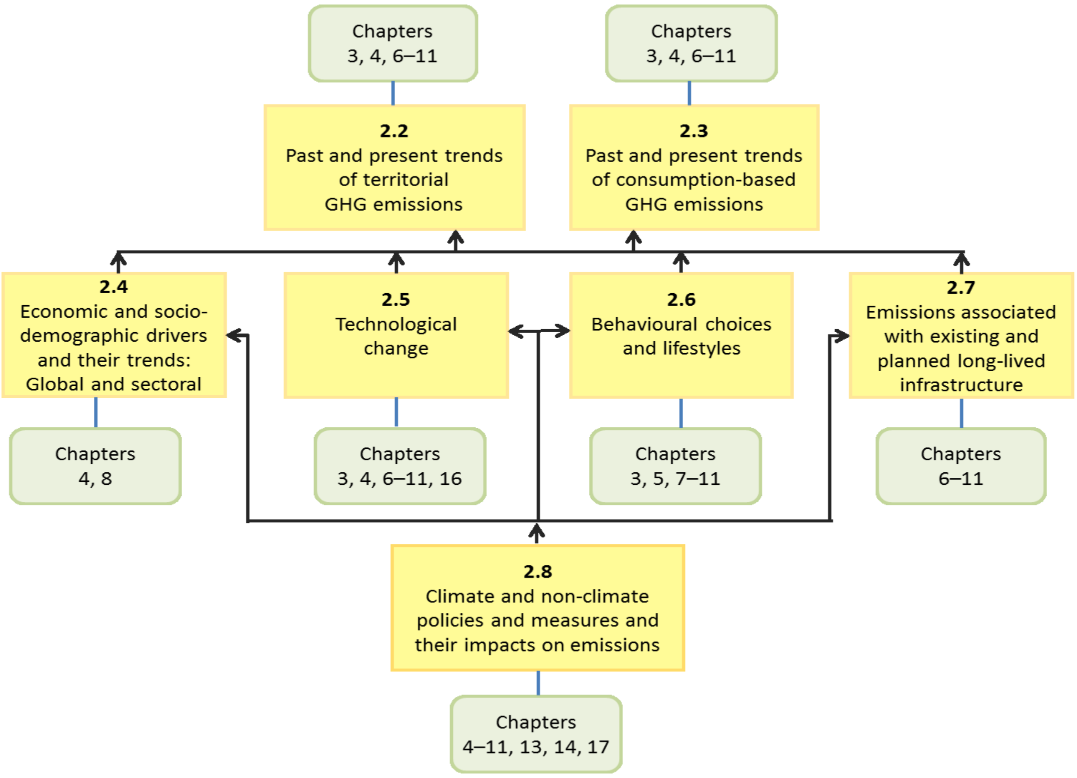

Figure 2.1 Road map and linkages to other chapters

Accordingly, boxes at the top of Figure 2.1 show that the first part of the chapter presents GHG emissions from two main perspectives: their geographical locations on the one hand and the places where goods are consumed and services are utilised, the provision of which cause GHG emissions. A complicated chain of factors called drivers underlie these emissions. They are linked across time, space and various segments of the economy and society in complex non-linear relationships. There are long traditions to explore some drivers such as economic activities and processes, demographic changes and transformations, many aspects of innovation, technological development as well as their interactions by various types of models. Some other drivers such as beliefs, traditions, religious and cultural rules shaping behavioural choices and lifestyles are difficult or outright impossible to quantify, hence model formally. Sections shown in the second row of boxes assess the latest literature and improve our understanding about the relative importance of these drivers in mitigating GHG emissions. A huge mass of physical capital embodying immense financial assets and potentially with a long lifetime produces vast GHG emissions and is a significant hindrance to fast and deep reduction of those emissions. Therefore, this long-lived infrastructure is also shown as important driver of GHG emissions in Figure 2.1. A large range of economic, social, environmental and other policies has been shaping these drivers of GHG emissions in the past and are anticipated to influence them in the future, as indicated by the policy box and its manifold linkages in Figure 2.1. Chapters in this report discuss these drivers and their operating mechanisms in detail. As noted, linkages between sections in this chapter and the thematically most closely related chapters in this volume are also presented in Figure 2.1 (blue lines).

2.2 Past and present trends of territorial GHG emissions

Total anthropogenic greenhouse gas (GHG) emissions as discussed in this chapter comprise CO_2 emissions from fossil fuel combustion and industrial processes[1] (FFI), CO_2 emissions from agriculture, forestry and land use change (AFOLU), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (F-

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FOOTNOTE: [1] Industrial processes relate to CO_2 releases from fossil fuel oxidation and carbonate decomposition.

gases). Other substances like aerosols and tropospheric ozone further contribute to trends in climate forcing, but are only treated here very briefly (Collins et al.).

In some sections of this chapter we convert different greenhouse gases into common units of CO_2 equivalent (CO_2eq) emissions using 100-year Global Warming Potentials (GWP100) with climate feedbacks from WGI of IPCCs Sixth Assessment Report (AR6) (Forster et al. 2020a) as reported in Cross-Chapter Box 2, Table 1. This reflects the dominant use in the scientific literature and is consistent with decisions made by Parties to the Paris Agreement for reporting and accounting of emissions and removals. Other GHG emissions metrics exist, all of which have limitations and uncertainties. The appropriate choice of GHG emissions metrics depends on policy objective and context (Myhre et al. 2013; Kolstad et al. 2015). A discussion of GHG metrics is provided in a Cross-Chapter Box later in the chapter (see Cross-Chapter Box 2).

Across this report, but most prominently in this chapter, we use the Emissions Database for Global Atmospheric Research (EDGAR) for a consistent assessment of the literature on GHG emission trends (Crippa et al. 2019a). To this we add CO_2 emissions and removals from land-use change and management (also known as AFOLU CO_2 emissions), which are not reported in EDGAR. These are taken as the average of estimates from three bookkeeping models (Houghton and Nassikas 2017; Hansis et al. 2015; Gasser et al. 2020) in a convention established by the Global Carbon Project (Friedlingstein et al. 2019a; Quéré et al. 2018). EDGAR is chosen because it provides the most comprehensive global dataset in its coverage of sources, sectors and gases (Andrew and Peters 2019), but we compare it to other global datasets in Section 2.2.1. We report emissions at two significant digits to reflect prevailing uncertainties in emissions estimates. Data is provisional and subject to revision for the final draft.

In section we first assess available global inventories for tracking greenhouse gas emissions as well as uncertainties in emissions estimates in Section 2.2.1. We believe that it is important to first go through these before presenting GHG emission trends. However, we admit

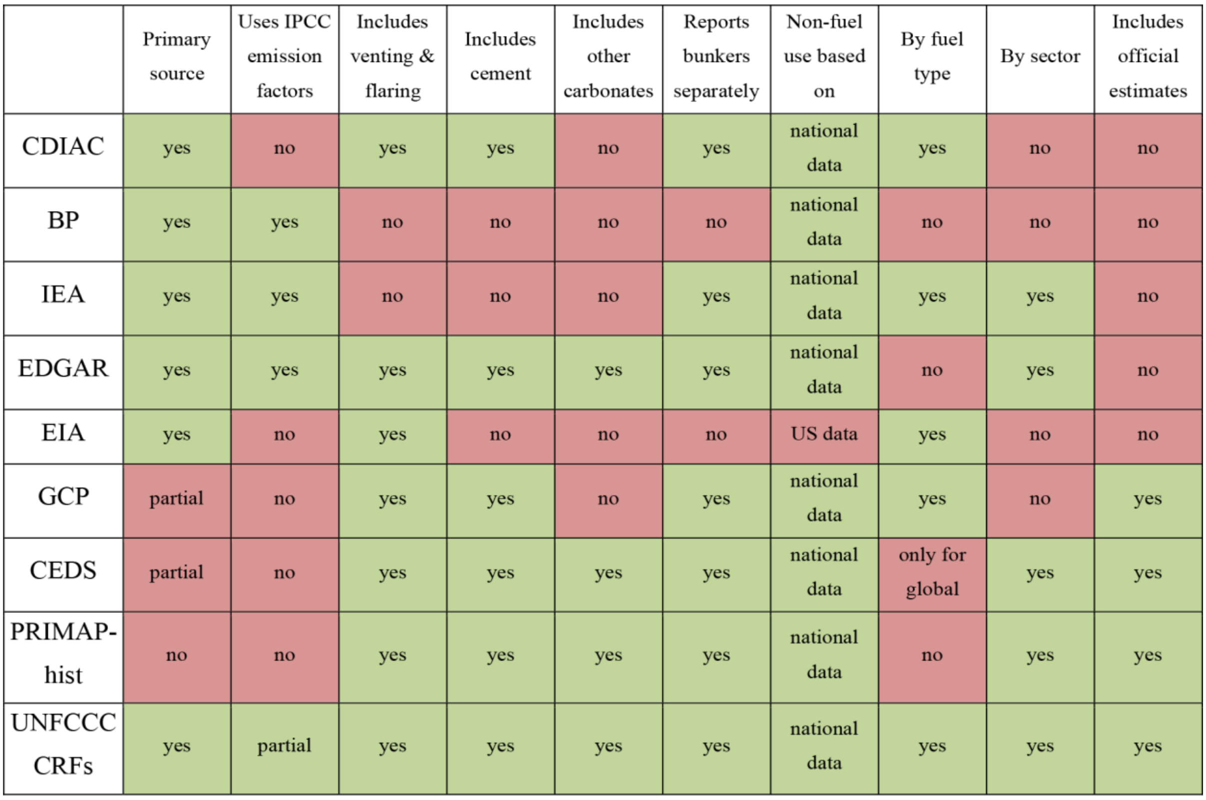
2.2.1 Uncertainties in GHG emissions

Estimates of historic GHG emissions – CO_2, CH_4, N_2O and F-gases – are uncertain to different degrees. Assessing and reporting uncertainties is crucial in order to understand whether available estimates are sufficiently accurate to answer, for example, whether GHG emissions are still rising or a country has achieved an emission reduction goal (Marland 2008). These uncertainties can be of scientific nature, when a process is not sufficiently understood. There is also estimation uncertainty which refers to model uncertainties associated with the mathematical equations used as well as parametric uncertainties associated with the quantification of the model parameters (activity data, emission factors etc.). There are at least four different ways to examine uncertainties in emission estimates: 1) by comparing estimates made by independent methods; 2) by comparing estimates from multiple sources; 3) by evaluating multiple estimates from a single source; 4) by modelling against remote sensing data (Marland et al. 2009). This section assesses the relevant peer-reviewed literature on uncertainties in historic GHG emission estimates and provides an expert judgement in the end.

2.2.1.1 Uncertainties in CO_2 emissions from fossil fuels and industrial processes (FFI)

Several studies have compared estimates of annual FFI CO_2-FFI emissions from different global inventories (Andres et al. 2012; Macknick 2011; Andrew 2020a; Janssens-Maenhout et al. 2019; Gütschow et al. 2016). However, estimates are not independent as they all ultimately rely on the same data sources. For example, all global inventories use one of four global energy datasets to estimate CO_2 emissions from energy use. These energy datasets themselves all rely on the same national energy statistics, with few exceptions (Andrew 2020a). Divergence between these estimates (see Figure 2.2) are mainly related to differences in the estimation methodology, conversion factors, emission coefficients, assumptions about combustion efficiency, and calculation errors (Marland et al. 2009; Andrew 2020a). Key differences for seven global datasets are highlighted in Table 2.1. But a second major source is differences in system boundaries of the respective datasets as shown in (e.g. Macknick 2011; Andrew 2020a; Andres et al. 2012). Hence, differences across FFI CO_2 emissions estimates do not reflect full uncertainty due to source data dependencies. At the same observed differences across estimates from different databases exaggerate uncertainty to the extent they originate in system boundary differences (Andrew 2020a; Macknick 2011).

Table 2.1 System boundaries and other key features of global FFI-CO_2 emissions datasets. Comparison of some important general characteristics of nine emissions datasets, with green indicating a characteristic that might be considered a strength. Columns four to seven refer to CO_2 emission estimates for industrial processes and product use. The partial use of IPCC default emissions factors by UNFCCC Common Reporting Format (CRFs) inventories is considered a strength because when default factors are not used more accurate country-specific factors are used. Note that CEDS produces estimates by fuel, but this information is not released. Source: (Andrew 2020a)



	Primary source	Uses IPCC emission factors	Includes venting & flaring	Includes cement	Includes other carbonates	Reports bunkers separately	Non-fuel use based on	By fuel type	By sector	Includes official estimates
CDIAC	yes	no	yes	yes	no	yes	national data	yes	no	no
BP	yes	yes	no	no	no	no	national data	no	no	no
IEA	yes	yes	no	no	no	yes	national data	yes	yes	no
EDGAR	yes	yes	yes	yes	yes	yes	national data	no	yes	no
EIA	yes	no	yes	no	no	no	US data	yes	no	no
GCP	partial	no	yes	yes	no	yes	national data	yes	no	yes
CEDS	partial	no	yes	yes	yes	yes	national data	only for global	yes	yes
PRIMAP-hist	no	no	yes	yes	yes	yes	national data	no	yes	yes
UNFCCC CRFs	yes	partial	yes	yes	yes	yes	national data	yes	yes	yes

Mean global annual FFI CO_2 emissions across global inventories track at 34.4±2 $GtCO_2$ in 2014 reflecting a variability of about ±5.4% (Figure 2.2). However, this variability can be almost halved, if system boundaries are harmonised (Andrew 2020a). EDGAR FFI CO_2 emission as used in this report tracks at the top of the range due to its comprehensive system boundaries. Once, system boundaries are harmonised it continues to track at the upper end of the range, but no longer at the top. EDGAR CO_2 FFI estimates are further well-aligned with emission inventories submitted by Annex I countries to the UNFCCC – even though some larger variation can occur for individual countries (Andrew 2020a).

Estimates of FFI CO_2 emissions are largely derived from energy consumption activity data, where data uncertainties are comparatively small due to well established statistical monitoring systems, although there are larger uncertainties in some countries and time periods (Andrew 2020a; Macknick 2011; Janssens-Maenhout et al. 2019; Andres et al. 2012; Ballantyne et al. 2015). Most of the underlying uncertainties are systematic related to underlying biases in energy statistics and accounting methods used (Friedlingstein et al. 2020). Uncertainties in FFI CO_2 emissions arise from the combination of uncertainty in activity data and uncertainties in emission factors including assumptions for combustion completeness and non-combustion uses. These uncertainties are lower for fuels with relatively uniform properties such as natural gas, oil or gasoline and higher for fuels with more diverse properties, such as coal (IPCC 2006; Blanco G. et al. 2014). Uncertainties in CO_2 emissions estimates from industrial processes, i.e. fossil fuel oxidation and carbonate decomposition, are higher than for fossil fuel combustion. At the same time, products such as cement also take up large amounts of cement over their life cycle, which are often not fully considered in carbon balances (Xi et al. 2016; Sanjuán et al. 2020). However, recent versions of the global carbon budget includes specific estimates for the cement carbonation sink and estimate average annual CO_2 uptake at 0.70 $GtCO_2$ for 2010-2019 (Friedlingstein et al. 2020). Finally, upstream emissions, such as from flaring or natural gas leaks, as well as oil refining processes (Jing et al. 2020), also have higher uncertainties.

Uncertainties of energy consumption data (and, therefore, FFI CO_2 emissions) are generally higher for the first year of their publication. 70% of data points are adjusted by an average of 1.3% of a country's total fossil fuel use in the subsequent year with further more modest revisions later on (Hoesly and Smith 2018). Uncertainties are also higher for developing countries, where statistical reporting systems do not have the same level of maturity as in many industrialised countries (Friedlingstein et al. 2019a, 2020; Janssens-Maenhout et al. 2019; Marland 2008; Guan et al. 2012; Korsbakken et al. 2016; Gregg et al. 2008; Andres et al. 2012; Andrew 2020b). Examples estimates of uncertainties for CO_2 emissions from fossil fuel combustion at the 95% confidence interval are 3-5% for the U.S., 15-20% for China and 50% or more for countries with poorly developed or maintained statistical infrastructure (Marland et al. 1999; Andres et al. 2012; Gregg et al. 2008). However, standard country groupings do not predict to which extent a country's energy data has undergone historical revisions (Hoesly and Smith 2018). Uncertainties in FFI CO_2 emissions before the 1970s are higher than for more recent estimates. Over the last two to three decades uncertainties have increased again because of increased production in some developing countries with less rigorous statistics (Friedlingstein et al. 2020; Marland et al. 2009).

The global carbon project (Friedlingstein et al. 2019a, 2020; Le Quéré et al. 2018a) assesses the uncertainty estimate in the global anthropogenic FFI CO_2 emissions within one standard deviation ($\pm1\sigma$) at ±5%. This is broadly consistent with $\pm2\sigma$ (95% confidence interval) estimates of ±8% in IPCC AR5 (Blanco G. et al. 2014) as well as ±8.4% (Andres et al. 2014), ±9% (Janssens-Maenhout et al. 2019; Solazzo et al. 2020) and ±5% - ±10% (Ballantyne et al. 2015) in the wider literature. In this report we apply a fixed uncertainty of ±8% at the 90% confidence interval following the EDGAR uncertainty assessment by Janssens et al. (2019) and accounting for the growing share of emissions from developing countries as well as the more recent reporting period 1990-2018 compared to AR5.

2.2.1.2 Uncertainties in CO_2 emissions from AFOLU

AFOLU CO_2 emissions include all anthropogenic fluxes attributable to land-use, land management and changes therein including CO_2 fluxes from deforestation (by anthropogenic fire and/or clear-cut), re/afforestation, logging and forest degradation (including harvest activity), shifting cultivation (cycle of cutting forest for agriculture, then abandoning), and regrowth of forests following wood harvest or abandonment of agriculture, and emissions from peat burning and drainage. Since in reality anthropogenic AFOLU CO_2 emissions co-occur with natural CO_2 fluxes in the terrestrial biosphere, models have to be used to distinguish anthropogenic and natural fluxes (Friedlingstein et al. 2020).

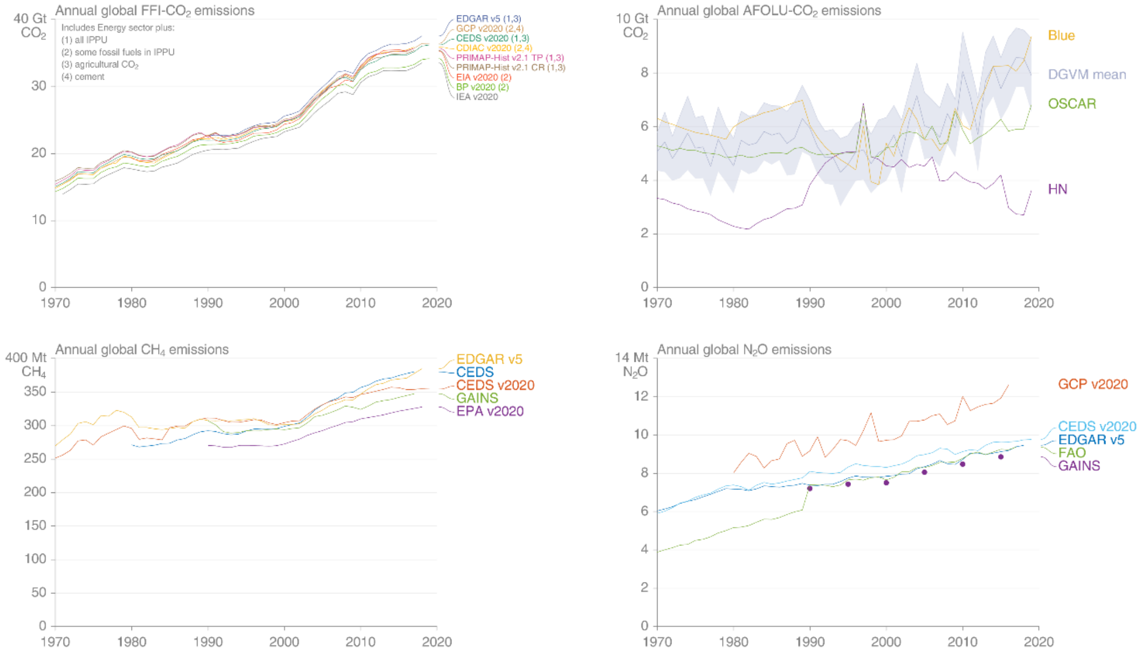


Figure 2.2 Estimates of global anthropogenic greenhouse gas emissions from different data sources 1970-2019: Panel A) FFI-CO_2 emissions from: EDGAR - Emissions Database for Global Atmospheric Research (Crippa et al. 2019a); GCP – Global Carbon Project ((Friedlingstein et al. 2019b, 2020)**; CEDS - Community Emissions Data System** (Hoesly et al. 2018; McDuffie et al. 2020; O'Rourke et al. 2020)**; CDIAC Global, Regional, and National Fossil-Fuel CO_2 Emissions** (Gilfillan et al. 2019)**; PRIMAP-hist - Potsdam Real-time Integrated Model for probabilistic Assessment of emissions Paths** (Gütschow et al. 2016, 2019)**; EIA - Energy Information Administration International Energy Statistics** (EIA 2019)**; BP - BP Statistical Review of World Energy** (BP 2019)**; IEA - International Energy Agency CO_2 Emissions from Fuel Combustion** (IEA 2019a)**; IPPU refers to emissions from industrial processes and product use. Panel B) AFOLU-CO_2 emissions from: BLUE – Bookkeeping of land-use emissions** (Hansis et al. 2015)**; DGVM-mean – Multi-model mean of AFOLU-CO_2 emissions from dynamic global vegetation models** (Friedlingstein et al. 2020)**; OSCAR – an earth system compact model** (Gasser et al. 2020)**; HN – Houghton and Nassikas Bookkeeping Model** (Houghton and Nassikas 2017)**; Panel C) Anthropogenic methane emissions from: EDGAR (above); CEDS (above); GAINS - The Greenhouse gas – Air pollution INteractions and Synergies Model** (Höglund-Isaksson 2012)**; EPA-2020: Greenhouse gas emission inventory** (EPA 2019)**; Panel D: Anthropogenic nitrous oxide emissions from: GCP – global nitrous oxide budget** (Tian et al. 2020)**; CEDS (above); EDGAR (above); GAINS (above); FAO – N_2O emissions from the FAOSTAT inventory** (Tubiello et al. 2013)**.**

AFOLU CO_2 estimates presented in this report represent the average of three global bookkeeping models – namely BLUE (Hansis et al. 2015), H&N (Houghton and Nassikas 2017), and OSCAR (Gasser et al. 2020). For 1990-2018, average emissions are estimated at 6.0, 4.3, and 5.5 $GtCO_2\ yr^{-1}$ for BLUE, H&N, and OSCAR (Figure 2.2). Gross emissions 1990-2018 for BLUE, H&N, OSCAR are 17, 9.6 and 19 $GtCO_2\ yr^{-1}$, while gross removals are 10, 5.3, 13 $GtCO_2\ yr^{-1}$ respectively, i.e. for 1990-2018 maximum average differences are 8.9 and 7.7 $GtCO_2\ yr^{-1}$ for gross emissions and removals (Friedlingstein et al. 2020). In the longer term, a consistent general upward trend since 1850 across models is reversed during the second part of the 20th century. Since the 1980s, however, trends differ across models related inter alia to the different land-use forcings (Gasser et al. 2020). Further differences between BLUE and H&N were traced back in particular to differences in carbon densities between natural and managed vegetation or primary and secondary vegetation, and higher allocation of cleared and harvested material to fast turnover pools in BLUE than H&N, and to a lesser extent to including sub-grid scale transitions (Bastos et al. 2020). Key differences across these models are summarised in Table 2.2.

Uncertainties in AFOLU CO_2 emissions are more comprehensively characterised through further comparison across a suite of dynamic global vegetation models (DGVM), which differ in methodology, input data and how comprehensively they represent land-use-related processes (Friedlingstein et al. 2020). They are not combined in the AFOLU CO_2 mean estimate because the typical DGVM setup includes the loss of additional sink capacity, which makes up about 40% of the DGVM estimate in recent years (Obermeier et al. 2020) and is excluded in bookkeeping estimates. An AFOLU CO_2 estimate from the DGVM multi-model mean is consistent with the average estimate from the bookkeeping models as shown in Figure 2.2. Variation across DGVMs is large with a standard deviation at around 1.8 $GtCO_2\ yr^{-1}$, but still smaller than the average difference between bookkeeping models at 2.6 $GtCO_2\ yr^{-1}$ as well as the current estimate of H&N (Houghton and Nassikas 2017) and its previous model versions (Houghton et al. 2012). We follow Friedlingstein et al. (2020) and take ±2.6 $GtCO_2\ yr^{-1}$ as a conservative value judgement for the $\pm 1\sigma$ uncertainty range. The absolute uncertainty estimate presented above corresponds roughly to a relative uncertainty of about ±50%, which is much higher than for most fossil-emission terms, but reflects the large model spread and large differences between the current estimate of H&N and its previous model version (Houghton et al. 2012). Much larger uncertainties in AFOLU CO_2 emissions have been identified across the literature but were traced back to different definitions used in various modelling frameworks (Pongratz et al. 2014) as well as inventory data (Grassi et al. 2018). In line with the AR5 assessment we assume a fixed relative uncertainty estimates of ±50%.

Finally, note that attempts to constrain the estimates of AFOLU CO_2 emissions by observed biomass densities have been undertaken, but were successful only in some non-tropical regions (Li et al. 2017a). Remote-sensing derived estimates have limited applicability for model evaluation, since they quantify usually only vegetation biomass changes and exclude legacy emissions from the pre-satellite era. Further, with the exception of the (pan-tropical) estimates by Baccini et al. (2012) they either track committed instead of actual emissions (e.g., Tyukavina et al. (2015) combine a static carbon density map with forest cover changes) or include the natural land sink (e.g., Baccini et al. (2017) infer fluxes directly from the carbon stock time series); neither distinguishes natural from anthropogenic disturbances.

Table 2.2 Key differences between global bookkeeping models for estimating AFOLU CO_2 emissions. Notes: DGVM – dynamic global vegetation model; LUH2 and FAO refer to land-use forcing datasets; arrows indicate tendency of process to increase or decrease emissions.

	Bookkeeping model		
	BLUE[a]	**H&N**[b]	**OSCAR**[c]
Geographical scale of computation	0.25 degree gridscale	country	10 regions and 5 biomes
Carbon densities and soil of vegetation	literature-based	inventory-based	calibrated to DGVMs
Land-use forcing	LUH2[d,e]	FAO[f]	LUH2 and FAO[d,e, f]
Representation of processes (indicative effect on AFOLU CO_2 emissions)			
Sub-grid scale (“gross” transitions	yes (↑)[g]	no (↓)	yes (↑)
Pasture conversion	From all natural vegetation types proportionally (↑)	from grasslands first (↓)	from all natural vegetation types proportionally (↑)

Distinction rangeland vs pasture	yes (↓)	no (↑)	no (↑)
Coverage peat drainage (as in Global Carbon Budget 2020)	World (↑)[h]	South East Asia (↓)	World (↑)[h]

Literature: [a](Hansis et al. 2015); [b] (Houghton and Nassikas 2017); [c] (Gasser et al. 2020); [d] (Hurtt et al. 2020); [e] (Chini et al. 2020); [f] (Food and Agriculture Organsiation of the United Nations 2015); [g] (Bastos et al. 2020); [h] (Conchedda and Tubiello 2020)

2.2.1.3 Uncertainties in CH_4 emissions

Anthropogenic sources trigger about 60% of total global methane emissions (Saunois et al. 2020) coming from a range of different sectors: agriculture, fossil production and use, waste as well as biomass and biofuel burning. Methane emissions can be derived either using bottom-up estimates that rely on anthropogenic inventories such as EDGAR (Janssens-Maenhout et al. 2019), land surface models that infer part of natural emissions (e.g. Wania et al. 2013) or observation-based upscaling for some specific sources such as geological sources (e.g. Etiope et al. 2019); or from top-down approaches that use atmospheric transport model and assimilate methane atmospheric observations to estimates past methane emissions (e.g. Houweling et al. 2017). Comprehensive assessments of methane sources and sinks have been provided by Saunois et al. (2016, 2020) and Kirschke et al. (2013).

EDGAR (Crippa et al. 2019b; Janssens-Maenhout et al. 2019) is one of multiple global methane inventories available. Other inventories – namely CEDS (Hoesly et al. 2018; McDuffie et al. 2020; O'Rourke et al. 2020), GAINS (Höglund-Isaksson 2012), US-EPA (EPA 2011, 2019) as well as FAOSTAT-CH_4 (Tubiello et al. 2013; Tubiello 2018; Federici et al. 2015) – can differ in terms of their country and sector coverage as well as detail. EDGAR, CEDS, US-EPA and GAINS cover all major source sectors (fossil fuels, agriculture and waste, biofuel) – except large scale biomass burning – but this can be added from different databases such as FINN (Wiedinmyer et al. 2011), GFAS (Kaiser et al. 2012), GFED (Giglio et al. 2013) or QFED (Darmenov and da Silva 2013). These inventories of anthropogenic emissions are not completely independent as they follow the same IPCC methodology to derive emission as a product of an activity factor and an emission factor for this activity and basically rely on the same FAOSTAT activity data. However, they may differ in the assumptions and data used for the calculation. While the USEPA inventory uses the reported emissions by the countries to UNFCC, other inventories produce their own estimates using a consistent approach for all countries, and country specific activity data, emission factor and technological abatement when available. CEDS is based on pre-existing emission estimates from FAOSTAT and EDGARv42 and then scales these emissions to match other region-specific inventories. CEDS shows the largest emissions and emission increase due to on overestimation of some emissions in EDGARv42, especially from the coal exploitation in China resulting from the use of default emission factor for this region (Saunois et al., 2020). This has been corrected in EDGARv32 resulting in lower estimates from this sector and region and translating to the global total emissions. EDGARv5 has revised the total global CH_4 emission about 10 Mt CH_4 per year higher than EDGARv42 due to a higher estimate for the waste sector. USEPA show the lowest estimates probably due to missing estimates from a significant number of countries not reporting to UNFCCC (USEPA2020 includes estimates from only 195 countries). EDGARv5 estimates of anthropogenic CH_4 emissions as used in this report are close to the mean of the different inventories and can be considered as an average estimates including the vast majority, but not exhaustively all anthropogenic sources - not covering CH_4 emissions from biomass burning particularly, which amount about 10-12 Mt per year.

Saunois et al (2020) provide estimates of methane sources and sinks based on BU and TD approaches associated with an uncertainty range based on the minimum and maximum values of available studies, because for many individual source and sink estimates the number of studies is often relatively small.

Thus they do not take into account the uncertainty of the individual estimates. As shown in Table 2.3 Uncertainties in total global methane emissions across all anthropogenic and natural sources are comparatively small at ±6% - a range larger than errors in transport models only (Locatelli et al. 2015). However, uncertainty in the chemical sink was not fully considered in the TD estimates in Saunois et al (2020). Uncertainty on the global burden of OH is about 10-15%, which translates to an uncertainty of approximately +/- 9% on total global emissions (Zhao et al. 2020). Based on both TD and BU ensemble, uncertainty on the global anthropogenic methane emissions is about ±10% to ±30% depending on the category, with larger uncertainty in the fossil fuel sectors than in the agriculture and waste sector (Saunois et al 2020). However, these uncertainties are underestimated as they do not consider the uncertainty on individual estimate, which includes uncertainty in activity data, emission factor, and equations used to estimate emissions. Indeed, estimated uncertainties in inventories at national scale, such as in the USA can be much larger depending on the sector (NASEM 2018). Global inventories, such as EDGAR, estimate uncertainties in national anthropogenic emissions of about ± 32% for the 24 member countries of OECD, and up to ±57% for other countries, whose activity data are more uncertain (Solazzo et al. 2020; Janssens-Maenhout et al. 2019). These are higher than the ±20% and ±30% total uncertainty judgement in AR5 and UN Environment emissions gap (Blanco G. et al. 2014; UNEP 2020), but justified by the large uncertainties reported in the methane budgets (Saunois et al. 2016, 2020; Kirschke et al. 2013) as well as for FAO activity statistics by Tubiello et al. (2015b). In this report, we apply a best value judgment of ±20% for global anthropogenic methane emissions.

Table 2.3 Uncertainty estimated on methane sources at the global scale, based on ensembles of bottom-up (BU) and top-down (TD) estimates, national reports and specific uncertainty assessments of EDGAR

	Estimated uncertainty in inventories in the USA [a]	Estimated uncertainty in EDGAR [d]	Global inventories uncertainty range [b]	Saunois et al. (2020) BU uncertainty range[c]	Saunois et al. (2020) TD uncertainty range[c]
Total global anthropogenic sources (incl. Biomass burning)			-	±6%	±6%
Total global anthropogenic sources (excl. Biomass burning)		±47%	±8%		
Agriculture and Waste				±8%	±8%
Rice	na		±22%	±20%	-
Enteric fermentation and manure management	±10 to 20% ± 20% and up to ± 65%	±60%	±5%	±8%	-
Landfills and Waste	±10% but likely much larger	±91%	±17%	±7%	-
Fossil fuel production & use				±20%	±25%
Coal	-15% to +20%	±75%	±40%	±28%	-
Oil and gas	-20 % to +150%		±19%	±15%	-
Other	na	±100%	±64%	±130%*	-
Biomass and biofuel burning			-	±25%	±25%
Biomass burning			-	±35%	-
Biofuel burning		Included in "Other"	+/-24%	±17%	-
Natural wetlands			-	±27%	±11%
Other natural emissions			-	±37%	±40%

[a] Based on (NASEM 2018)

[b] Uncertainty calculated as ((min-max)/2)/mean*100 from the estimates of year 2017 of the six inventories plotted in Figure 2.2. This does not consider uncertainty on each individual estimate.

[c] Uncertainty calculated as ((min-max)/2)/mean*100 from individual estimates for the 2008-2017 decade. This does not consider uncertainty on each individual estimate, which is probably larger than the range presented here.

[d] Based on EDGARv432 for year 2010 (Janssens-Maenhout et al. 2019).

[*] Mainly due to difficulties in attributing emissions to small specific emission sector.

2.2.1.4 Uncertainties in N_2O emissions

Here, we consider anthropogenic N_2O emissions from different sectors including agriculture, fossil fuel and industry, biomass burning, waste, and other. The agriculture sector consists of four components: direct and indirect emissions from soil and water bodies (inland, coastal, and oceanic waters), manure left on pasture, manure management, aquaculture. The other sector represents the sum of the effects of climate, elevated atmospheric CO_2, and land cover change, which is a new sector that was developed as part of the global nitrous oxide budget (Tian et al. 2020) – a recent assessment to quantify all sources and sinks of N_2O emissions overseeding previous attempts (Kroeze et al. 1999; Syakila and Kroeze 2011; Mosier et al. 1998; Mosier and Kroeze 2000). Overall, anthropogenic sources contributed just over 40% to total global N_2O emissions (Tian et al. 2020).

There are a variety of approaches for measuring N_2O fluxes including emissions inventories (e.g. Tubiello et al. 2015a, 2013; Janssens-Maenhout et al. 2019; Winiwarter et al. 2018), statistical extrapolation of flux measurements (e.g. Wang et al. 2020b) as well as process-based land and ocean modelling (e.g. Tian et al. 2019; Yang et al. 2020b).There are at least four relevant global N_2O emissions inventories available: EDGAR (Crippa et al. 2019a; Janssens-Maenhout et al. 2019), GAINS (Höglund-Isaksson 2012), FAO-N_2O (Tubiello et al. 2013; Tubiello 2018), CEDS (Hoesly et al. 2018; McDuffie et al. 2020; O'Rourke et al. 2020) as well GFED (Giglio et al. 2013). While EDGAR and GAINS cover all sector except biomass burning, FAOSTAT-N_2O is focused on agriculture and biomass burning and GFED on biomass burning only. As shown in Figure 2.2 EDGAR, GAINS, CEDS and FAOSTAT emissions are consistent in magnitude and trend. Main discrepancies across inventories are in agriculture, where emissions estimates from the global nitrous oxide budget (also referred to by "GCP") (Tian et al. 2020) and FAOSTAT are on average 1.5 Mt N_2O yr^{-1} higher than that of GAINS and EDGAR during 1990-2016 due to much higher estimates of direct emissions from fertilised soils and manure left on pasture. GCP provides the largest estimate, because it synthesised from the other three inventories and further informed by bottom-up modelling estimates – and is as such more comprehensive. In particular, it includes an additional sector that considers the sum of the effects of climate, elevated atmospheric CO_2, and land cover change (Tian et al. 2020). EDGAR estimates of anthropogenic N_2O emissions as used in this report must be considered lower bound estimates including the vast majority, but not exhaustively all anthropogenic sources.

Anthropogenic N_2O emissions estimates are subject to considerable uncertainty – larger than those from FFI-CO_2 or CH_4 emissions. N_2O inventories suffer from high uncertainty on input data (fertiliser use, livestock manure availability, storage and applications (Galloway et al. 2010; Steinfeld et al. 2010) as well as nutrient, crops and soils management (Ciais et al. 2014; Shcherbak et al. 2014),emission factors (IPCC 2019; Crutzen et al. 2008; Hu et al. 2012; Yuan et al. 2019) and sources that are not yet well understood (e.g. peatland degradation, permafrost) (Winiwarter et al. 2018; Wagner-Riddle et al. 2017; Elberling et al. 2010). Model-based estimates face uncertainties associated with the specific model configuration as well as parametrisation (Tian et al. 2020, 2019; Buitenhuis et al. 2018).

The global N_2O budget estimated average annual anthropogenic N_2O emissions in 2007-2016 at 7.3 (4.2-11.4 MtN_2O yr^{-1}). This large range was principally attributable to the uncertainty in agricultural emissions (2.5-5.8 MtN_2O yr^{-1}) (Tian et al. 2020). Reported estimates are also larger than those presented in AR5 (Ciais et al. 2014). At a sector level, uncertainties are larger for agriculture than for biomass burning, fossil fuel and industry, and waste. For EDGAR uncertainties in N_2O emissions are estimated based on default values (IPCC 2006) at 42% for 24OECD90 countries and at 93% for other countries. This is broadly in line with IPCC AR5 und UNEP (Blanco G. et al. 2014; UNEP 2020) as well as Olivier et al. (2017). We estimate the overall relative uncertainty in global anthropogenic N_2O emissions at ±60% for a $\pm 2\sigma$ sigma confidence interval.

Table 2.4 Comparison of four global N_2O inventories: EDGAR (Crippa et al. 2019a; Janssens-Maenhout et al. 2019); GCP (Tian et al. 2020); GAINS (Höglund-Isaksson 2012); FAOSTAT (Tubiello 2018; Tubiello et al. 2013)

Name	Time coverage	Geographical coverage	Activity split	IPCC emissions factors	Reported emissions in 2015 (in MtN_2O)					
					agriculture	Fossil fuel and industry	Biomass burning	Waste and waste sector	other	Total
EDGAR	1970-2018	Global, 226 countries	4 main sectors, 24 sub-sectors	Yes	6.5	1.8	0.5	0.4	-	9.1
GCP	1980-2016	Global, 10 regions	5 main sectors, 14 sub-sectors	no	8.4	1.6	1.1	0.6	0.3	11.9
GAINS	1990-2015 (every 5 years)	Global, 172 regions	3 main sectors, 16 sub-sectors	no	6.8	1.3	-	0.7	-	8.8
FAOSTAT	1961-2017	Global, 231 countries	2 main sectors, 9 sub-sectors	Yes	8.3	-	0.9	-	-	9.2

2.2.1.5 *Synthesis and expert judgement*

In the previous section with compared the extended EDGAR dataset used in this report with other global emissions inventories and assessed uncertainties. Our assessments highlights that the extended EDGAR dataset comprehensively covers anthropogenic sources of greenhouse gas emissions (*high confidence*). However, most recent and comprehensive assessments of the methane (Saunois et al. 2020) and nitrous oxide (Tian et al. 2020) budget suggest that anthropogenic CH_4 and N_2O emissions could be 10% and up to 20% higher than reported in EDGAR, respectively (*medium confidence*). This is partially due to system boundary issues (e.g. exclusion CH_4 biomass burning), but relates also to different methodological choices (e.g. N_2O emissions from agriculture).

Based on the above assessment, we apply uncertainty estimates for GHGs at a 90% confidence interval that range from relatively low for fossil fuel CO_2 (± 8%), to intermediate values for CH_4 and the F-gases (± 20%), to higher values for N_2O (± 60%) and CO_2 from AFOLU (±50%). We further provide an uncertainty estimate for total greenhouse gases in terms of CO_2eq emissions at ±10% (*medium confidence*). This is in line with IPCC AR5 (Blanco G. et al. 2014). We highlight that the uncertainty assessment is still in full swing and invite reviewer comments on this matter. Based on recent uncertainties analyses or expert judgements higher estimates for CH_4 and F-gases as well as overall GHG emissions will be considered (Janssens-Maenhout et al. 2019; Solazzo et al. 2020; UNEP 2020).

When we convert different greenhouse gases into common units of CO_2 equivalent (CO_2eq) emissions, we use 100-year Global Warming Potentials (GWP100) with climate feedbacks from the Sixth Assessment Report (AR6) (Forster et al. 2020a). Sustained emissions of Short-lived Climate Forcers (SLCFs) such as methane do not cause the same temperature response as sustained emissions of CO_2 (for details see Box 2.1, Annex B Section A.B.10 and WGI Chapter 7). Showing superimposed emission trends of different gases over multiple decades using GWP100 as equivalence metric therefore does not necessarily represent the overall contribution to warming from each gas. But we are often most interested in the actual warming caused by historical emissions of each gas. In Figure 2.3 we therefore also show the modelled warming from emissions of each gas - calculated using the reduced-complexity climate model FAIRv1.6 and calibrated to reproduce the pulse-response functions assessed for each gas in WGI chapter 7 (Forster et al. 2020a). Despite important differences, Figure 2.3 highlights that GWP-100 does not provide a vastly different story than modelled warming with CO_2 and CH_4 as being the key contributors.

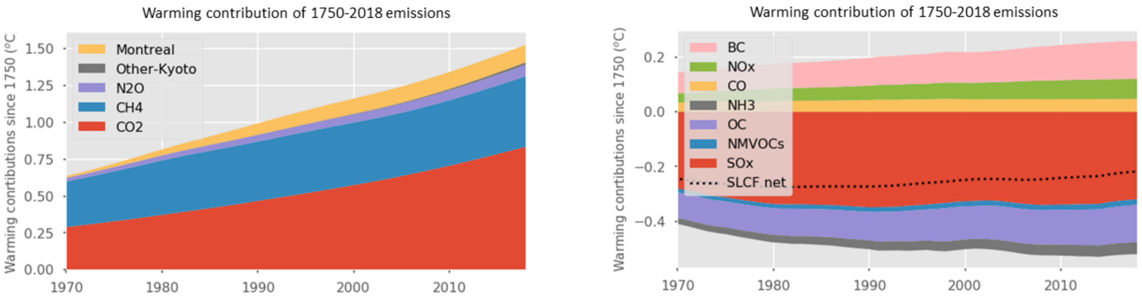


Figure 2.3 Contribution of different greenhouse gases to warming since 1750. a) **major GHGs gases and aggregates of minor gases; b) breakdown of Kyoto minor gases, c) shot-lived climate forcers. The dotted line in c) gives the net temperature change from short-lived climate forcers.**

Cross-Chapter Box 2: GHG emissions metrics

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Greenhouse gases and aerosols differ widely in their atmospheric lifetimes and the sign and magnitude of their impacts on climate. GHG emission metrics[2] provide simplified information about the effect of emitting different greenhouse gases on global temperature or other key measures of climate change, usually expressed relative to the effect of emitting CO_2. This information can support choices about priorities and trade-offs in mitigation policies and emission targets for non-CO_2 gases and baskets of gases relative to CO_2. This assessment builds on the evaluation of GHG emission metrics from a physical science perspective by Working Group I (AR6 WGI Section 7.6; Forster et al.(2020a)) and focuses on the performance of different GHG emission metrics to support climate change mitigation. For additional details to support the conclusions summarised in this Box, see Annex B Section A.B.10.

FOOTNOTE: [2] Emission metrics also exist for aerosols, but these are not commonly used in climate policy. This assessment focuses on GHG emission metrics only.

Choices in the design of metrics affect the weighting given to emissions of non-CO_2 gases relative to CO_2. This can affect the timing and emphasis on abatement especially of Short-Lived Climate Forcers (SLCFs) within multi-gas abatement strategies. A wide range of GHG emission metrics has been developed in the scientific literature, which differ in terms of: (i) the key measure of climate change they consider, (ii) whether they consider climate outcomes for a specified point in time, or integrated over a specified time horizon, (iii) the time horizon over which the metric is applied, (iv) whether they apply to a single emission pulse, to emissions sustained over a period of time, or to a combination of both, and (v) whether they consider the climate effect from an emission compared to the absence of that emission, or compared to a reference emissions level or climate state (see Glossary).

Parties to the Paris Agreement decided to report aggregated emissions based on the Global Warming Potential with a time horizon of 100 years (GWP100) with values from IPCC AR5 or from a subsequent IPCC report as agreed upon by the CMA[3], and to account for their second and subsequent NDCs in accordance with this approach. Parties can also, however, report supplemental information using other GHG emission metrics assessed by the IPCC (FCCC/PA/CMA/2018/3/Add.1 and Add.2).

The Global Warming Potential (GWP) and the Global Temperature change Potential (GTP) were the main metrics assessed in AR5 and continue to be the dominant metrics used in the scientific literature. Both GWP and GTP compare the effect on climate from individual non-CO_2 and CO_2 emission pulses, relative to the absence of those emissions and otherwise constant background concentrations. GWP represents the ratio of radiative forcing from those emissions integrated over the entire stated time horizon, whereas GTP represents the ratio of global mean surface temperature change at the endpoint of the stated time horizon. The AR5 (Intergovernmental Panel on Climate Change 2014; Kolstad et al. 2014; Myhre et al. 2013) found *robust evidence* and *high agreement* that the choice of appropriate metric and time horizon depends on the type of application and policy context, including judgements about how to value damages at different points in time. The AR5 concluded, based on *medium evidence* available at that time, that metric choice has a minor effect on global mitigation costs under scenarios of full participation but could be more significant for specific sectors or countries with a high proportion of non-CO_2 emissions (Intergovernmental Panel on Climate Change 2014).

The use of GWP100 has been criticised on the basis that GWP does not correspond to a specific climate policy objective and the metric value depends strongly on the choice of time horizon (O'Neill 2003; Shine 2009; Myhre et al. 2013; Kolstad et al. 2014). Another criticism, expanded since the AR5 and discussed further below, is that GWP-based 'equivalence' does not imply equivalent climate outcomes from cumulative emissions. Treating short- and long-lived gases interchangeably based on GWP100 as part of long-term emission targets thus creates ambiguity about actual climate outcomes (see WGI Section 7.6; Allen et al. 2016; Fuglestvedt et al. 2018; Tanaka and O'Neill 2018; Denison et al. 2019).

Recent theoretical analyses (Aaheim and Mideksa 2017; Mallapragada and Mignone 2017, 2019) confirm that GWP is consistent with a cost-benefit framework, with the choice of time horizon corresponding to the choice of discount rate to evaluate economic damages from each emission. For methane, GWP100 implies a social discount rate of about 3-5% (*medium confidence*; Sarofim and Giordano 2018; Shindell et al. 2017; Mallapragada and Mignone 2019), which is broadly similar to discount rates used in integrated assessment models (see Chapter 3 of this report) and investments with multi-decadal lifetimes (Giglio et al. 2015; HM Treasury 2018). The dynamic GTP (Shine et al. 2007) is more aligned with a cost-effectiveness framework, as it evaluates emissions in each year based on their contribution to warming in a specified future year (e.g. the year of peak warming in a mitigation pathway consistent with a specified temperature goal). A cost-effectiveness approach implies a shrinking time horizon and increasing importance given to SLCF emissions as the target year is

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[3] FOOTNOTE: The CMA is the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement

approached. However, the dynamic GTP does not fully match the price ratio between gases in least-cost mitigation pathways because the most cost-effective weighting of each emission also depends on the discount rate (Johansson 2011; Tanaka et al. 2020; Strefler et al. 2014). The GTP with a static time horizon (e.g. GTP100) is not clearly matched to either a cost-benefit or a cost-effectiveness framework, as the year for which temperature outcomes are evaluated would not match the year when the global temperature limit is reached (Edwards and Trancik 2014; Tol et al. 2012; Mallapragada and Mignone 2017; Strefler et al. 2014).

A number of studies since the AR5 have evaluated the impact of different pulse GHG emission metrics and time horizons on the global economic costs of limiting global average temperature change to a pre-determined level, including to well-below 2°C (Deuber et al. 2014; Van Den Berg et al. 2015; Huntingford et al. 2015; Ekholm et al. 2013; Harmsen et al. 2016; Strefler et al. 2014; Tanaka et al. 2020). These studies give *high confidence* that using GWP100 to inform abatement choices between gases would help meet the long-term temperature goal of the Paris Agreement at close to least global cost (based on least-cost pathways inferred from economic models), and with limited overshoot. Global costs to achieve the same temperature constraints are typically higher in these studies if CH_4 emissions are weighted consistently less than indicated by GWP100 (e.g. if using GTP100 or GWP500). The increase in global mitigation costs ranges from a few percent to more than 30 percent in most studies, depending not only on the specific metric values used but also on the temperature limit, degree of overshoot, and abatement costs and potentials of different gases assumed. These studies also indicate, albeit less consistently and less significantly than for GTP_{100}, that global mitigation costs would also increase if CH_4 emissions are valued consistently more highly than by GWP100 (e.g. using GWP20).

The above studies indicate that using a cost-effectiveness metric such as the dynamic GTP instead of GWP100 could reduce global mitigation costs by a few percent in theory (*high confidence*), but the ability to realise those cost savings in practice depends on the temperature limit, policy foresight and flexibility in abatement choices as the weighting of SLCF emissions increases over time (*medium confidence*). Similar benefits to a dynamic GTP might be obtained by regularly reviewing and potentially updating the time horizon used for GWP in light of actual emission trends compared to climate goals (Tanaka et al. 2020). One reason why the dynamic GTP offers only a limited, if any, reduction in global mitigation costs compared to GWP100, despite its theoretical advantage, lies in the similarity of the metric values for methane if the goal is to limit warming to well-below 2°C and ideally 1.5°C (Cross-Chapter 1, Table 1). For modelled mitigation pathways achieving such temperature goals with limited overshoot, GWP100 results in abatement choices that are not very different from those based on the dynamic GTP or economic optimisation, even though GWP100 in itself reflects a cost-benefit framework.

The choice of metric not only affects global mitigation costs but also the distribution of costs and the timing of abatement between countries and sectors (see Annex B Section A.B.10 for details). Sectoral and national perspectives on GHG emission metrics may therefore differ from a global least-cost perspective (Klinsky and Winkler 2018), but the literature has not developed a consistent framework for assessing GHG emission metrics based on a wider set of equity principles.

A key limitation of GWP and GTP, and a key development in the GHG metrics literature since the AR5, is that they are designed to compare effects on climate from individual emission pulses (e.g. annual emissions) of CO_2 and non-CO_2 gases, but this does not imply an equivalence with regard to the climate effects of cumulative emissions (see WGI Section 7.6). For CO_2, warming from each emission persists over centuries to millennia. Hence there is a near-linear relationship between cumulative emissions and temperature change, which implies that global average temperature continues to increase until global net CO_2 emissions reach zero. Limiting temperature to any level therefore implies a finite remaining carbon budget (see WGI Chapters 1 and 5). By contrast, for SLCFs such as methane, there is no simple relationship between cumulative emissions and temperature, as the warming largely follows the changing rate of emissions. Rapidly declining SLCF emissions therefore result in a declining contribution from those gases to global temperature even if their emissions remain greater than zero and hence their cumulative emissions continue to increase. This result cannot be captured if it is assumed that global warming follows cumulative CO_2-equivalent emissions using GWP100 or GTP.

Novel metrics developed since the AR5, such as the Combined Global Temperature-change Potential (CGTP; Collins et al. 2019) and GWP* (Allen et al. 2018; Cain et al. 2019; Lynch et al. 2020; Allen et al. 2016), construct an equivalence between a step-change in the rate of SLCF emissions and a CO_2 emissions pulse. These new metrics provide a near-linear relationship between temperature and cumulative CO_2-equivalent SLCF emissions based on CGTP or GWP*, similar to the linear relationship between cumulative CO_2 emissions and temperature. These novel metrics therefore allow a simple and more accurate representation than GWP or GTP of the interaction between more or less ambitious SLCF mitigation, particularly methane, and the remaining carbon budget within a given temperature limit (*medium confidence*; see also WGI Section 7.6; (Forster et al. 2020a)).

However, even though GWP* and CGTP build on the same underlying physical climate processes as GWP and GTP, they differ in their use of reference emission levels, which has important implications for their potential applications in climate mitigation policy. GWP and GTP describe the *marginal* effect of emissions, i.e. how much warmer the climate would be with, compared to without a specified emission that occurs in addition to all other past and future emissions. Consequently, these metrics provide information on how much warming could be avoided (over a given time period, or at a given future point in time) by avoiding the emission of a unit of an SLCF compared to avoiding a unit of CO_2.

By contrast, CGTP and GWP* describe the effect on climate from a sustained step-change in SLCF emissions that is *additional* to a specified reference level of SLCF emissions, and compare this to the effect on temperature from the emission or removal of a unit of CO_2 (Collins et al. 2019; Allen et al. 2018; Cain et al. 2019). The different focus on marginal vs additional effect on temperature explains why rapidly declining CH_4 emissions are given a negative CO_2-equivalent value based on GWP* (rapidly declining SLCF emissions result in declining temperature, relative to the warming caused by past SLCF emissions at a previous point in time) but a positive CO_2-equivalent value based on GWP or GTP (each SLCF emission results in global average temperature being higher than it would be without this emission, even if the rate of SLCF emissions is declining).

The potential application of GWP* in actual climate policy has been contested, although peer-reviewed literature is very limited. Most of this debate centres on the equity implications of a focus on marginal versus additional effects on climate from short- and long-lived GHGs (Rogelj and Schleussner 2019; Cain et al., submitted; Rogelj and Schleussner, submitted). Another point of discussion is that changing GHG emission metrics, but retaining the same numerical CO_2-equivalent emissions targets, would result in different climate outcomes (see WGI Section 7.6; (Forster et al. 2020b)). For example, achieving a balance of GHG emissions and removals as stated in Article 4.1 of the Paris Agreement could result in different peak temperatures and in either stable or more or less rapidly declining temperature after the peak, depending on the choice of GHG emission metric to aggregate emissions and removals of different gases (Schleussner et al. 2019; Fuglestvedt et al. 2018; Tanaka and O'Neill 2018; Allen et al. 2018). A change in GHG emission metrics would therefore require a re-evaluation and re-formulation of existing emission targets at sectoral, national and global levels to avoid an implicit and potentially inadvertent change to currently stated levels of mitigation ambition and intended climate outcomes (*very high confidence*).

The WGIII contribution to the AR6 uses updated GWP100 values from AR6 WGI (see Cross-Chapter 1, Table 1) as default GHG emission metric wherever possible and unless stated otherwise. The choice of GWP100 was made both for consistency with decisions under the Paris Agreement, and because GWP100 has been demonstrated to be one of the best-performing simple and standard physics-based emission metrics used in the literature from a cost-benefit and cost-effectiveness perspective under stringent mitigation pathways. This choice does not constitute a recommendation to use GWP100 for any specific policy application as the most appropriate choice depends on the policy goal and implementation of the metric.

However, all metrics simplify the complexity of the physical climate system and hence have limitations and uncertainties. For this reason, the WGIII contribution to the AR6 reports emissions and mitigation options for individual gases where possible; CO_2-equivalent emissions are reported only in addition where this is judged to be policy relevant, with transparency regarding gases included and the metric values used. This approach aims to reduce the inevitable ambiguity regarding actual climate outcomes over time when any GHG emission metric is used, and allows any value judgements about the climate outcome of concern, time horizons and reference emission levels to be made explicitly rather than embedded in GHG emission metrics.

Cross-Chapter Box 2, Table 1 Illustrative GWP and GTP metric values for CH_4 and N_2O under a range of metrics and time horizons, based on Forster et al. (2020a). Different time horizons GTP are given for GTP to illustrate metric values for emissions in 2020 that would correspond temperature outcomes in different future target years. See the WGI assessment for values of other metrics and gases. The values for fossil methane exceeds those for biogenic methane because fossil methane also adds CO_2 to the atmosphere upon its decay. [NOTE: THIS TABLE WILL BE UPDATED WITH FINAL VALUES FROM THE WGI ASSESSMENT]

	GWP100	GTP20	GTP40	GTP60	GTP80	GTP100
Corresponding target year for emissions in 2020	N/A	2040	2060	2080	2100	2120
CH_4 (fossil)	34.75	65.75	24.75			9.45
CH_4 (biogenic)	32	63	22			6.7
N_2O	261	281	284			320

2.2.2 Trends in the global GHG emissions trajectories and short-lived climate forcers

2.2.2.1 Anthropogenic greenhouse gas emissions trends

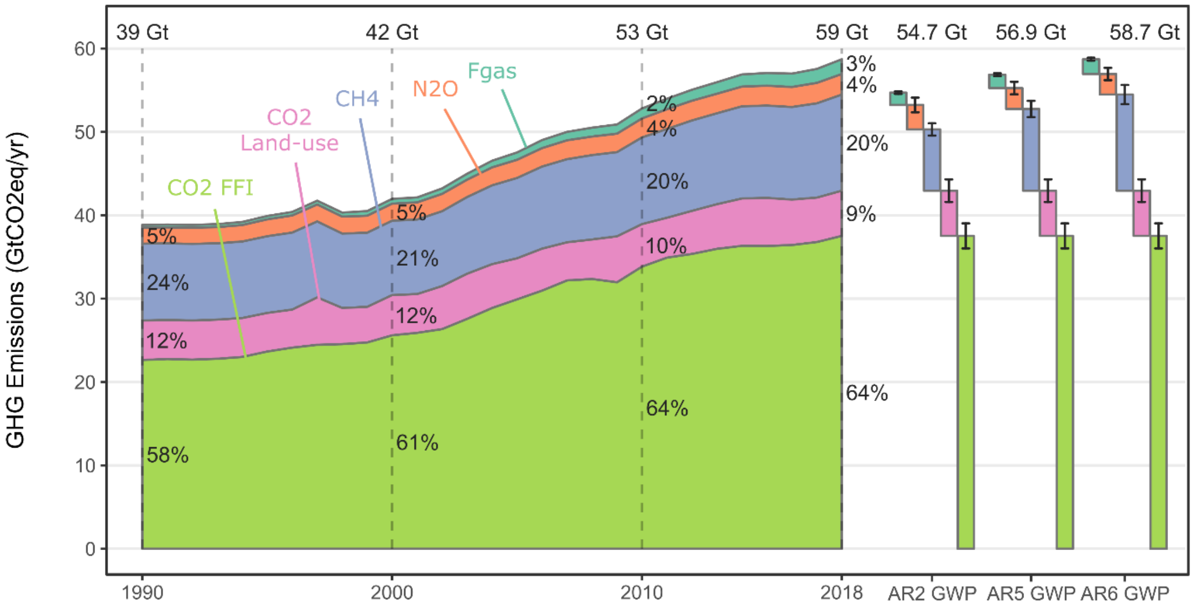
Despite growing national efforts to reduce GHG emissions in many countries, global GHG emissions continued to rise since AR5, but the rate of emissions growth slowed (*high confidence*) (Table 2.5, Figure 2.4). Average annual GHG emissions for 2009-2018 were 56±5.6 $GtCO_2eq$ compared to 47±4.7 and 40±4.0 $GtCO_2eq$ for 2000-2009 and 1990-1999, respectively. Growth in average annual GHG emissions was observed across all (groups of) gas as shown in Table 2.5, but for categories such as AFOLU-CO_2 or N_2O this is much more uncertain.

Table 2.5 Total anthropogenic GHG emissions (GtCO$_2$eq yr^{-1}) 1990-2018: CO$_2$ from fossil fuel combustion and industrial processes (FFI); CO$_2$ from Forestry and Other Land use (AFOLU);); methane (CH$_4$); nitrous oxide (N$_2$O); fluorinated gases (F-gases). Aggregate GHG emission trends by groups of gases reported in Gt CO$_2$eq converted based on global warming potentials with a 100-year time horizon (GWP-100) from the IPCC Sixth Assessment Report. Uncertainties are reported for a 90% confidence interval (see Section 2.2.1.5).

	Average annual emissions (GtCO$_2$eq)					
	CO$_2$ FFI	CO$_2$ AFOLU	CH$_4$	N$_2$O	Fluorinated gases	GHG
2018	38±3.0	5.4±2.7	12±2.3	2.5±1.5	1.8±0.35	59±5.9
2009-2018	36±2.8	5.4±2.7	11±2.2	2.4±1.4	1.4±0.29	56±5.6
2000-2009	29±2.3	5.0±2.5	9.5±1.9	2.2±1.3	0.84±0.17	47±4.7
1990-1999	24±1.9	4.7±2.3	9.1±1.8	2.0±1.2	0.41±0.08	40±4.0
1990	23±1.8	4.7±2.3	9.2±1.8	1.9±1.2	0.33±0.07	39±3.9

GHG emissions reached 59±5.9 GtCO$_2$eq in 2018 Table 2.5 and Figure 2.4. This is higher than at any point in human history before (*medium confidence*). This is 11.0% (5.9 GtCO$_2$eq) higher than GHG emission levels in 2010 (53±5.3 GtCO$_2$eq) (AR5 reference year) and 51% (20 GtCO$_2$eq) higher than in 1990 (38±3.8 GtCO$_2$eq) (Kyoto Protocol reference year and frequent NDC reference). In 2018, CO$_2$ emissions from FFI were 38 (±3.0) Gt, CO$_2$ from AFOLU 5.4±2.7 Gt, CH$_4$ 12±2.3 GtCO$_2$eq, N$_2$O 2.5±1.5 GtCO$_2$eq and F-gases 1.8±0.35 GtCO$_2$eq. CO$_2$ emissions from FFI contributed 3.7 of the 5.9 Gt increase in annual GHG emissions with additional contributions of 1.1 Gt CO$_2$eq from CH$_4$, 0.2 Gt from N$_2$O and 0.57 Gt from F-gases. From 2010 to 2018 GHG emissions grew on average by about 1.3% compared to an average annual growth of 2.3% between 2000 and 2010 (*high confidence*).

a. Trends in global greenhouse gas emissions and the impact of alternative GWP metrics



b. Trends in global greenhouse gas emissions and their uncertainties

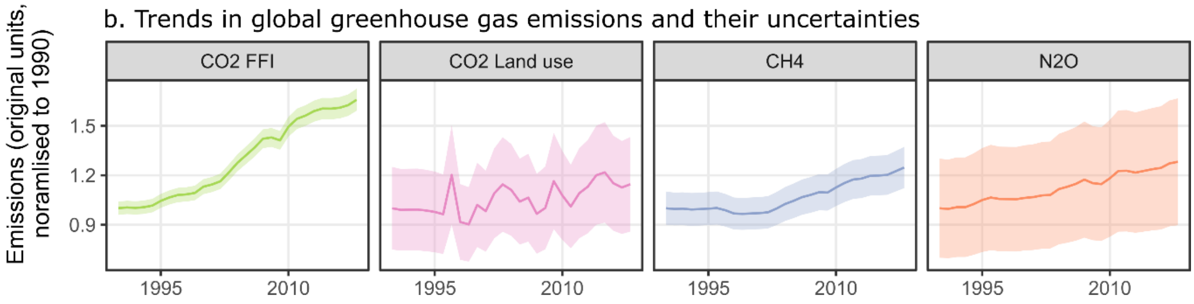


Figure 2.4 Total anthropogenic GHG emissions (Gt CO_2eq yr^{-1}) 1990-2018: CO_2 from fossil fuel combustion and industrial processes (FFI); CO_2 from Agriculture, Forestry and Other Land use (AFOLU); methane (CH_4); nitrous oxide (N_2O); fluorinated gases (F-gases). Panel a: Aggregate GHG emission trends by groups of gases reported in Gt CO_2eq converted based on global warming potentials with a 100-year time horizon (GWP-100) from the IPCC Sixth Assessment Report. Waterfall diagrams juxtaposes GHG emissions for the most recent year 2018 in CO_2 equivalent units using GWP-100 values from the IPCC's Second, Fifth, and Sixth Assessment Report, respectively. Error bars show the associated uncertainties at a 90% confidence interval. Panel b shows individual trends in CO_2-FFI, CO_2-AFOLU, CH_4 and N_2O emissions in (original) mass units (Gt yr^{-1}) for the period 1990-2018, normalised to 1 in 1990.

At first sight, total annual GHG emission estimates vary considerably in the Working Group III contributions between AR5 (Blanco G. et al. 2014) and AR6 (this chapter). For the year 2010, AR5 total GHG emissions were estimated at 49±4.9 Gt CO_2eq in AR5 (Blanco G. et al. 2014), while we report 53±5.3 Gt CO_2eq here. However, in AR5 total GHG emissions were weighted based on GWP-100 values from IPCC SAR. Applying the most recent AR6 GWP-100 values to recalculate GHG emission totals from 2010 yields 52 Gt CO_2eq (Forster et al. 2020a). Hence, the difference is almost entirely due to a change in the use of the more recent 100-year GWPs, which have a 33% higher warming potential for methane compared to AR5 and 15% lower values for nitrous dioxide (for a discussion of the underlying drivers of these, see discussions in IPCC WGI (Forster et al. 2020a)). We provide a discussion of global warming metrics in Cross-Chapter Box 2.

Emission growth has been varied, but persistent across different gases (*high confidence*). GHG emissions as a whole have grown by 51% since 1990. Individually, CO_2 emissions from FFI have grown by 66%, while CH_4 and N_2O have grown by 25% and 28%, respectively. Growth in fluorinated gases (F-gas) has by far been highest with about 434%, but it occurred from low levels. As a result, F-gas levels are jointly no longer negligible and track at a total of 1.8 $GtCO_2eq$, or 3% of global emissions in 2018. The only exception to these patterns of growth is CO_2 emissions from AFOLU, where the data does not show a clear trend and is very uncertain. In fact, two bookkeeping models underlying the AFOLU data show opposing positive and negative trends (BLUE, H&N, respectively), while the third model (OSCAR) tracks the approximate mean of these (see also, Section 2.2.1.2). The range of estimates across these models provide the uncertainty range in Figure 2.4 (see also Figure 2.2). Dynamic global vegetation models show higher estimates recently, as they consider the loss in sink capacity, while the bookkeeping models do not (see Section 2.2.1.2, Figure 2.2). The share of CO_2 emissions from fossil fuel combustion and industrial processes kept increasing over time, from about 53% in 1970 to 59% in 1990, to 65% in 2010, but did not increase further. Note that net emissions from bioenergy are covered by the AFOLU estimates with some notable exceptions (see Sections 2.2.1.3-2.2.1.5).

Anthropogenic CO_2 emissions reached 43±4.1 Gt in 2018 compared to 39±3.7 Gt in 2010. Annual average growth was 1.3% across this period. In 2019 emissions grew further to 44±4.2 $GtCO_2$, but growth of FFI-CO_2 halved compared to the previous year (Friedlingstein et al. 2020; Crippa et al. 2020). Since AR5, there was a short period between 2014-2016 with little or no growth in anthropogenic CO_2 emissions triggering speculations whether global CO_2 emissions might have peaked (Jackson et al. 2016). This flattening was mainly due to reductions in CO_2 emissions from coal combustion (Peters et al. 2017b; Qi et al. 2016). Subsequently, CO_2 emissions started to rise again (Peters et al. 2017a; Figueres et al. 2018; Peters et al. 2020). Overall, the increase in annual CO_2 emissions in the post-AR5 reporting period 2010-2018 was driven mainly by CO_2 emissions from gas and oil combustion with 1.3 Gt and 1.2 $GtCO_2$ rather than coal and cement with 0.7 and 0.3 $GtCO_2\ yr^{-1}$ respectively (Le Quéré et al. 2018a; Friedlingstein et al. 2019a, 2020; Peters et al. 2019).

Starting in the spring of 2020 a major break in global emissions trends was observed due to lockdown policies implemented in response to the COVID-19 pandemic. In many countries these policies involved the mandatory closure of schools and workplaces, with the effect of drastically shifting daily patterns of energy demand. Due to the very recent nature of this event, it remains unclear what the long term impact on global emissions trends will be. However, authors have been able to use real-time activity and power-generation data, satellite observations and modelling to estimate the short-run effects of COVID-19 on energy demand, CO_2 emissions and local air pollution (Forster et al. 2020b; Le Quéré et al. 2020; Lenzen et al. 2020; Liu et al. 2020c,d). Le Quéré et al. (2020) – as shown in Figure 2.5 - estimated global daily emissions in April 2020 compared to April 2019, finding a decline in emissions from aviation (-60%) and surface transport (-36%), but more moderate impacts on industry (-19%) and the power sector (-7.4%) (Le Quéré et al. 2020). Median reductions in annual FFI-CO_2 emissions relative to the previous year across four different methods are 7% (2.7-13%) with additional uncertainties from each method on top of that. Without a major structural shift in energy systems and other sectors, most of these reductions will be temporary and will not fundamentally alter prospects for staying within Paris-compatible carbon budgets. Overall, total anthropogenic CO_2 emissions (FFI and AFOLU) are projected to drop by about 7.5% (~3$GtCO_2$) relative to 2019 (Friedlingstein et al. 2020).

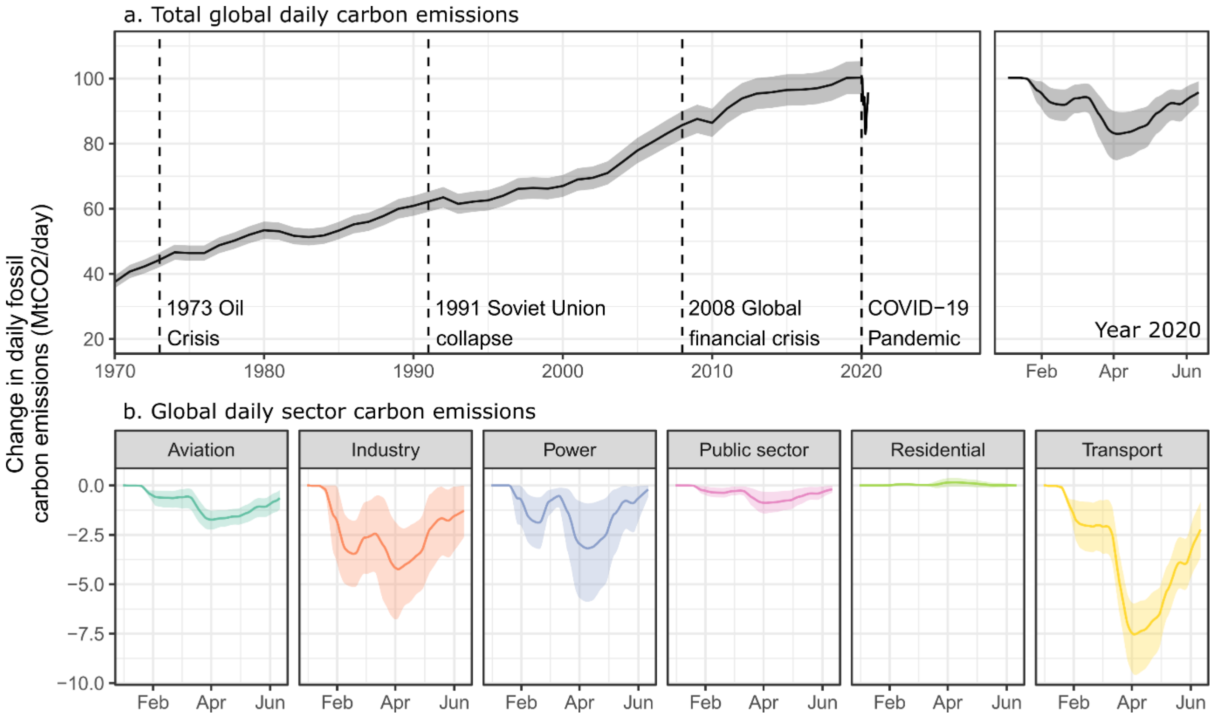


Figure 2.5 - Estimated mean change in global daily fossil CO_2 emissions during the COVID-19 pandemic. Panel a indicates the change for all sectors since 1970, with monthly emissions estimated for 2020. Panel b indicates the monthly change estimated for individual sectors in 2020, relative to annual mean daily emissions from those sectors in 2019. Reproduced based on Le Quere et al. (2020) and Peters et al. (2012). Daily emissions in 2020 are smoothed with a 7-d box filter to account for the transition between confinement levels.

Looking at the long term, anthropogenic CO_2 emissions were mainly from land-use, land use change and forestry at the outset of the industrial revolution (Figure 2.6). While these emissions have remained comparatively stable, CO_2 emissions from FFI kept growing constantly year-by-year only with brief intermissions due to global economic crisis, war or other social instabilities (Peters et al. 2012). Global annual FFI-CO_2 emissions have increased every decade from an average of 11±0.9 $GtCO_2$ in the 1960s to an average of 36±2.8 $GtCO_2$ during 2009-2018 (see Table 2.5). Global annual CO_2 emissions from AFOLU have remained relatively constant around 5.5±2.8 $GtCO_2$ over the past half-century but with a large spread across estimates (Le Quéré et al. 2018b; Friedlingstein et al. 2019a) (Section 2.2.1.2). Since the 1950s CO_2 emissions from FFI consistently represent the largest share of anthropogenic CO_2 emissions growing to about 87% in 2017 (Canadell and Monteiro 2019 et al. Le Quéré et al. 2018b; Friedlingstein et al. 2019a).

Since 1850 total cumulative CO_2 emissions release from anthropogenic sources is about 2400 (±390) $GtCO_2$ emissions (Friedlingstein et al. 2019a, 2020) as shown in Figure 2.6. Between 1850 and 2018 total cumulative CO_2 emissions FFI and AFOLU were 2400±390 $GtCO_2$. Of these, about 980±98 $GtCO_2$ were added to the atmosphere since climate change became well known following AR1 (1990). 330±31 $GtCO_2$ were added since AR5 (2010). This is about the same size than the remaining carbon budget of 310±250 (390, 500) $GtCO_2$ for keeping global warming below 1.5°C and between 2-3 times smaller than the 960±250 (1140, 1390) $GtCO_2$ for keeping warming below 2°C with a probability of 67% (50%, 33%), respectively (Canadell et al. 2020). These emission budgets are relatively small compared to the current emissions levels and could be swiftly exhausted unless a path of substantive and sustained emission reductions is entered. For example, at current rates of emissions, the 67th percentile 1.5°C and 2°C budgets will be exhausted in 7 and 22 years, respectively. Following the current NDC trajectories (Rogelj et al. 2016; Roelfsema et al. 2020; den Elzen et al. 2019) – i.e. without further enhancements in national mitigation ambition - will lead to an exhausted 1.5°C budget before 2030. Even if emissions start falling at average annual rates of 2% or 5% of 2018 emissions until net-zero CO_2 emissions are reached, the 1.5°C budget will be exhausted in 2028 or 2031, respectively. In contrast, a 2°C budget is not binding for extremely rapid constant annual CO_2 emission reductions equal to 5% of 2018 emissions, and will be exceeded in the second half of the 21st century (2060) for emission reductions at a 2% rate. Net-zero years at constant annual rates of 2% and 5% are 2067 and 2038. This implies temporarily exceeding the budget (budget overshoot) in some of the above examples (Figure 2.6). Meeting the carbon budget requires the capability to reduce global net CO_2 emissions below zero in order to compensate budget overshoot through net removals of CO_2 emissions from the atmosphere (Minx et al. 2018; Fuss et al. 2018; Hilaire et al. 2019; Smith et al. 2016; Hepburn et al. 2019) – also often referred to as net negative emissions. Relevant discussions of carbon budgets, short-term ambition in the context of NDCs, transformation pathways and carbon dioxide removals are mainly discussed in chapters 3, 4, and 12, but also Section 2.7 of this chapter.

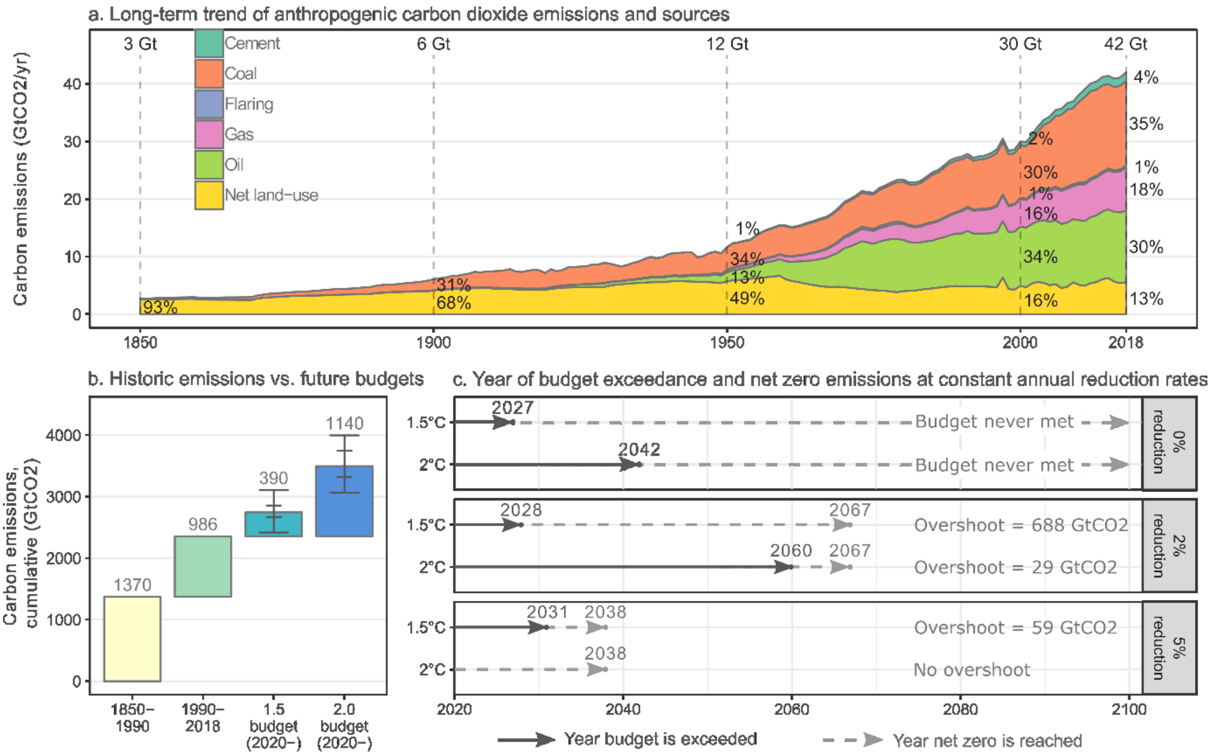


Figure 2.6 - Historic anthropogenic CO_2 emission and cumulative CO_2 emissions (1850-2018) as well as remaining carbon budgets for 1.5°C and 2°C. Panel a shows historic annual anthropogenic CO_2 emissions ($GtCO_2$ yr^{-1}) by fuel type and process: AFOLU-CO_2 emissions (see Section 2.2.1.2) from land-use change (yellow); oil combustion (green); gas combustion (pink); gas flaring (blue); coal combustion (red); cement production (cyan). Panel b shows historic cumulative anthropogenic CO_2 emissions for the period 1850-1990 (yellow) and 1990-2018 (green) as well as remaining future carbon budgets as of 1.1.2020 to keep warming below 1.5°C (turquois) and 2°C (blue) at the 50th percentile of the transient climate response to cumulative CO_2 emissions. Whiskers indicate the range of 33rd and 67th percentile carbon budgets (narrow inner whiskers), with additional uncertainty projected on top due to scenario uncertainty in non-CO_2 emissions (large outer whiskers). Panel c illustrates the remaining years until carbon budget exceedance for keeping warming below 1.5°C and 2°C respectively at a) the current levels of emissions; b) constant global annual emission reductions at 2% of emissions in 2018; and c) constant global annual emission reductions at 5% of emissions in 2018. Sources: Friedlingstein et al. (2020) and Canadell et al. (2020)

Despite reduced emissions growth for the period 2010-2018 compared to the previous decade, CO_2 emissions still track rather at the mid- to upper range of baseline scenarios across the various IPCC mitigation scenario ensembles as shown in Figure 2.7. Global emissions generally followed a medium-high pathway, captured by "middle-of-the-road" scenario narratives in the earlier series, and by combinations of "global-sustainability" and "middle-of-the-road" narratives in the most recent series (SRES and SSP-baselines) (Strandsbjerg Tristan Pedersen et al. 2021; Pedersen et al. 2020). However, there is growing dispute over very high emission baselines that are heavily used by the climate modelling community, but do not represent a very likely socio-economic pathway. As such this could cause confusion and bias (Hausfather and Peters 2020). Part of this discussion relates to how baseline scenarios are most adequately defined (Grant et al. 2020).

However, literature since AR5 highlights that compared to historical trends baseline scenarios are biased towards fossil fuel use (Ritchie and Dowlatabadi 2017; Ritchie 2019; Ritchie and Dowlatabadi 2018; Minx et al. 2020b; Creutzig et al. 2020). For example, Ritchie and Dowlatabadi (2017) show that primary energy consumption tends to increase substantially more on a per capita levels compared to long-term historical evidence. For example, while SSP5 envisions a 6-fold increase in per capita coal use by 2100 – against flat long-term historical observations – no optimistic baseline is offered. Even the most optimistic SSP1-Sustainability narratives is associated with coal consumption that is broadly in line with historical long-term patters (Ritchie and Dowlatabadi 2017; Minx et al. 2020b). In contrast, models struggle to reproduce historical upscaling of wind and solar and other granular energy technologies (Creutzig et al. 2017; Wilson et al. 2020; Sweerts et al. 2020; Wilson et al. 2013; van Sluisveld et al. 2015; Minx et al. 2020b; Shiraki and Sugiyama 2020). Hence, there is evidence for a potential bias towards fossil fuel consumption when baselines scenarios are compared to historical evidence. Moreover, the SSP baseline marker scenarios do not contain a really optimistic reference case for the substitution of fossil fuels by renewable energy technologies, whilst SSP5 marks a major discontinuity of historical long-term trends that could only be explained by a fundamental regime shift in fossil fuel use (e.g. coal to liquid).

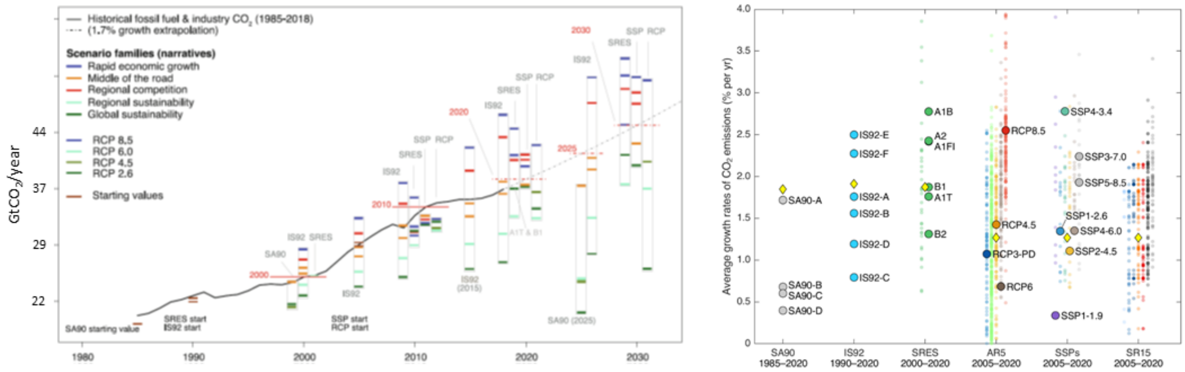


Figure 2.7 - Left panel: Historical FFI-CO₂ emissions trend over the past three decades (black line) compared with emission scenarios SA90, IS92, SRES, RCPs, and SSP-BL. The black dotted line shows extrapolation beyond 2018 of the 1.7% growth rates for 1990–2018 historical emissions. 'Rapid growth' (includes IS92e/SRES-A1B/SSP5), 'Middle of the road' (SA90-A/IS92a/b/SSP2), 'Regional competition' (IS92f/SRES-A2/SSP3/SSP4), 'Regional sustainability' (SA90-B/IS92d/SRES-B2), 'Global sustainability' (SA90-C/D/IS92c/SRES-B1/SSP1). Right panel: Growth rates of historical and scenario CO₂ emissions. The average annual growth rates of the historical emission estimates (black crosses) and the emission scenarios for the time periods of overlaps (shown on the horizontal axis). The growth rates are more comparable for the longer time intervals considered. Major IPCC scenario collections are benchmarked against historical CO₂ emissions (SA90; IS92; SRES; AR5; SSPs; SR1.5). Yellow diamonds indicate observed emissions growth rate over time period indicated. Sources: (Peters et al. 2013; Strandsbjerg Tristan Pedersen et al. 2021)

2.2.2.2 Other short-lived climate forcers

There are other forcing agents with shorter atmospheric lifetimes that contribute to temperature changes. Some of them like aerosols, sulphur emissions or organic carbon mask, while others like black carbon, carbon monoxide or non-methane organic compounds (NMVOC) contribute to warming. This assessment is provided in the Working Group 1 contribution (Forster et al. 2020a). Many of these other short-lived climate forcers (SLCFs) are co-emitted during combustion processes in power plants, cars, trucks, airplanes, but also during household activities such as traditional cooking with open biomass burning. As these co-emissions have implications for net warming, they play an important role in mitigation and are considered in mitigation scenarios in chapter 3 of this report. These air pollutants are also detrimental to human health. For example, Lelieveld et al. (2015) estimates a total of 3.3 (1.6-4.8) million pre-mature deaths in 2010 from outdoor air pollution. Reducing air-pollutants in the context of climate policies therefore lead to substantial co-benefits of mitigation efforts (Rauner et al. 2020; Rao et al. 2017; Von Stechow et al. 2015; Lelieveld et al. 2019). Here we only briefly outline the major trends in emissions of short-lived climate forcers.

Variations of global SLCF emissions could be divided into three typical categories depending on their recent trends. The first category includes conventional air pollutant that have undergone strict control all over the rich world, including SO_2, NO_x, BC and CO. Their emissions have kept the decreasing trend in the last five years. For instance, from 2015 to 2019, global SO_2 emissions have decreased while NOx emissions have declined, mainly contributed by reductions in the energy systems. Substantial reductions in BC and CO emissions could be attributable to industrial sectors over the same period. The second category includes CH_4, OC and NMVOC, whose emissions remain relatively stable in the past five years, especially for the case of CH_4. Nonetheless, OC and NMVOC seem to have entered the flat plateau and are expected to start declining as a result of current legislation to control ozone pollution in many developed and developing countries such as China. The Third category highlights NH_3, which still shows a strong climbing trend from the AFOLU sectors since there are relatively few control measures in place in the developing world.

For NH_3, global emissions have been substantially increasing due to the strong growth of emissions in APC region, and emissions of LAM and AME regions grow slightly. However, DEV's NH_3 emissions remain steady and EEA's NH_3 emissions show a downward trend in recent decades. From the sectoral perspective, AFOLU is the main source of NH_3 emissions, followed by industry and Energy systems. For SO_2, DEV, APC and EEA are the major emitters. APC's SO_2 emissions have increased significantly after 1950 but DEV's and EEA's have fallen sharply, and the strong growth of Asian emissions has been offset by reduction in developed countries and EEA. In addition to the above 5 overarching regions, international transport is also an important source of SO_2 emissions, emitting about 10 million tons SO_2 in 2015. BC and OC have similar emission characteristics. APC and AME are the main emitters of BC and OC, showing increasing trends after 1950. However, emissions of BC and OC in other regions have dropped slowly. The building sector is the major emitter of BC and OC. The APC's, LAM's and AME's CH_4 emissions have significantly increased over the past century, whereas DEV's have fallen slowly. In particular, EEA's CH_4 emissions increase rapidly after 1950 but fall abruptly after 1990. Energy system and AFOLU are the major emitters of CH_4. DEV and APC emit the vast majority of CO and NO_x. APC's CO and NO_x emissions trend is still increasing, but DEV's fall rapidly after 1990. Note that international transport is also a non-negligible source of NO_x emissions, emitting about 18 million tons NO_x in 2015 and keeping increasing over the past few years. The building, transport and industry sectors are the major CO emitters, while transport and energy system are major NO_x emitters. For NMVOC, most emissions occur in DEV, APC and AME. Specifically, NMVOC emissions of APC and AME continue to rise substantially, but DEV's emissions decline rapidly over the last half century. The energy system, industry, transport and building sector are important emitters of NMVOC, but their importance varies noticeably in different regions.

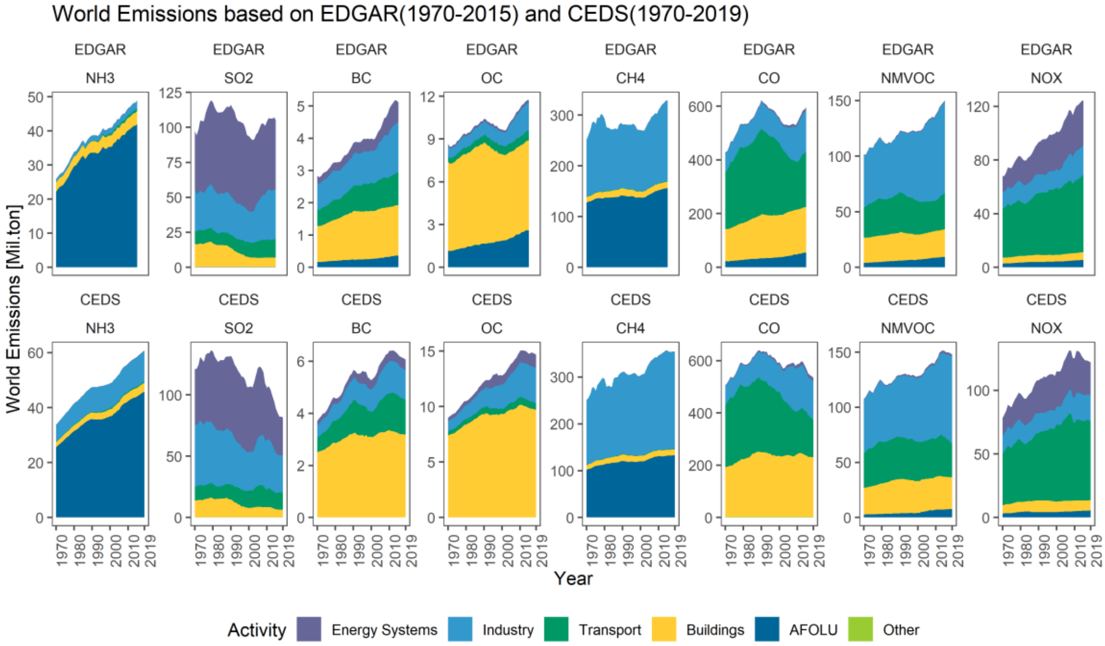


Figure 2.8 – Air pollution emissions in by major section 1970-2015/9 from CEDS and EDGAR inventories.

Source**:** (Crippa et al. 2019c, 2018; O'Rourke et al. 2020; McDuffie et al. 2020)

2.2.3 Regional GHG emissions trends

Regional contributions to global GHG emissions have shifted since the beginning of the international climate negotiations in the 1990s. Developed countries as a group have not managed to reduce GHG emissions substantially, with fairly stable levels at about 15 $GtCO_2eq\ yr^{-1}$ between 1990 and 2010. Concurrently, countries in Asia and the Developing pacific have rapidly increased their share of global GHG emissions since the 2000s (Figure 2.9).

Most of the global GHG emission growth occurred in Asia and Developing Pacific, where 73% of the 20 $GtCO_2eq$ increase in GHG emissions since 1990 and 72% of the 5.9 $GtCO_2eq$ increase in GHG emissions since 2010 occurred.[4] Africa and the Middle East contributed 19% of the GHG emissions growth since 1990 (3.7 $GtCO_2eq$) and 2% (1.1 $GtCO_2eq$) since 2010. In Latin America and the Caribbean, GHG emission growth contributed 9% (3.7 $GtCO_2eq$) to GHG emissions growth for 1990-2018, but almost 0% (0.03 $GtCO_2eq$) for 2010-2018. Average annual GHG emission growth across all regions slowed during the most recent period 2010-2018 compared to 1990-2010 with the exception of Eastern Europe and West-Central Asia. In this region GHG emissions declined by 0.66 $GtCO_2eq$ over the period 1990-2018 as a whole. Yet, for the most recent period 2010-2018 GHG emissions in the region grew by 0.53 $GtCO_2eq$. Slowing of global GHG emissions in the recent period 2010-2018 compared to the previous decade was primarily triggered by substantial reductions in GHG emissions growth in China. Still, two countries (China, India) contributed more than 60% to the net increase in GHG emissions during 2010-2018, while ten countries (China, India, Russian Federation, Indonesia, Iran, Saudi Arabia, Brazil, Korean Republic, Canada) jointly contributed about 85%.

FOOTNOTE: [4] Note that GHG emissions from international aviation and shipping as well as CO_2 emissions from AFOLU could not be attributed to individual countries or regions. Change in GHG emissions that can be easily assigned to countries or regions is 18.2 of 19.5 $GtCO_2eq$ for 1990-2018 and 5.3 of 5.9 $GtCO_2eq$ for 2010-2018.

59% of global cumulative GHG emissions between 2010 and 2018 were from developing countries. In 2018, GHG emission levels were highest in Asia and Developing Pacific with 25 $GtCO_2eq$, but surpassing Developed Countries only in 2006 (Figure 2.9). Developed countries sustained the highest levels of per capita GHG emissions at 13.1 t CO_2eq/cap in 2018 compared to less than 6 tCO_2eq/cap/yr in Asia and Developing Pacific. Variability in per-capita GHG emissions is large within and overlapping across regions. For example, Africa and the Middle East has some of the world's largest emitters in per capita terms and many least developed countries with negligible contributions to GHG emissions so far. Similarly, the per capita emissions in the group of developed countries ranges from 3 to 31 tCO_2eq/cap.

Least developed countries contributed only a negligible proportion of GHG emissions growth between 2010 and 2018 (3%) and had the lowest per capita emissions. At the same time, countries below 5 tCO_2/capita in CO_2 emissions have yet to overcome development challenges, such as ensuring universal access to household electricity, improved sanitation and secondary education – although they have continued to make improvements in these dimensions despite minimal emissions growth (Figure 2.10). By contrast, countries between 10-20 tCO_2/capita have largely resolved these basic development challenges, although gaps remain in further SDG dimensions.

36 countries have sustained territorial-based CO_2 and GHG emissions reductions longer than 10 years (Figure 2.11). These comprise three broad groups that have (1) recently peaked in emissions in the 2000s following a period of growth; (2) sustained long term reductions since the early 1980s; and (3) experienced a sudden decline in emissions following the collapse of the Soviet Union in 1990. Across all groups, total cumulative GHG reductions since respective peak years sum to approximately 4.1$GtCO_2eq$, or 7% of global GHG emissions in 2018. The former Soviet Union collapse was responsible for the largest share of cumulative GHG emissions reductions (2.1 $GtCO_2eq$, compared to 1.3 $GtCO_2eq$ for the long-term reductions group and 0.7 $GtCO_2eq$ for recently peaking countries). The large majority of reductions across countries were in the electricity and heat sector, with progress partially explained by policies driving fuel switching and renewable energy growth, but also reduced levels of energy use and emissions displacement to developing countries. In some countries (e.g. the US, Russia), a switch from coal to gas reduced emissions, but was partially compensated by increasing fugitive CH_4 emissions. Transport emissions also increased substantially over the same period in many European and former Soviet Union countries. While total cumulative GHG reductions of these *decarbonising* countries are trivial compared to recent global emissions growth, some of them achieved a relative decline of up to 50% in emissions, showing what is possible even under circumstances that were only moderately favourable for climate action. Similarly, national GHG reduction rates in some years are in line with scenario pathways that limit warming well below 2°C at 66% probability (e.g. -4% average annual reductions), even outside of periods of economic decline (Figure 2.12). Overall, there are first country cases emerging that highlight the feasibility of sustained emission reductions without sacrificing economic success. However, such pathways will need to be taken by many more countries for keeping the goals of the Paris Agreement in reach (Roelfsema et al. 2020; den Elzen et al. 2019; Höhne et al. 2020; Kriegler et al. 2018a) as analysed by chapter 4 of this report. Moreover, observed reductions are not yet consistent and long-term, nor applied across all sectors (Le Quéré et al. 2019; Lamb et al. 2020).

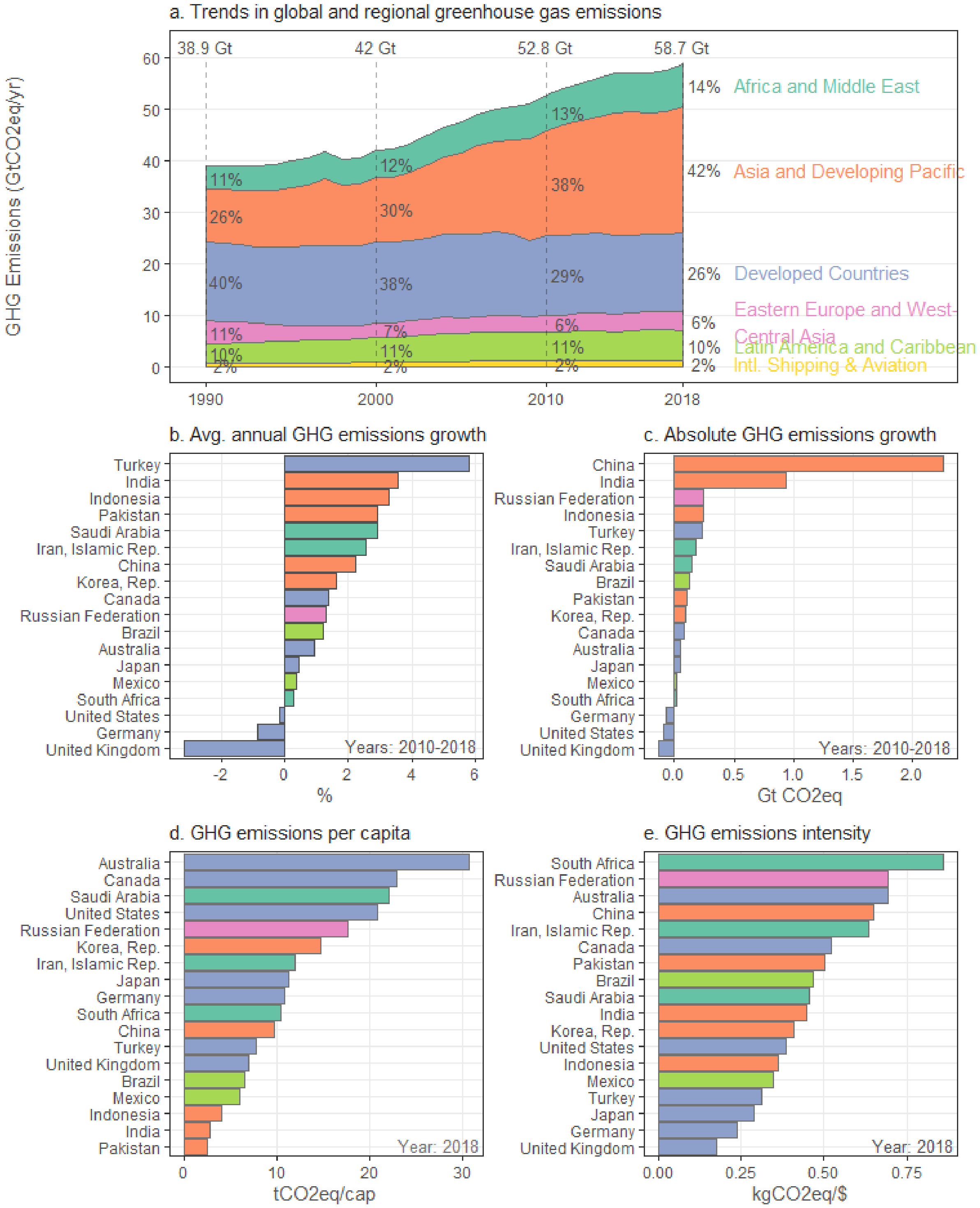


Figure 2.9 - Change in regional GHGs from multiple perspectives and their underlying drivers. Panel a: Regional GHG emission trends (in GtCO$_2$eq yr^{-1}) for the time period 1990-2018. GHG emissions from international aviation (AIR) and shipping (SEA) are not assigned to individual countries and shown separately. Panels b and c: Changes in GHG emissions for largest emitters (75% of global emissions) for the post-AR5 reporting period 2010-2018 in relative (% annual change) and absolute terms (GtCO$_2$eq). Panels d and e: GHG emissions per capita and per GDP in 2018 for the largest emitters (75% of global emissions). GDP estimated using constant international purchasing power parity (USD 2011). Emissions are converted into CO$_2$-equivalents based on global warming potentials with a 100 year time horizon (GWP-100) from the IPCC Sixth Assessment Report.

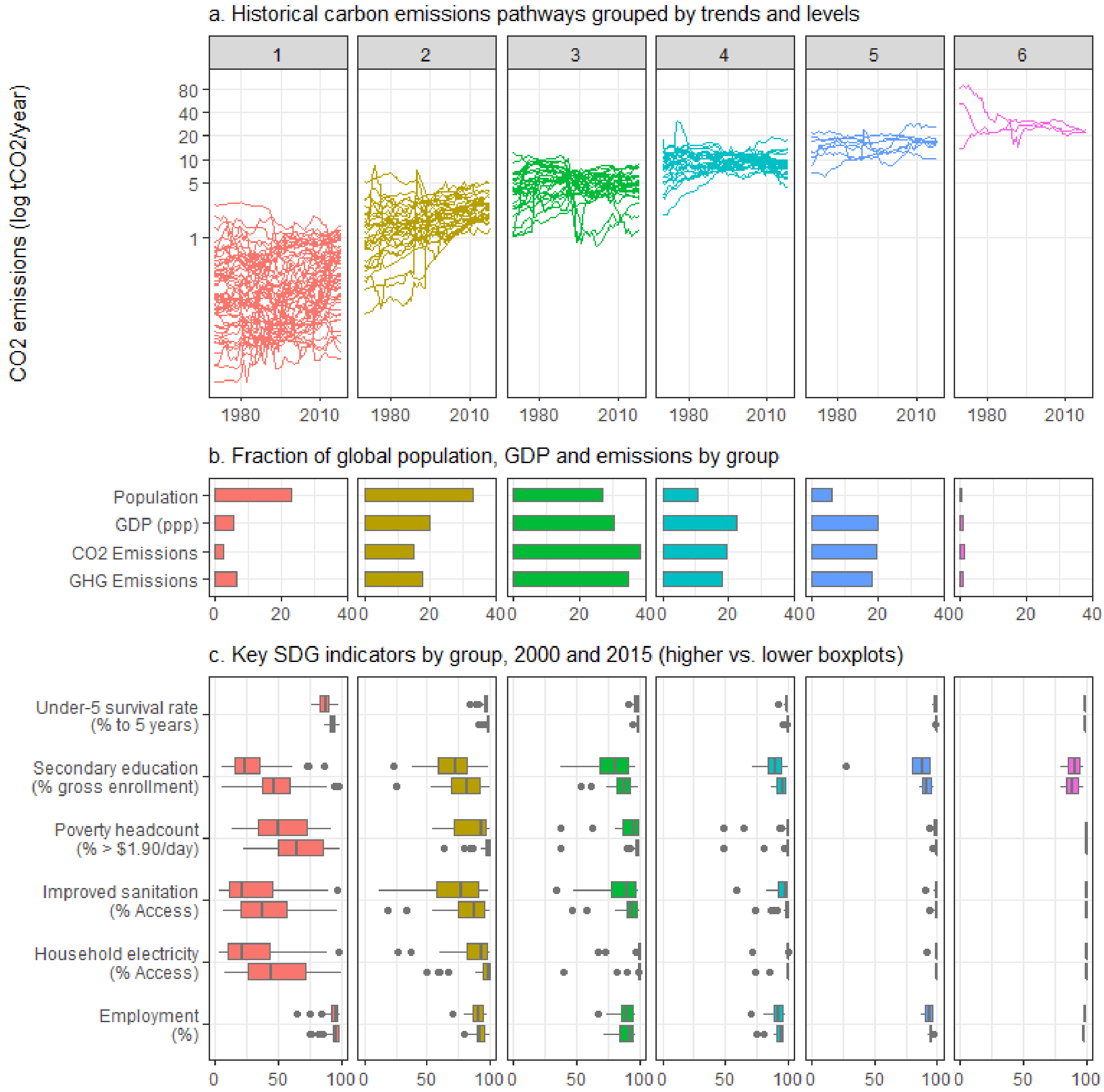


Figure 2.10 - National CO_2 emissions trends and associated SDG outcomes. Countries are clustered into six groups based on their CO_2 emissions at 5 year intervals between 1980 and 2015 (with 2018 included). Note the log scale in panel a.

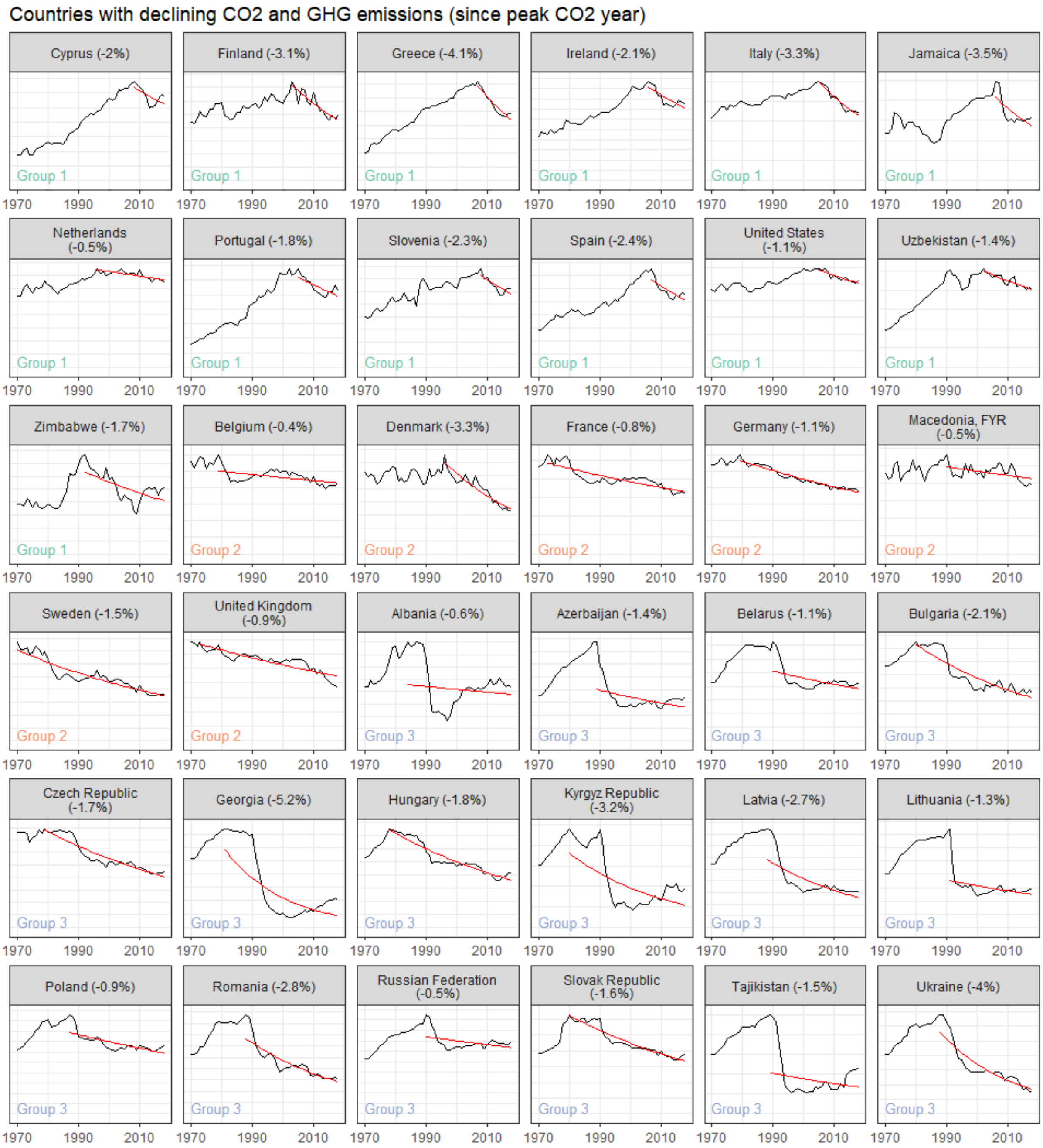


Figure 2.11 Countries with declining CO_2 and GHG emissions. Emission reduction rates are calculated from a year of peak CO_2 emissions before 2009 (i.e. at least 10 years of reductions to 2018). Countries with growing GHG emissions over the same time period, with absolute CO_2 reductions of less than 10%, and recent histories of civil conflict are removed. Three groups indicate distinct emissions profiles: countries that only recently peaked in emissions following a period of growth (group 1); countries with long term emissions reductions (group 2); and countries with a sudden decline in emissions following the collapse of the Soviet Union (group 3). Source: (Lamb et al. 2020)

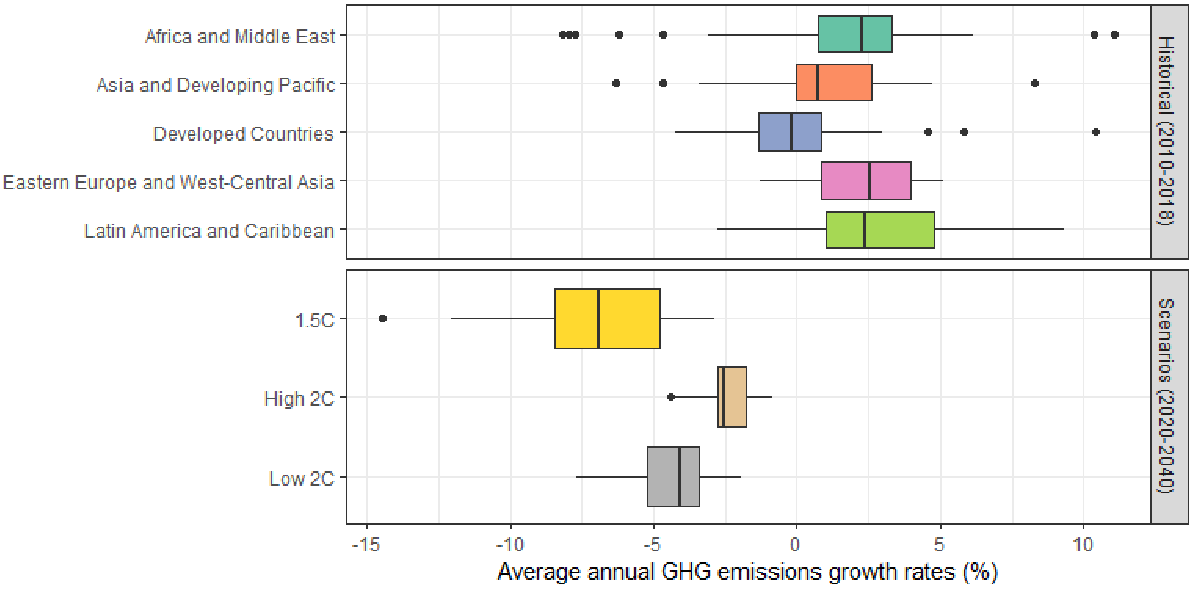


Figure 2.12 - Historical GHG emissions growth rates of countries (upper panel) versus rates of reduction in 1.5 and 2 degree scenarios as defined in Rogelj et al. (2018). Scenario data is taken from Huppmann et al (2018), but will be updated in the final draft to the AR6 scenario data collected by chapter 3 of this report. Emissions are converted into CO_2-equivalents based on global warming potentials with a 100 year time horizon (GWP-100) from the IPCC Sixth Assessment Report.

2.2.4 Sectoral GHG emission trends

In 2018, 35% (20 $GtCO_2eq$) of the 59 $GtCO_2eq$ GHG emissions came from the energy sector, 23% (13 $GtCO_2eq$) from industry, 23% (13 $GtCO_2eq$) from AFOLU, 14% (8.3 $GtCO_2eq$) from transport and 6% (3.4 $GtCO_2eq$) from buildings. AR5 still reported AFOLU to be the second largest emitting sector (Blanco G. et al. 2014). Results depend on the exact definition of sector boundaries. Moreover, such an emission-source focussed reporting of GHGs tends to underrepresent the role of final energy demand and demand-side solutions in climate change mitigation (see Chapter 5) (Creutzig et al. 2018, 2016b). The largest individual sub-sector contributing to global GHG emissions in 2018 was electricity and heat generation at 13.9 $GtCO_2eq$. This subsector can be reallocated to consuming sectors as indirect (Scope 2) emissions (Figure 2.13). This increases the emission share of the industry sector to 33% and of the buildings sector to 14%.

Average annual GHG emissions growth has been fastest in the transport sector with about 1.9% for the most recent period 2010-2018, followed by the industry sector (1.4%) and the energy sector (0.9%) (Figure 2.14). This is very different to growth patterns observed in the previous decade as reported in AR5 (IPCC 2014a; Blanco G. et al. 2014). Between 2000 and 2010 fastest GHG emissions growth was observed for industry with 4.4% followed by the energy sector with 2.9%. GHG emission growth in the transport sector has been stable across both periods at about 2%. AFOLU and direct building emissions growth averaged below 1% during 2010-2018, acknowledging high uncertainties from land-use CO_2 emissions in the former (see Section 2.2.1.2). Ranking of high emitting sectors highlights the importance of the 'other industry' (8 $GtCO_2eq$), residential buildings (6.4 $GtCO_2eq$), road transport (6.2 $GtCO_2eq$), land-use CO_2 (5.4 $GtCO_2eq$) and metals sub-sectors (4.5 $GtCO_2eq$). Overall, some of the fastest growing sources of sub-sector emissions from 2010 to 2018 have been international aviation (+2.7%), oil and gas fugitive emissions (+2.1%), coal mining fugitive emissions (+1.9%), metals (+1.9%) and road transport (+1.9%).

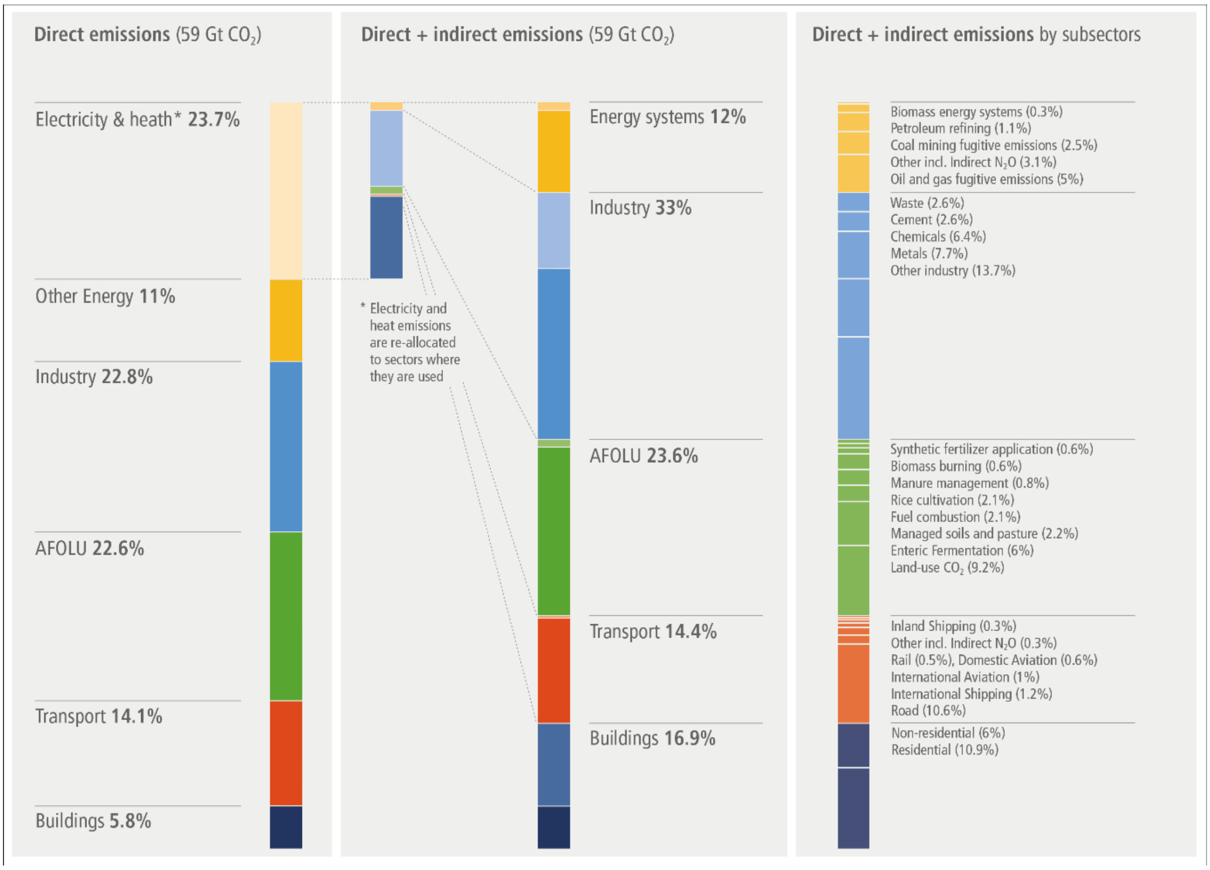


Figure 2.13 Total anthropogenic direct and indirect GHG emissions for the year 2018 (in $GtCO_2eq$) by sector and sub-sector. Direct emissions estimates assign emissions to the sector in which they arise (scope 1 reporting). Indirect emissions – as used here - refer to the reallocation of emissions from electricity and heat to the sector of final use (scope 2 reporting). More comprehensive conceptualisations of indirect emissions including all products and services (scope 3 reporting) are discussed in Section 2.3 of this chapter. Emissions are converted into CO_2-equivalents based on global warming potentials with a 100 year time horizon (GWP-100) from the IPCC Sixth Assessment Report.

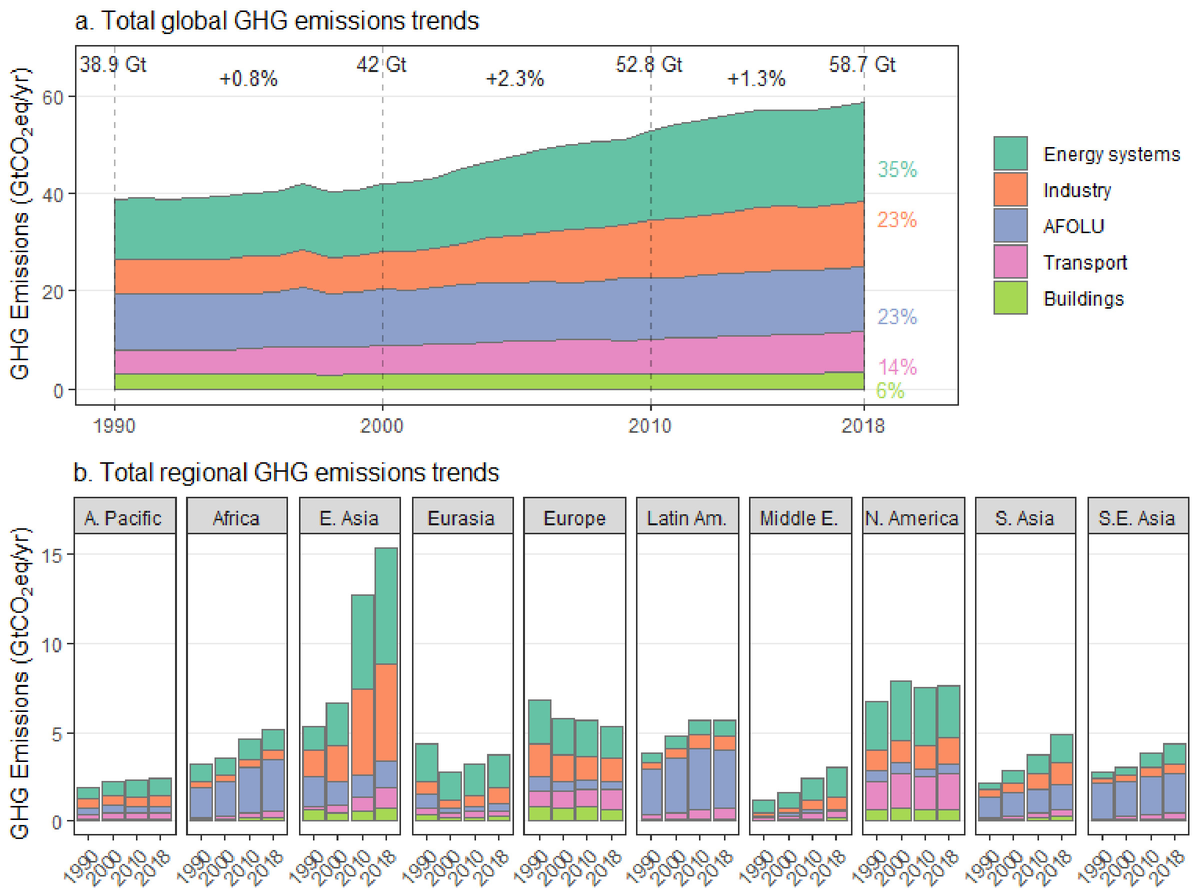
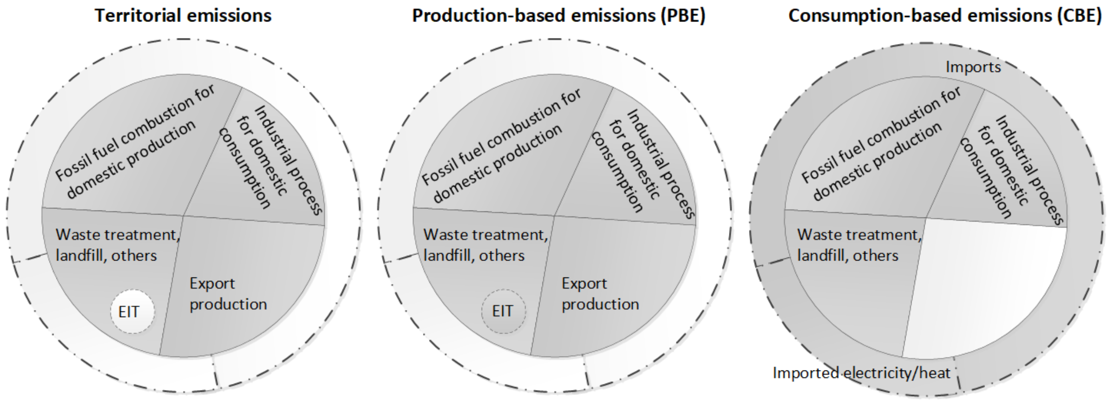


Figure 2.14 Total annual anthropogenic GHG emissions by major economic sector and their underlying trends by region. AFOLU refers to GHG emissions from agriculture, forestry and other land-use change. Panel a: Trends in total annual anthropogenic GHG emissions (in GtCO$_2$eq) by major economic sector. Panel b: Trends in total annual anthropogenic GHG emissions (in GtCO$_2$eq) by major economic sector and region. Emissions are converted into CO$_2$-equivalents based on global warming potentials with a 100 year time horizon (GWP-100) from the IPCC Fifth Assessment Report.

2.3 Past and present trends of consumption-based CO$_2$ emissions (CBE) and emissions embodied in trade

2.3.1 Introduction

Consumption is increasingly met by global supply chains oftentimes involving large geographical distances and causing emissions in producing countries (Hubacek et al., 2014, 2016; Wiedmann and Lenzen, 2018). Therefore, accounting of emissions of production along the entire supply chain to fulfil final demand, so-called consumption-based emissions (CBE) is necessary to understand why emissions occur and to what extent consumption choices and associated supply chains contribute to total emissions, and ultimately how to manage consumption to achieve climate mitigation targets and environmental justice (Vasconcellos, 2019).



EIT: Emissions From international territories (e.g., international aviation/shipping and non-resident activities)

Figure 2.15 Boundaries of CO_2 emission accounting. Both territorial and production-based emissions are calculated from the production and consumption of goods and services within a region but PBE include emissions from international territories (e.g., international aviation/shipping and non-resident activities), which are excluded in territorial emissions. Consumption-based emissions are associated with consumption of goods and services via global supply chains, irrespective of the place of production.

Figure 2.15 compares the boundaries of different scopes of regional emissions. Production-based emissions (PBE) and territorial emissions resulting from the production and consumption of goods and services within a region as well as for export production are often used by authorities to report carbon emissions (Peters, 2008) (see also section 2.2). PBE include emissions from international territories (e.g., international aviation/shipping and non-resident activities), which are excluded in territorial emissions (Karstensen et al., 2018; Shan et al., 2018). In contrast, CBE refer to emissions along the entire supply chains induced by consumption irrespective of the place of production (Liu, Feng, et al., 2015). This reflects a shared understanding that a wider system boundary going beyond territorial emissions is important to avoid outsourcing of pollution and to achieve global decarbonisation. CBE allow to identify new policy levers through providing information on a country's trade balance of embodied emissions, household's carbon implications of their lifestyle choices, companies' upstream emissions as input for supply chain management, and cities' often considerable footprints outside their administrative boundaries (Feng et al. 2013; Davis and Caldeira 2010).

There are other proposed emission accounting approaches used in different circumstances, such as historical cumulative emissions (Botzen et al. 2008; Ritchie 2019), extraction-based emissions (Steininger & Schinko, 2015; Erickson & Lazarus, 2013), and income-based emissions (Liang et al. 2017a). Historical cumulative emissions (HCE) are used when analysing countries' historic contribution to emissions and responsibility for emission reduction. HCE account for a country's cumulative past emissions, which may be significantly different from the country's current annual emissions. For example, the United States and EU-27 countries plus the United Kingdom contributed respectively 13.4% and 8.7% to global PBE in 2019 (Crippa et al. 2020), however, they emitted around 25% and 22% of global historical PBE since 1751 (Ritchie 2019). In contrast, some large current CO_2 emitting countries, such as China, India and Brazil, have a relatively small share of cumulative emissions (Yang et al. 2015). Extraction-based emissions (EBE) accounting allocates all emissions from burning fossil fuels throughout the supply chains to the country where the fuels were extracted (Steininger & Schinko, 2015). Extraction-based emissions can be calculated by multiplying primary energy extraction of fossil fuels with their respective carbon content adjusting for the fraction of fossil fuels that is not combusted (Erickson and Lazarus 2013). While extraction-based accounting traces CO_2 emissions through fuel extraction sectors and fuel supply chains and allocates it to the point of fuel extraction, income-based emission accounting (IBE) traces emissions throughout all supply chains and allocates emissions to primary inputs (e.g., capital and labour). In other words, IBE investigates a country's direct and indirect downstream GHG emissions enabled by its primary inputs (Liang et al. 2017a). All of these approaches provide complementary information and different angles to assigning responsibility for emission reductions.

Box 2.1 Policy relevance of production-based (PBE) and consumption-based (CBE)

PBE accounts are relevant for:

- National-level emissions accounting
- National-level target or budget setting
- Nationally determined contributions to global mitigation targets
- Domestic carbon pricing and taxation policies
- Domestic sector-level policies on carbon mitigation, including promoting renewable energy technologies, energy efficiency and cleaner production
- Domestic emissions trading schemes

CBE accounts are relevant for:

- Complementary national-level emissions accounting and target or budget setting
- Raising awareness and increasing understanding of the GHG effects of consumption
- Accounting for and understanding of distributional and responsibility issues in GHG emissions mitigation, both nationally and internationally.
- Incentives to change consumption patterns or reduce consumption (e.g., through taxation policies)
- Accounting for and understanding carbon leakage and emissions embodied in trade*)
- Commitments in international climate policy negotiations
- International emissions trading schemes or linked national schemes
- Trade policies addressing emissions embodied in trade and international supply chains (e.g., border tax adjustments and clean technology transfers, carbon offsetting or financing, etc.)
- Including embodied emissions in product performance standards and labelling
- Policies of public and private procurement
- Agreements with international suppliers

Discussing the inequality in consumption and emissions (Bolea et al., 2020; Hubacek et al., 2017; Wang & Zhou, 2018)

Above points are based on a synopsis of Afionis et al. (2017), Steininger et al. (2014), and Steininger et al. (2015).

* Note, however, that comparing embodied emissions in trade between countries is complicated by the fact that emission intensities differ across countries, rendering the assignment of responsibility for CBE problematic. Approaches to adjust for these differences and facilitate comparisons have been suggested, e.g., by Kander et al. (2015), Baumert et al. (2019), Dietzenbacher et al. (2020), and Jakob (2020). Many different approaches on how to share responsibility between producers and consumers have been proposed as a critical tool in designing effective integrated global climate policies (Liu & Fan, 2017; Zhu et al., 2018; Khajehpour et al., 2019; Yang et al., 2015).

2.3.2 Regional trends

2.3.2.1 National trends

The growth of global CBE before 2000 was largely due to the increase of consumption in developed countries and Asian and developing Pacific countries, while the share of CBE in Eastern Europe and West-Central Asia slightly declined by 2%. Figure 2.16 also shows the change rates of total CBE and CBE per capita for 43 individual countries adding up to more than 85% of the global emissions. Most developed countries, in particular the EU countries, had a relatively big decline in their total CBE and CBE per capita from 2010 to 2017.

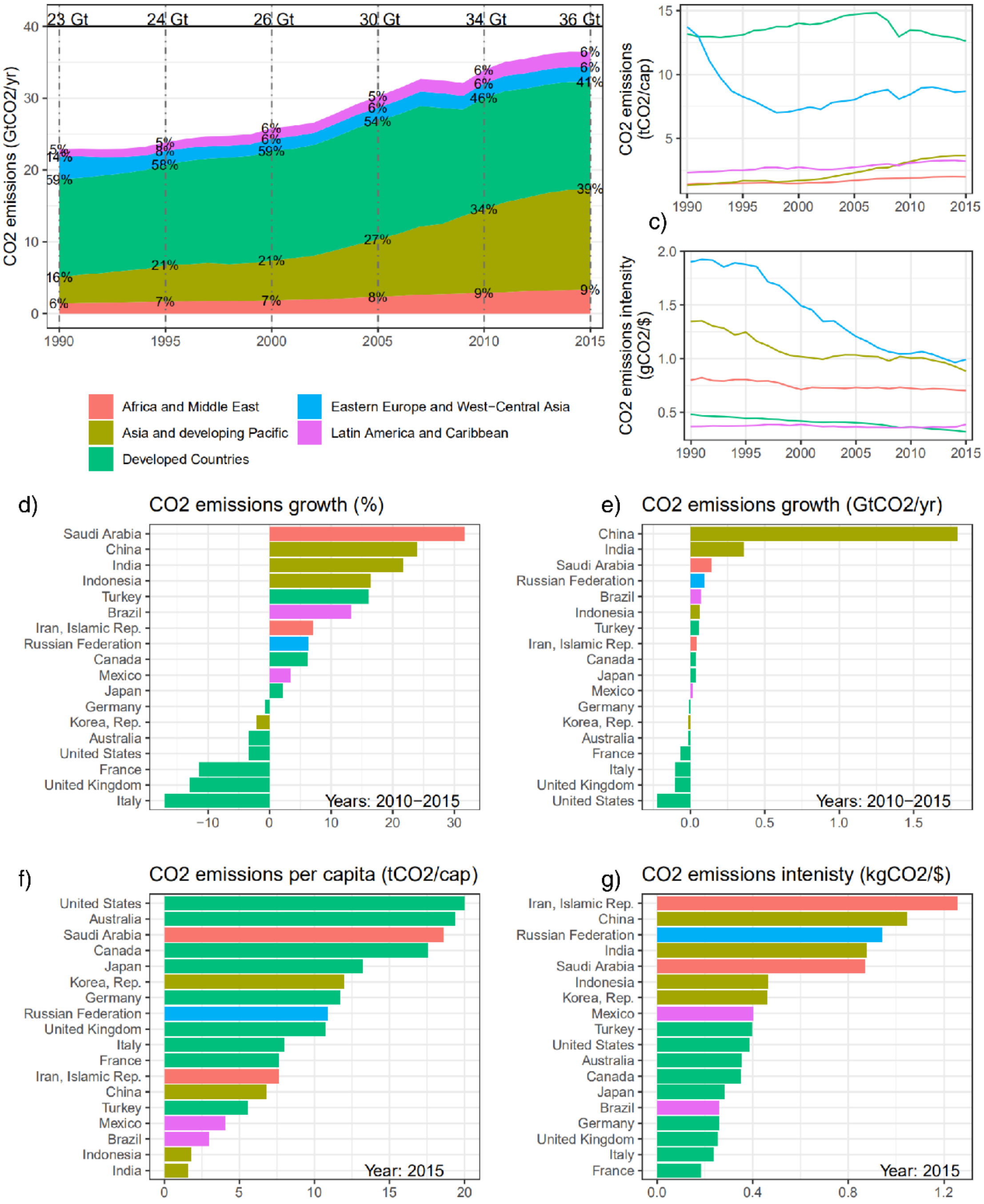


Figure 2.16 Consumption-based CO_2 emission trends for the period 1990-2015. The CBE of countries are calculated using in global multi-regional input-output model with Eora 26 GMRIOs (v199.82) (https://www.worldmrio.com/footprints/carbon/) and EDGAR production-based emissions (Lenzen et al., 2013).

The top three panels (a-c) in Figure 2.16 show the total and per capita CBE and emission intensity for five regions. Developed countries account for the largest share of CBE globally with the highest per-capita emissions and the lowest emission intensity. Developing countries, especially those from Asia and Pacific regions, have experienced a rapid growth of CBE between 1990 and 2015. The bottom four panels (d-g) in Figure 2.16 show additional information for the 18 top-emitting countries with the highest CBE in 2015.

2.3.2.2 Urban trends

The literature on CBE for cities is much less extensive than PBE due to a lack of data at the city-level. There are only few studies that report CBE for a larger number of cities. For example, Wiedmann et al. (2020a) discussed the three-scope GHG inventories of 79 C40 cities, whereas an earlier study by Moran et al. (Moran et al. 2018) estimated the CBE of 13,000 cities from 189 countries in 2015 based on downscaling from the national CBE according to city characteristics such as consumption patterns and purchasing power. Although there are great uncertainties in the downscaling approach, such as not considering urban density or economies of scale, Moran et al (Moran et al. 2018) can still provide to some extent an overview and comparison of cities' carbon footprint. The result shows that a relatively small proportion of urban areas (top 100 cities in terms of emissions, or 0.77% of the 13,000 cities) account for a disproportionately large share (18%) of global consumption-based CO_2 emissions.

Per capita CBE vary widely across cities. For example, Hong Kong had the largest per capita CBE of 34.6 ±6.3 tons in 2015, while Sydney emitted 11.7 ±3.0 (ranking 281) and Nottingham 8.9 ±3.6 tCO_2 per capita (ranking 495). Developed countries generally have much slower urban growth and much higher average per capita carbon footprints than developing countries (e.g. 1.7 tCO_2/cap in China, 6.7 tCO_2/cap in the EU and 10.4 tCO_2/cap in the USA in 2012 (Wiedenhofer et al. 2017). Cities in South/West/Southeast Asia and Africa have the lowest per capita emissions (less than 6 tCO_2eq in 2017), the median group in per capita emissions include cities from Latin America and East Asia (between 6 and 10 tCO_2eq per capita in 2017). Cities in Europe, North America, and Oceania have the highest per capita emissions (between 13-20 tons in 2017) (C40 2019). Even within countries, urban carbon emissions can vary widely due to the huge imbalance in regional development, especially in developing countries. For example, per capita emissions in Nanping (a city in China; 2.38 tons) were less than one-tenth of those in Hohhot (29.76 tons) in 2010 (Shan et al. 2017). Such a wide range of cities' per capita CBE are mainly due to differences in income levels. The top income decile is responsible for 38% of the 13,000 cities' overall CBE (Moran et al. 2018). Other influencing factors may include economic structure (Wiedmann et al., 2010), consumption level (Wang et al., 2015), and lifestyles (Shigetomi et al. 2018).

In terms of consumption composition, utilities and housing (including energy used for heating and cooling), transportation (public and private), food, infrastructure construction and government services contribute more than 70% of cities' CBE (C40 2018) but the shares vary significantly. For example, in Latin America, the largest contributor to CBE is transportation (public and private), in East and Southeast Asia, it is capital investment, whereas in South and West Asia the largest contributor is emissions associated with food supply. In Europe and North America, utilities and housing are the main contributors to emissions (C40 2019, 2018).

Similar to findings at the national level, high-income cities tend to have higher CBE than PBE, while less developed cities or manufacturing cities show the opposite pattern (Moran et al. 2018). Cities in North America and Europe tend to have larger CBE than PBE (some cities' CBE are at least three times higher than their PBE), while cities in South and West Asia, Southeast Asia and Africa tend to have smaller CBE (C40, 2018, 2019). For example, Beijing had 142 Mt CBE and 81 Mt PBE in 2007, whereas the CBE of Tangshan, the world's largest iron and steel manufacturing centre was 41 Mt whereas its PBE was 74 Mt in 2007 (Mi et al. 2016). The gap in cities' PBE and CBE is partly caused by differences in energy mix as well as the different technologies used in the production of imports and exports. In addition, cities' differences in terms of PBE and CBE can be explained by their position in global supply chains. Wiedmann et al. (Wiedmann et al. 2020a) suggested that service-based cities (usually high-income) could have more mitigation potentials by adopting CBE mitigation policies while manufacturing-based cities may mainly focus their mitigation efforts on territorial emissions.

2.3.3 Decoupling of emissions from economic growth

There has been a long-standing discussion on whether environmental impacts such as carbon emissions and use of natural resources can be decoupled from economic growth. Although it is controversial whether absolute decoupling can be achieved at a global scale (Hickel and Kallis 2020; Ward et al. 2016), a number of studies found that it is feasible to achieve decoupling at the national level and reasons for decoupling (Deutch, 2017; Roinioti & Koroneos, 2017; Zhao et al., 2016; Li et al., 2019; Schandl et al., 2016; Habimana Simbi et al., 2021; Shan et al., 2020; Ward et al., 2016).

Absolute decoupling refers to a decline of emissions in absolute terms or as being stable while GDP grows or when emissions decline at a faster rate than a declining GDP (i.e., a decoupling index[5] greater than 1); relative decoupling refers to growth of emissions being lower than growth of GDP (a decoupling index between 0 and 1); and no decoupling, which refers to a situation where emissions grow to the same extent or faster than GDP (a decoupling index of less than 1) (Wu et al. 2018).

Figure 2.17 shows the extent of decoupling of CBE and GDP of country groups. During the most recent five-year period from 2010 to 2015, 43 countries (or 26%) have achieved absolute decoupling of CBE and GDP (the green area in the 4th quadrant). The main driver for decoupling has been a reduction in carbon intensity (that is change in energy mix and energy efficiency (Hubacek et al. Under review) rather than economic growth per se (Stern et al. 2017) (see also section 2.4). 58 (or 35%) countries have relatively decoupled (purple area in the 1st quadrant) and 52 (or 32%) coupled economic growth with CBE (read area in the 1st quadrant), respectively. 13 countries (or 8%) were in a recession during the period (the grey area in the 2nd and 3rd quadrants). It is important to note that a country's degree of decoupling changes over time. For example, 57 countries achieved absolute decoupling from 2005 to 2010 and only 21 of them remained decoupled over the next five years.

FOOTNOTE: [5] The decoupling index can be calculated based on the changes of their GDP and CO_2 emissions (Akizu-Gardoki et al. 2018; Wu et al. 2018), see the equation below. DI refers to decoupling index; G_1 refers to the GDP of reporting year while G_0 refers to the base year; E_1 refers to emissions of the reporting year while E_0 refers to emissions of the base year.

$$DI = \frac{\Delta G\% - \Delta E\%}{\Delta G\%} = \left(\frac{G_1 - G_0}{G_0} - \frac{E_1 - E_0}{E_0}\right) \Big/ \frac{G_1 - G_0}{G_0}$$

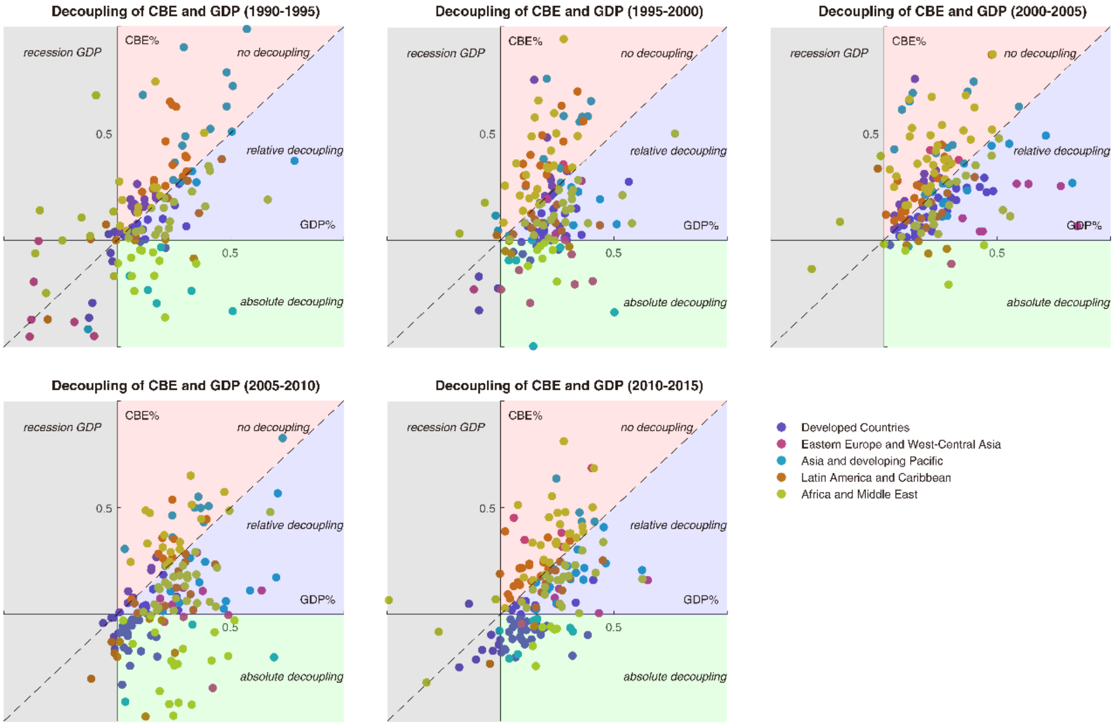


Figure 2.17 Degree of decoupling of CBE and GDP between 1990 and 2015. CBE are calculated with EDGAR and Eora GMRIO (Lenzen et al., 2013), GDP data are from the World Bank.

Table 2.6 Country groups with different decoupling extent between CBE and GDP in 2010 and 2015

		Absolute decoupling	Relative decoupling	No decoupling
Number of countries		43	58	52
CBE (gigatons)	Total	12.0 / 11.4	17.4 / 20.2	1.9 / 2.4
	Global share	35.9% / 31.7%	51.9% / 56.2%	5.8% / 6.7%
PBE (gigatons)	Total	12.0 / 9.2	17.4 / 21.3	1.9 / 2.4
	Global share	35.9% / 26.6%	51.9% / 61.6%	5.8% / 6.9%
Population (million)	Total	833 / 859	4619 / 4900	1005 / 1099
	Global share	12.4% / 12.0%	68.5% / 68.5%	14.9% / 15.4%
GDP (billion)	Total	31127 / 34452	24080 / 29959	4762 / 5460
	Global share	48.0% / 46.2%	37.1% / 40.2%	7.3% / 7.3%
Per capita GDP (thousand USD in 2010 prices)	Average	37.4 / 40.1	5.2 / 6.1	4.7 / 5.0
	Median	16.7 /18.9	4.6 / 5.3	2.9 / 3.3
	Max	105.0 / 107.6	87.7 / 90.0	73.4 / 73.7
	Min	0.23 / 0.23	0.33 / 0.41	0.40 / 0.44
Per capita CBE (ton)	Average	14.4 / 13.3	3.8 / 4.1	1.9 / 2.2
	Median	9.8 / 8.5	2.7 / 2.8	1.3 / 1.5
	Max	39.1 / 32.3	51.2 / 50.4	29.7 / 29.2
	Min	0.10 / 0.08	0.03 / 0.03	0.02 / 0.03
CBE intensity (ton per thousand USD in 2010 prices)	Average	0.39 / 0.33	0.72 / 0.68	0.40 / 0.45
	Median	0.47 / 0.36	0.56 / 0.51	0.48 / 0.53
	Max	1.72 / 1.61	2.77 / 1.95	2.00 / 2.18
	Min	0.18 / 0.06	0.08 / 0.06	0.003 / 0.004
Per capita PBE (ton)	Average	14.4 / 10.7	3.8 / 4.3	1.9 / 2.2
	Median	9.8 / 4.9	2.7 / 2.4	1.3 / 1.2
	Max	39.1 / 16.9	51.2 / 24.9	29.7 / 38.1
	Min	0.10 / 0.03	0.03 / 0.05	0.02 / 0.05
	Average	0.39 / 0.27	0.72 / 0.71	0.40 / 0.44
	Median	0.47 / 0.24	0.56 / 0.40	0.48 / 0.42

PBE intensity (ton per thousand USD in 2010 prices)	Max	1.72 / 1.31	2.77 / 2.00	2.00 / 1.76
	Min	0.18 / 0.03	0.08 / 0.05	0.003 / 0.07

Note: This table reflects the degree of decoupling from 2010 to 2015. The first number in each cell presents the value in 2010 and the second one presents the value in 2015. CBE are calculated based on EDGAR PBE and Eora GMRIO, GDP and population are from the World Bank.

Table 2.6 shows that countries with absolute decoupling tend to achieve decoupling at relatively high levels of economic development and high per capita emissions. Most of EU and North American countries are in this group. They also decoupled PBE and GDP (Cohen et al. 2018). Decoupling was not only achieved by outsourcing pollution, but also improvements in production efficiency and energy mix, leading to declines of PBE and CBE (Le Quéré et al. 2019). Similarly, Wood, Neuhoff, et al. (2019d) found that EU countries have reduced their overall consumption-based GHG emissions by 8% between 1995 and 2015, mainly due to the use of more efficient technology.

A number of countries, such as China, India and Japan, experienced relative decoupling of GDP and CBE over the period of 2010 to 2015. . As our emission data only goes until 2015, some countries' emissions may have again increased fast after a short-term decoupling (Myllyvirta 2019a,b).

Another 52 countries, mainly fast-growing developing countries, such as Brazil and Bangladesh, have experienced no decoupling between GDP and emissions from 2010 to 2015, meaning the growth of their GDP is closely tied with domestic consumption and production of emission-intensive goods. Further increase in GDP in these countries will likely lead to higher emissions if following the historical trends of the past two decades.

2.3.4 Emissions embodied in trade (EET)

As global trade patterns have changed over recent decades, so have the emissions embodied in trade (EET) (Jiang & Green, 2017). EET refers to emissions associated with production of traded goods and services and is equal to the difference between PBE and CBE (Wiebe and Yamano 2016). EET includes two parts: emissions embodied in imports (EEI) and emissions embodied in exports (EEE). For a given country or region with CBE higher than PBE, the country is a net importer with a higher EEI than EEE, and vice versa.

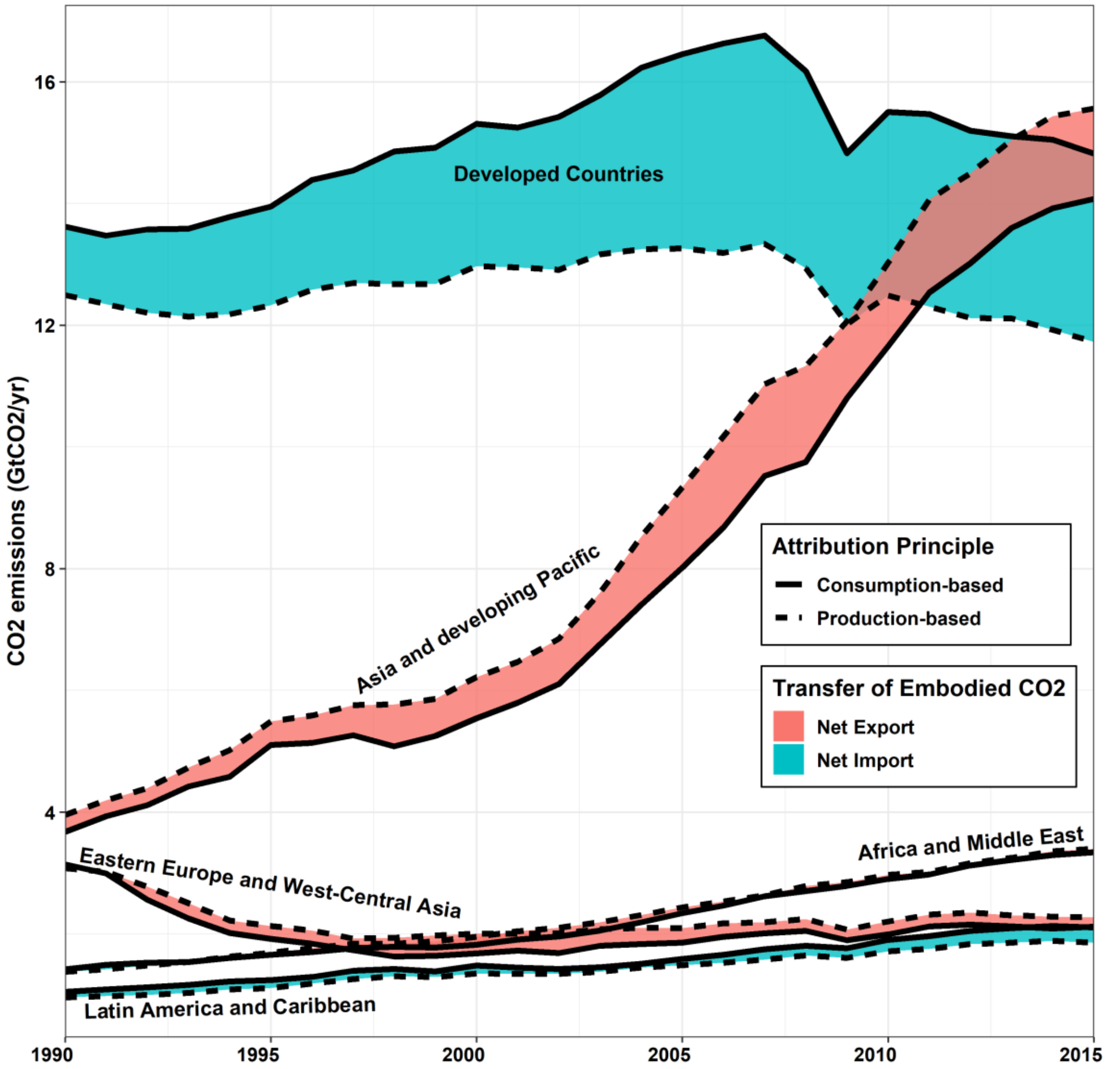


Figure 2.18 Total annual CO_2 emissions for countries by global region attributed on the basis of consumption and production-based emissions. The shaded areas are the net CO_2 trade balances (differences) between each of the four country income groups. Blue shading indicates that the country income group is a net importer of embodied CO_2 emissions, leading to consumption-based emission estimates that are higher than traditional territorial emission estimates. Red shading indicates the reverse. The production-based emissions are collected from EDGAR and consumption-based emissions are calculated with Eora GMRIO tables (Lenzen et al., 2013).

EET have been rising faster since the 1980s due to an increase in trade volume (Xu & Dietzenbacher, 2014; Wood et al., 2018; Zhong et al., 2018; D. Liu et al., 2019). CO_2 emissions from the production of internationally traded products peaked in 2006 at about 27% of global CO_2 emissions. Since then, international CO_2 emissions transfers declined but are likely to remain an important part of the climate policy agenda (Wood, Grubb, et al., 2019). About 23% of global economic output was traded in 2010 (Liang et al. 2017b) and 20-33% of global CO_2 emissions are embodied in international trade of goods and services before 2011 (Wiedmann & Lenzen, 2018).

2.3.4.1 Net emission transfers

Located downstream of global supply chains, developed countries (mostly in Western Europe and North America) tend to be net emission importers, i.e. EEI are larger than EEE. For example, over 40% of national CO_2 footprints in France, Germany, Italy, and Spain are from imports (Fan et al. 2017). Developing countries tend to be net emission exporters with higher PBE than their CBE (Peters et al.

2011b; Quéré et al. 2018), especially for Asia and Developing Pacific (as shown in Figure 2.18). Eastern Europe, West-Central Asia, Africa, Middle East, Latin America and Caribbean have a lower share of trade embodied emissions. That is to say, there is a net emission transfer and outsourcing trend shifting production from developed to developing economies via global trade (Jiang et al., 2018), mainly caused by cheap labour costs (Tate and Bals 2017) and cheap raw materials (Mukherjee 2018). Increasing openness to trade (Fernández-Amador et al. 2016) and less stringent environmental legislation (acting as so-called pollution havens) (Malik and Lan 2016; Hoekstra et al. 2016; Banerjee and Murshed 2020) are also possible reasons. As a result, carbon leakage among countries has increased (Fernández-Amador et al. 2016), as well as global emissions.

Net emissions transferred between low- and developed countries have slightly increased from 6.1% of global CO_2 emissions in 1995 (Wood et al. 2018) to a peak of 7.3% in 2006 and then a subsequent decline (Wood et al. 2019a). The main reason for the decline was an improvement in the carbon intensity of traded products of about 40% between 1995 and 2015, rather than a decline in trade volume, see Figure 2.19 (Wood et al. 2019b). Despite continued improvements, developing economies tend to have higher emission intensity and lower production efficiency than developed economies due to less efficient technologies and a carbon-intensive fuel mix (Liu et al., 2015; Jiang & Guan, 2017).

2.3.4.2 Geographical shifts of trade embodied emissions

With the rapid growth of developing countries, the geographical centre of global trade as well as trade embodied emissions is changing. The fast growth of Asian countries is shifting the global trade centre from Europe to Asia. Asian exports in monetary units increased by 136% from 1996 to 2011, and its share of global exports increased from 27% to 48%, whereas Europe's share of global exports decreased from 51% in 1996 to 35% in 2011 (Zhang et al., 2019).

In addition to changes in trade volume, the trading patterns are also changing significantly in Asian countries. They are replacing traditional trading countries (such as Russia and Germany) by having fast growth in trade flows especially with countries of the global South (Zhang et al., 2019). The largest geographical shifts in trade-embodied emissions between 1995 and 2011 occurred in high-tech, electronic and electrical goods, and machinery (Jiang et al., 2018; Malik & Lan, 2016). For example, China is shifting its exports to include more low-carbon and higher value-added goods and services. As a result, China's exported emissions declined by 20% from 2008 to 2015 (Mi et al., 2018).

As a result, developing countries are playing an important role in global trade. Emissions embodied in trade between developing countries, so-called South-South trade, has more than doubled between 2004 (0.47 Gt) and 2011 (1.11 Gt), which is seen as a reflection of a new phase of globalisation (Meng et al., 2018). Developing countries, therefore, have gained importance as global suppliers of goods and services and have also become more relevant as global consumers as they grow their domestic demand (Fernández-Amador et al. 2016). Since 2014, CO_2 emission transfer between developing countries has plateaued and then slightly declined and seems to have stabilised at around the same level of transfers between non-OECD and OECD countries at around 2.4 $GtCO_2\ yr^{-1}$ (Wood et al. 2019b). In both cases, a decrease in carbon intensity of trade just about offset increased trade volumes (Wood et al. 2019b).

2.3.5 Variability in consumption-based carbon dioxide emission accounts

The dominant method for calculating consumption-based emissions (CBE, or 'carbon footprints') of nations is global multi-region input-output (GMRIO) analysis (Wiedmann & Lenzen, 2018), with other methods playing a minor role, e.g. analysing bilateral trade flows of products and their life-cycle emission factors, e.g. (Sato 2014). Generally, uncertainty of CBE results depend on the choice of the dataset/model used for calculation, which differ in a) national economic and trade data used, b) emissions data used, c) sector or product-level aggregation, d) regional aggregation, e) conceptual scope (e.g. residential vs territorial accounting principle) and f) model construction techniques which include table balancing algorithms and ways of dealing with missing or conflicting data (Moran & Wood, 2014;

Owen, 2017; Wieland et al., 2018; Wood et al., 2018; Wood, Moran, et al., 2019). When excluding systematic error sources, previous studies with limited scope have shown that the stochastic variation of national CBE accounts is not significantly different to PBE accounts and in the region of 5-15% (Lenzen et al., 2010; Wood et al., 2018; Wood, Moran, et al., 2019).

Five global accounts for consumption-based GHG emissions at the country level exist (Table 2.7). Each dataset has been constructed by different teams of researchers, covers different time periods and contains CBE estimates for different sets of countries and regions (Owen 2017).

Table 2.7 Features of six global datasets for consumption-based emissions accounts

Name of consumption-based account datasets	Years available	Number of countries/regions	Number of sectors
Eora (Lenzen et al., 2013)	1990-2013	187	Varies from 25 to >500
EXIOBASE (Wood et al. 2018)	1995-2012	49	200 products and 163 industries
GTAP (Peters et al., 2011)	2004, 2007, 2011	140	57
OECD (Yamano and Webb 2018)	1995-2011	67	36
WIOD (Dietzenbacher et al. 2013)	1995-2009	41	35
Global Carbon Budget	1990-2017	119	N/A

Using this baseline dataset for CBE analysis and validation, Wood, Moran, et al. (2019c) present the first comprehensive and systematic model intercomparison and find a variation of 5-10% for both PBE and CBE accounts of major economies and country groups (EU28, OECD, BRICS) (Figure 2.19). The estimates for the US were the most closely aligned, with 3.7% Relative Standard Deviation (RSD). For smaller countries, variability is in the order of 20-30% and can reach more than 40% in cases of very small, highly trade-exposed countries such as Singapore, Luxembourg or Hong Kong (Wood et al. 2019c). It is recommended to interpret CBE results for such countries with care.

Overall, production accounts showed a slightly higher convergence (8% average of relative standard deviation, RSD) than consumption accounts (12%). The variation across model results can be approximately halved, when normalising national totals to one common value for a selected base year. The difference between PBE result variation (4% average RSD after normalisation) and CBE results (7%) remains after normalisation.

In general, the largest contributors to uncertainty of CBE results are - in descending order of priority - the total of territorial GHG emission accounts, the allocation of emissions to economic sectors, the total and composition of final demand, and lastly the structure of the economy. Harmonising territorial emissions across GMRIO datasets is the single most important factor that reduces uncertainty by about 50% (Tukker et al. 2020). More work is required to optimise or even institutionalise the compilation of multi-region input-output data and models to enhance the accuracy of consumption-based accounting (Tukker et al., 2018; Wood et al., 2018).

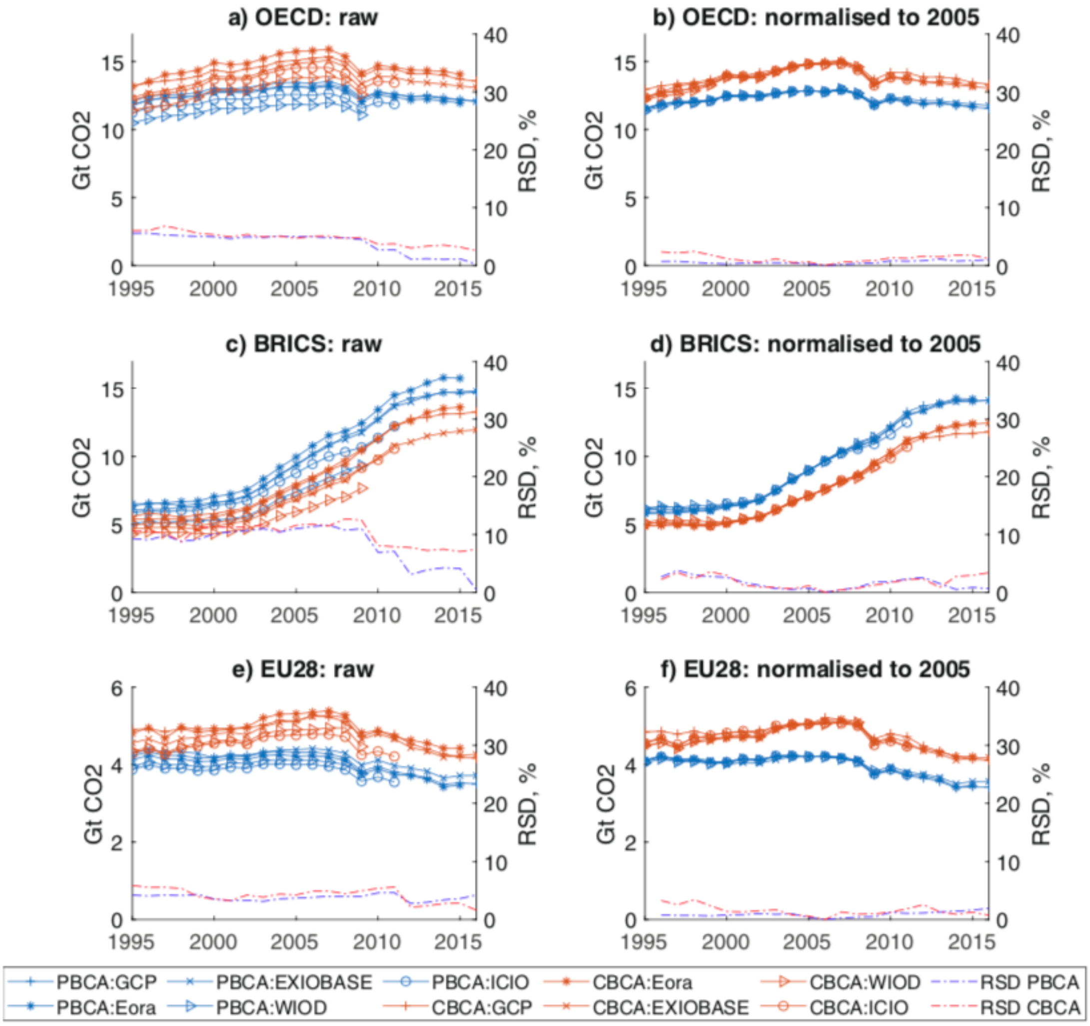


Fig. 1 PBCA and CBCA results for major regions calculated from each of the five models, with relative standard deviation (right axis). (**a**) OECD countries raw model results; (**b**) OECD countries after normalising to 2005; (**c**) BRICS raw model results; (**d**) BRICS after normalising to 2005; (**e**) EU28 raw model results; (**f**) EU28 after normalising to 2005.

Figure 2.19 PBE and CBE for major regions calculated from five models, with relative standard deviation on the right axis (taken from (Wood et al. 2019c)).

2.4 Economic drivers and their trends by regions and sectors

This section provides a summary of the main economic drivers of GHG emissions (mostly production-based) by regions and sectors, including those that are more indirect drivers related to economic activity, such as inequality, rapid urbanisation and trade. Socio-demographic drivers are described in Section 2.6.

2.4.1 Economic drivers at global and regional levels

In general, economic growth (measured as GDP) and its main components, affluence (GDP per capita) and population growth, all remained the strongest drivers of GHG emissions in the last decade, following a long-term trend (Burke et al. 2015), (Yao et al. 2015), (Malik et al. 2016), (Sanchez and Stern 2016), (Stern et al. 2017), (Chang et al. 2019), (Dong et al. 2019), (Liobikiene and Butkus 2019), (Liu et al. 2019a), (Mardani et al. 2019), (Pan et al. 2019), (Dong et al. 2020), (Parker and Bhatti 2020). Globally, affluence remained by far the strongest upward driver, increasing almost in tandem with energy consumption and CO_2 emissions up until 2015, after which some modest decoupling occurred (Figure 2.20).

The main counteracting, yet insufficient, factor that led to emissions reductions was decreased energy use per unit of GDP in almost all regions (-2.1% between 2010 and 2018, globally). These reductions in energy intensity are a result of technological innovation, regulation, structural changes and increased economic efficiency in underlying sectors (Yao et al. 2015), (Sanchez and Stern 2016), (Chang et al. 2019), (Dong et al. 2019), (Liu et al. 2019a), (Marin and Mazzanti 2019), (Mohmmed et al. 2019), (Stern 2019), (Wang et al. 2019c), (Goldemberg 2020). The decades-long trend that any efficiency gains were outpaced by an increase in worldwide affluence continued unabated in the last ten years (Wiedmann et al. 2020b). Therefore, GHG emissions only show relative decoupling from GDP at the global level (Deutch 2017b), (Wood et al. 2018). In addition, the emissions-reducing effects of energy efficiency improvements are diminished by the energy rebound effect, which has been found in several studies to largely offset any energy savings (Rausch and Schwerin 2018; Bruns et al. 2019; Stern 2020).

A significant decarbonisation of the energy system was only noticeable in North America, Europe and Eurasia, whereas globally the amount of CO_2 per unit of energy used has practically remained unchanged over the last three decades (Tavakoli 2018), (Chang et al. 2019). Population growth has also remained a persistent – and globally the second largest – upward driver in almost all regions (+1.2% globally since 2010, Figure 2.20).

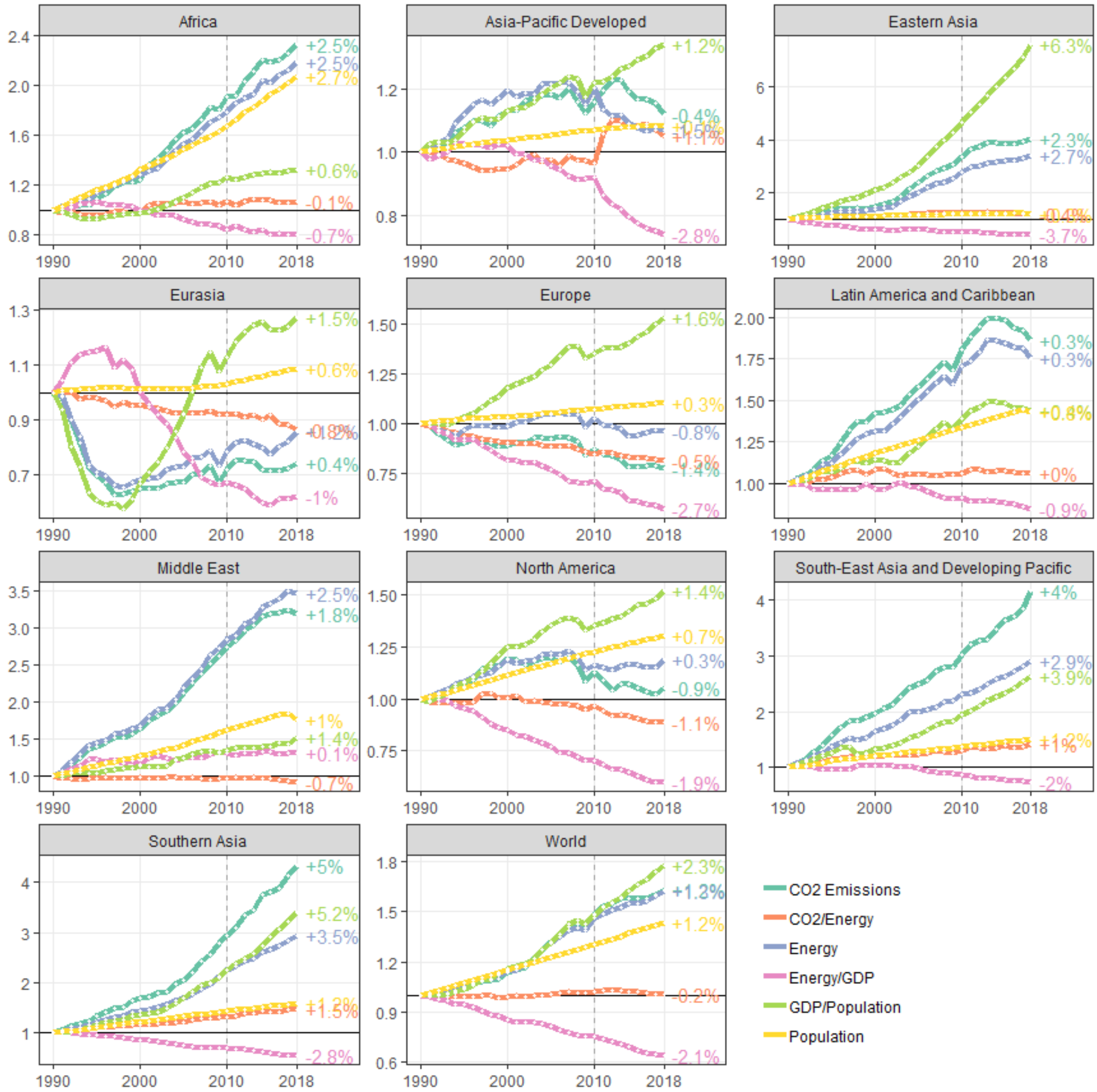


Figure 2.20: Kaya decomposition of CO_2 emissions drivers by world region (Lamb et al, forthcoming). The indicated, annual growth rates are averaged across the years 2010-2018. Note that the energy term by itself is not part of the decomposition, but is depicted here for comparison with the Kaya factors. This figure is for fossil fuel CO_2 emissions only, in order to ensure compatibility with underlying energy data.

Despite having lower per-capita emissions, developing countries remained major accelerators of global CO_2 emissions growth since 2010, mostly driven by increased consumption and production, in particular in East Asia (Jiborn et al. 2020). While energy intensity declined to a similar extent in OECD and non-OECD countries between 2009 and 2018, economic growth has been much stronger in non-OECD members. This led to an average growth rate of 3% of CO_2 emissions in these countries, whereas they decreased by 0.5% in OECD countries (UNEP 2019). The majority of developed economies reduced both production-based (territorial) and consumption-based emissions modestly (Jiborn et al. 2020). This was due to slower economic growth, increased energy efficiency (less energy per unit of GDP), fuel switching from coal to gas (mostly in North America, (Wang et al. 2020d)) and the use of less and cleaner energy from renewables in Europe (Peters et al. 2017c), (Karstensen et al. 2018), (Chang et al. 2019), (Wood et al. 2019).

Global economic growth as the main driver of GHG emissions plays out particularly strong in China and India (Liu et al. 2019a), (Ortega-Ruiz et al. 2020), (Wang et al. 2020e) (Yang et al. 2020a), (Zheng et al. 2020), although both countries show signs of relative decoupling because of structural changes (Marin and Mazzanti 2019). A change in China's production structure and consumption patterns (i.e. the type of goods and services consumed) have become the main moderating factors of emissions after 2010, while economic growth, consumption levels and investment remain the dominating factors driving up emissions (Mi et al. 2017b), (Wang and Jiang 2019), (Jiborn et al. 2020), (Zheng et al. 2020). In India low emission efficiency and expansion of production and trade caused growth of emissions (Wang and Zhou 2020).

There are pronounced differences both in recent changes in the absolute levels and drivers of GHG emissions when differentiating countries by income levels (Dong et al. 2019) or by regions (Chang et al. 2019). In high-income countries, significant improvements in energy intensity led to declining CO_2 emissions between 2010 and 2015, despite increasing income levels and populations (Dong et al. 2019). In upper middle-income and lower middle-income countries, rising income more than offset any energy structural or intensity gains, leading to increased emissions. And CO_2 emissions increased the most in low-income countries, by 46%, due to significant increases in carbon intensities, income levels and populations (Dong et al. 2019). Overall, both decoupling emissions from economic development as well as reducing over-consumption of wealthy populations (Wiedmann et al. 2020b) are important mitigation strategies going forward.

2.4.2 Sectoral drivers

GHG emissions continued to rise since 2010 across all sectors and subsectors; most rapidly in electricity production, industry and transport. Decarbonisation gains from improvements in energy efficiency across different sectors and worldwide have been largely wiped out by increases in demand for goods and services. Prevailing consumption patterns have also tended to aggravate energy use and emissions, with the long-term trend led by developed regions. Decarbonisation trends in some developed regions are limited in size and geographical scope and globally there are enormous unexploited mitigation potentials from adopting best available technologies.

2.4.2.1 Energy Systems

Global energy system emissions growth has slowed down in recent years, yet the sector remains the single largest contributor to global GHG emissions in 2018 with 20.7 $GtCO_2eq$ (35%) (Lamb et al, forthcoming). Most of the 13.9 $GtCO_2eq$ from electricity and heat generation (24% of global GHG emissions in 2018) were due to energy use in industry and in buildings, making these two sectors also prominent targets for mitigation (Crippa et al. 2019b; Davis et al. 2018a).

At the global level, growth in CO_2 emissions from energy systems have closely tracked rising GDP per capita (Figure 2.21), affirming the substantial literature describing the mutual relationships between energy, electricity demand and economic growth (Khanna and Rao 2009; Stern 2011). This relationship has played out strongly in developing regions, particularly in Asia, where a massive scale up of energy supply has accompanied economic growth – with average annual increases of energy demand between 3.5% and 4.8% in the past decade. These drivers of electricity demand are covered in the industry and building sectors below. The key downward driver has been declining energy intensities in almost all regions, associated with ongoing improvements in generation and transmission efficiency. Carbon intensities of energy supply have had a neutral effect, remaining globally stable since the 1990s, albeit with regional variations.

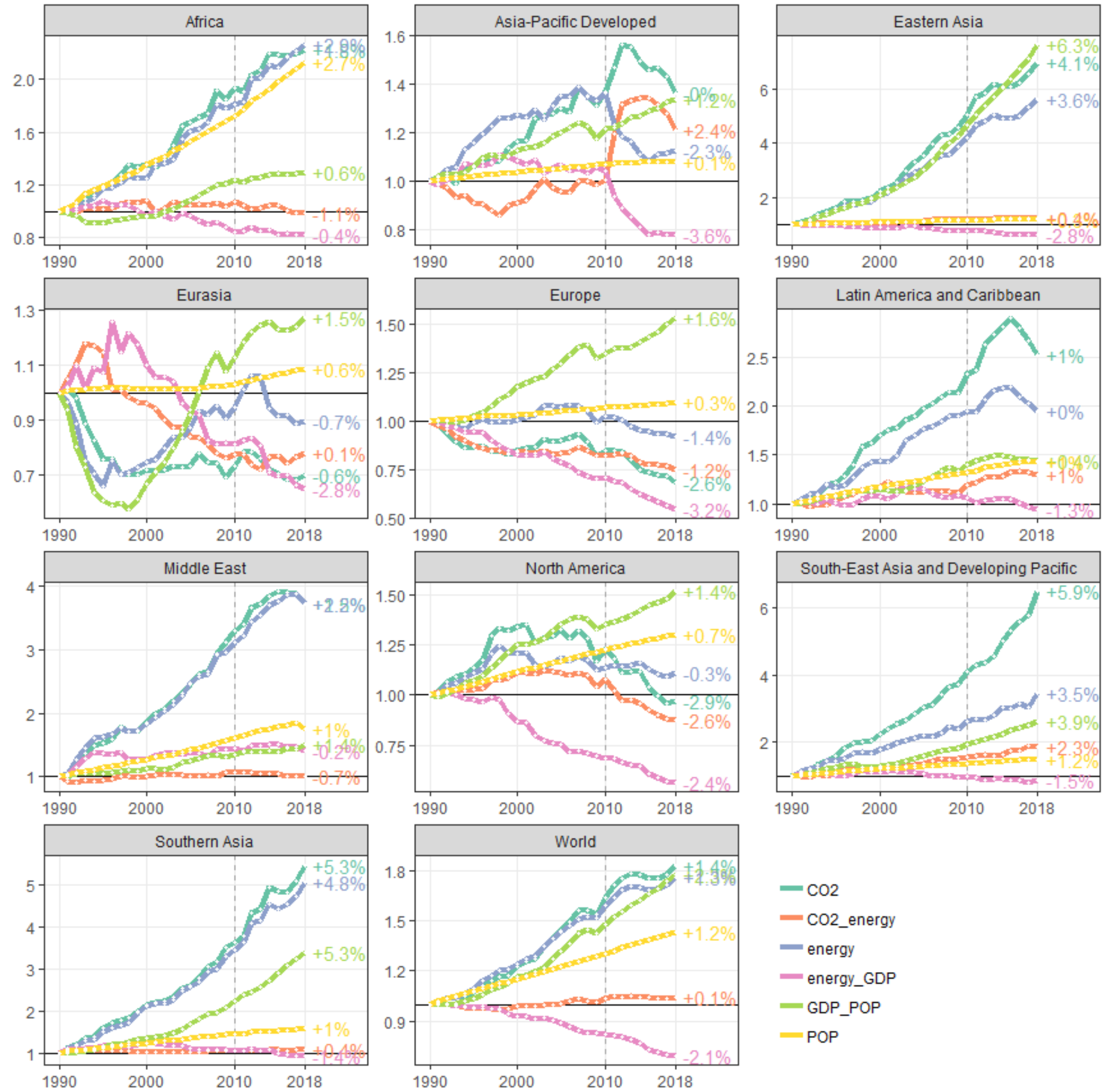


Figure 2.21: Kaya decomposition of CO_2 emissions drivers for the energy systems sector (Lamb et al, forthcoming). The indicated, annual growth rates are averaged across the years 2010-2018.

On the energy production side, almost all regions have seen steady decreases in energy intensities, at a global average of -2.1% per year since 2010, and at a similar steady pace in most individual regions albeit at varying rates (Figure 2.21). However, power generation efficiencies vary widely between (and also within) regions (Chapter 6).

Improvements in carbon intensity can be decomposed into two distinct drivers: fossil intensity (the emissions intensity of fossil fuels) and fossil share (the substitution of fossil fuels by renewables) (Peters et al. 2017b). In the United States fossil intensity improvements have had a larger overall effect since 2006, due to a widespread coal to gas switch driven by low gas prices following a shale gas boom, and federal tax credit incentives (Mohlin et al. 2019; Feng 2019; Peters et al. 2020, 2017b). Nonetheless, the overall share of fossil fuels in electricity production has also recently declined in North America (from 66% in 2010 to 59% in 2018) (Mohlin et al. 2019). Since 2007, Europe's carbon intensity improvements have been driven the steady expansion of renewables in the share of electricity generation (Le Quéré et al. 2019; Peters et al. 2017b; Rodrigues et al. 2020; Peters et al. 2020), with a fossil share decrease of 57% in 2010 to 47% in 2018. Some studies attribute these effects to climate policies, such as the carbon floor price in the UK, the EU emissions trading scheme, and generous renewable energy subsidies across the continent (Dyrstad et al. 2019; Wang et al. 2020c). Asia-Pacific Developed stands out in contrast to other developed regions, with a dramatic increase of regional carbon intensity and fossil share since 2010 (Figure 2.21). This was due to the ramp up of coal and gas capacity in Japan following the Fukushima nuclear accident (Kharecha and Sato 2019). Generally, the use of natural gas for electricity production is growing strongly in most countries and gas has contributed to the largest increase in global fossil CO_2 emissions in recent years (Jackson et al. 2019; Peters et al. 2020). Furthermore, gas brings the risk of increased CH_4 emissions from fugitive sources, as well as large cumulative emissions over the lifetime of new gas power plants that may erase early carbon intensity reductions (Shearer et al. 2020).

Steady or increasing carbon intensities can be observed in most other regions, indicating further deepening of fossil fuel-based energy systems worldwide. A major driver of these trends is the global "renaissance of coal" that started in the 1990s, primarily driven by a huge increase of coal generation capacity in China (Steckel et al. 2015; Jiang and Guan 2016). The growth of coal emissions slowed after 2010, primarily due to a slowdown of economic growth and fewer coal capacity additions in China, and even declined between 2011 and 2018 (Friedlingstein et al. 2019a; Peters et al. 2020). Discussions of a global 'peak coal', however, may be premature, as further growth was observed in 2019 (Peters et al. 2020; Friedlingstein et al. 2019a). In addition, the coal renaissance has not been limited to China alone, with large ongoing and planned capacity increases in India, Turkey, Indonesia, Vietnam, South Africa and other countries (UNEP 2017; Jan Christoph Steckel; Jérôme Hilaire; Michael Jakob; Ottmar; Edenhofer et al. 2018a).

Recent studies show that incumbent energy utilities have only in rare exceptions transitioned a sizable share of their portfolios towards renewable energy (Alova 2020; Green et al. 2020). It is rather new actors and interests driving these investments, often against considerable opposition and backlash from interest groups, particularly if implemented policies do succeed in scaling up renewable technologies (Moe 2015; Stokes and Breetz 2018). Fossil-based development pathways may also be chosen to meet the narrow goals of national and international interest groups, such as rent extraction or energy independence, and are shaped by issues such as lobbying, political ideology, and corruption (Lamb and Minx 2020; Jakob et al. 2020; Dorband et al. 2020; Roy and Schaffartzik 2021).

Overall, global energy system emissions growth has slowed down in recent years and the worldwide share of fossil fuels shrank slowly, down from 73% in 1990 to 68% in 2018. Despite this, global oil and gas use is still growing (Jackson et al. 2019). The focus of decarbonisation efforts in the energy systems sector needs to be on rapidly shifting to zero-carbon sources and actively phasing out all fossil fuels, rather than relying on the short-lived effects of fuel switching (Peters et al. 2020; Jackson et al. 2019). Energy demand reduction remains an important mitigation tool (Creutzig et al. 2016b), (Climate Action Tracker 2020), (ClimateWorks Australia 2020), (Falk et al. 2020).

2.4.2.2 Industry Sector

When indirect emissions from electricity and heat production are included, industry becomes the single highest emitting sector. Facilitated by globalisation, East Asia has been the main source and primary driver of global industry emissions growth since 1990, while industry emissions have declined in Europe and remained relatively steady in North America, Asia-Pacific Developed regions and Eurasia. In all other regions they are growing - most rapidly in Southern Asia (+5.2% annually for direct emissions since 2010, Figure 2.22), (Lamb et al, forthcoming).

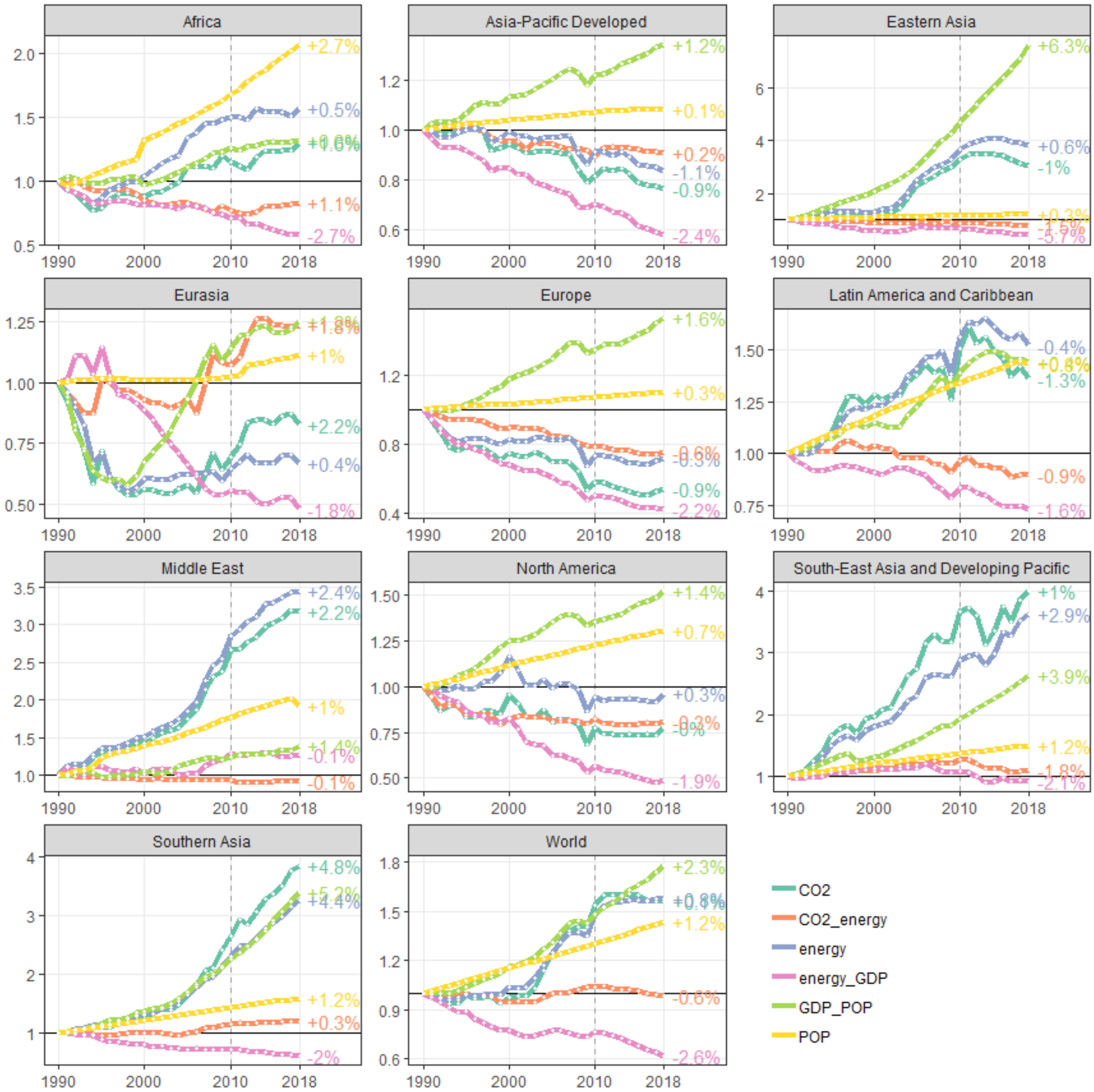


Figure 2.22: Kaya decomposition of direct CO_2 emissions drivers for the industry sector (Lamb et al, forthcoming). The indicated, annual growth rates are averaged across the years 2010-2018. This graph does not include indirect emissions.

The main global driver of industry emissions has been a massive rise in the demand for basic materials, construction minerals and manufactured products, which in turn is driven by rising affluence and consumption, as well as a rapid rise in urban populations and associated infrastructure development (Krausmann et al. 2018). Similar to the energy sector, the industry sector generates products that are indirectly used in final sectors - namely the materials that make up the manufactured capital of the physical economy, such as cement, chemicals, steel, aluminium, wood, paper, plastics, lubricants, fertilisers, and so on. These materials are used to build and maintain stocks of manufactured capital, including buildings, roads, vehicles, electronics, and machinery (Krausmann *et al* 2017).

There is strong evidence that the growth of concrete, steel and other construction material use is tightly coupled to economic growth, urbanisation, and associated infrastructure development (Cao et al. 2017; Pauliuk et al. 2013; Plank et al. 2018; Haberl et al. 2020; Krausmann et al. 2017). Per-capita stocks of cement and steel show a typical pattern of rapid take-off as countries urbanise and industrialise, before slowing down to low growth at high levels of GDP. Selected wealthy countries even seem to stabilise at high per-capita levels of stocks, although it is unclear if these stabilisations persist and if they result in significant absolute reductions of material use (Liu et al. 2013; Cao et al. 2017; Pauliuk et al. 2013; Krausmann et al. 2018). Hence, in countries that are recently industrialising and urbanising - i.e. Eastern, Southern and South-Eastern Asia - we observe a particularly strong increase of emissions from these subsectors and a strong overall relationship between GDP growth and industrial CO_2 emissions (Figure 2.22). Material consumption in wealthier countries has shown only limited rates of decrease (Wiedenhofer et al. 2015; Krausmann et al. 2017), even though their large existing and only slowly growing material stocks open up (as yet unexploited) opportunities for prolonging lifetimes and improving end of life recycling, so as to achieve absolute reductions in extraction activities (Zink and Geyer 2017; Krausmann et al. 2017).

As with the AFOLU sector, industrial emissions are strongly linked to international trade. Materials, especially metals, chemicals, plastics and wood products, are routinely transported between different stages of extraction, refining and production along global supply chains (Schaffartzik et al. 2016; Plank et al. 2018). Owing to a series of socio-economic conditions including low priced labour, state-led industrial policy and agglomeration effects, China currently dominates global industrial production, particularly in the manufacture of steel and other basic materials (Reck et al. 2010; Wang et al. 2019a). The global shift of energy-intensive industries away from historical centres in the United States and Europe to developing regions explains, to some extent, reductions of industry GHG emissions in the former – even though they continue to consume manufactured products via trade.

On the production side, improvements in the efficiency of material extraction, processing and manufacturing have reduced industrial energy use per unit of output (Wang et al. 2019a). These measures, alongside improved material substitution, light-weight designs, extended product and servicing lifetimes, improved service efficiency and increased reuse and recycling will enable substantial emissions reductions in the future (Hertwich et al. 2019). Switching to lower or zero carbon feedstocks and power further leads to industry sector decarbonisation. Indeed, the ratio of industrial energy use to GDP has steadily declined since 2010 in all regions (Figure 2.23). Absent these improvements in energy intensity, the growth of population and GDP per capita would have driven the industrial CO_2 emissions to rise by more than 100% by 2017 compared with 1990s, instead of 56%. Nonetheless, many studies point to deep regional differences in efficiency levels and large globally unexploited potentials to improve industrial energy efficiency by adopting best available technologies and practices for metal, cement and chemical production (Gutowski et al. 2013; Schulze et al. 2016; Talaei et al. 2018; Gonzalez Hernandez et al. 2018). Yet, decarbonising process emissions by technological improvements alone is unlikely to outweigh growing demand, calling for additional demand-side mitigation options to curb emissions from the industry sector (Creutzig et al. 2016).

Overall, demand for services driven by global affluence and population growth have led to an escalation of material use and associated industry GHG emissions. The growing complexity of international supply chains and the fact that GHG emissions embodied in building materials, infrastructure, machinery and transport equipment already exceed 50% of their present carbon footprint (Chen et al. 2018), makes governance of mitigation solutions difficult and requires multi-sector and integrated policies. Historically, energy efficiency provided the largest mitigation wedge, but still failed to prevent GHG emissions from increasing. Furthermore, efficiency potentials will decrease in the coming decades as technological options are exhausted. This puts increasing focus on historically weak drivers of decarbonisation, such as demand management in end-use sectors (i.e. more efficient delivery of services), material efficiency (product light-weighting, longer lifetimes, circular use of secondary materials), fuel switching and electrification, and the decarbonisation of power and feedstocks (Creutzig et al. 2016b), (Climate Action Tracker 2020), (ClimateWorks Australia 2020), (Falk et al. 2020), (IRP 2020), (Pauliuk et al. 2020)

2.4.2.3 Buildings Sector

Global GHG emissions from the buildings sector reached 9.9 $GtCO_2eq$ in 2018, or 17% of global emissions) (Lamb et al, forthcoming). The majority of these total emissions, 66% (6.5 $GtCO_2eq$) were upstream emissions from power generation and commercial heat. The remaining 34% (3.4 $GtCO_2eq$) of emissions were directly produced in buildings, for instance by gas and coal boilers, and cooking and lighting devices that burn kerosene, biomass and other fuels. Residential buildings accounted for the majority of this sector's emissions (64%, 6.4 $GtCO_2eq$, including both direct and indirect emissions), followed by non-residential buildings (35%, 3.5 $GtCO_2eq$).

Further emissions components are associated with this sector under alternative accounting schemes. The embodied greenhouse gas emissions associated with building materials and components, as well as the construction, assembly and maintenance of buildings, make up an estimated 11% of global energy and process-related CO_2 emissions (Ürge-Vorsatz et al. 2020). Adding these to the building sector would further increase emissions by approximately 2.2 $GtCO_2eq$ in 2018 (IEA 2019b).

Buildings sector CO_2 emissions increased 0.8% per year between 2010 and 2018 (Figure 2.23), growing the most in absolute terms in East and South Asia, whereas they declined the most in Europe and North America, mostly due to fuel switching and the expansion of renewables in the energy sector.

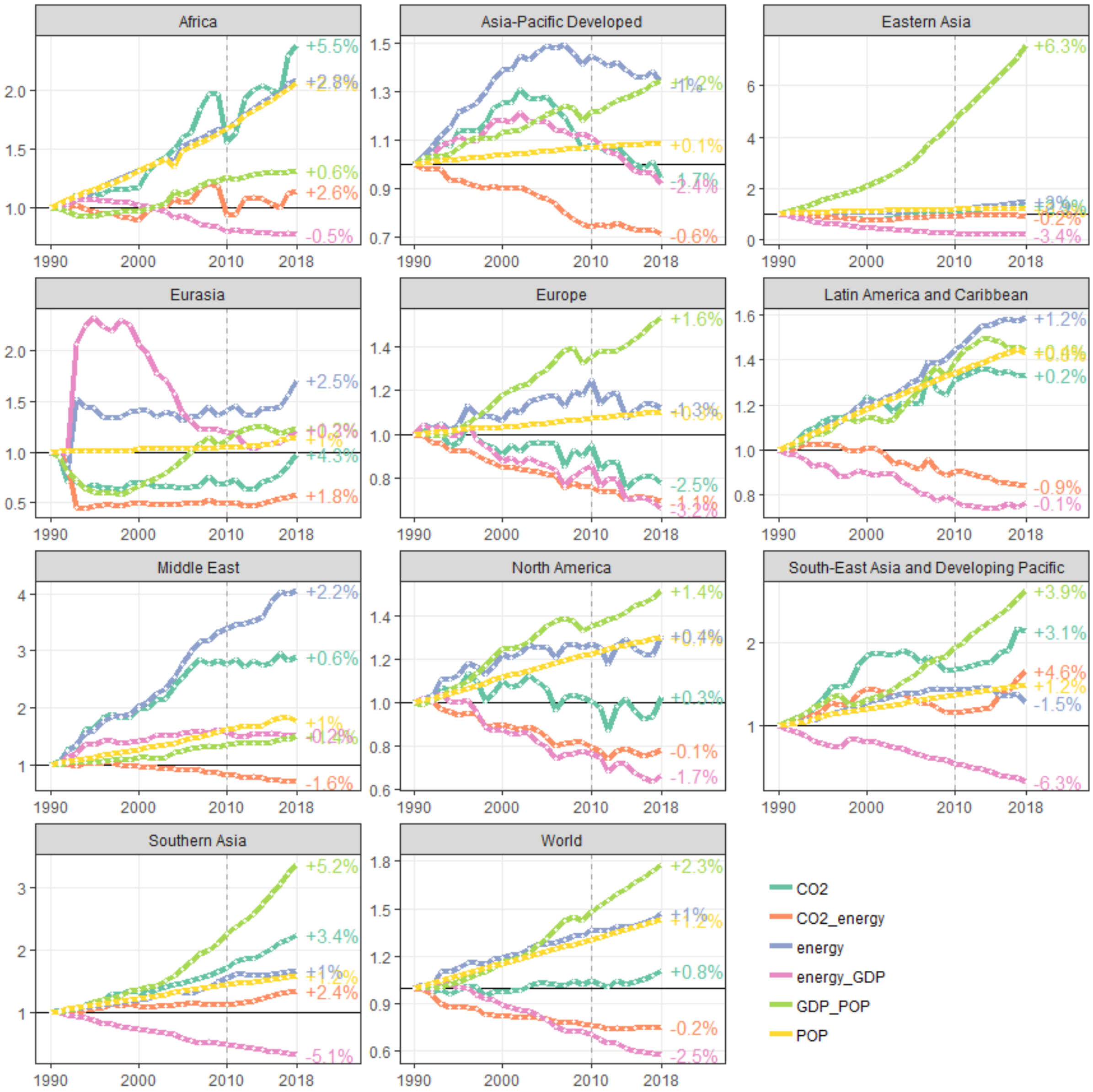


Figure 2.23: Kaya decomposition of CO_2 emissions drivers for the buildings sector (Lamb et al, forthcoming). The indicated, annual growth rates are averaged across the years 2010-2018. This graph does not include indirect emissions.

As countries increase in wealth, developers tend to construct larger properties and more floor space is required to service growing demand in the retail, office and hotel sectors (Deetman et al. 2020; Daioglou et al. 2012). At the same time, patterns of urbanisation and sprawl further shape the density and overall scale of a country's building stock (Chapter 8 of this report). Beyond population and wealth, demographic and social factors drive a cross-national trend of increasing floor space per capita. As populations age and decrease in fertility, and as individuals seek greater privacy and autonomy, households decline in size (Ellsworth-Krebs 2020). These factors lead to increased floor space per capita, even as populations stabilise. And increasing floor space per capita is a key driver for building sector emissions, because building characteristics such as size and type, rather than occupant behaviour, tend to explain the majority of energy use within dwellings (Guerra Santin et al. 2009; Huebner and Shipworth 2017), (Ürge-Vorsatz et al. 2015) (Chapter 9 of this report).

Energy activity levels further drive regional differences. In Eurasia, Europe and North America, thermal demands for space heating dominate building energy use, at 66%, 62% and 48% of residential energy demand, respectively (IEA 2019b). In contrast, cooking has a much higher share of building energy use in regions of the Global South, including China (Serrano et al. 2017; Cao et al. 2016). And despite temperatures being on average warmer in the Global South, electricity use for cooling is a more prominent factor in the Global North (Waite et al. 2017). This situation is changing, however, as rapid income growth and demographic changes in the global South enable households to heat and cool their homes (Ürge-Vorsatz et al. 2020, 2015).

Steady improvements in building energy intensities across regions can be attributed to policies and baseline improvements in building fabrics, appliance efficiencies, and fuel shifts. Many countries have adopted a mix of relevant policies, such as energy labelling, building energy codes and mandatory energy performance requirements (Nejat et al. 2015; Nie and Kemp 2014). Efforts towards buildings refurbishments and retrofits have also been pursued in several nations, especially for historical buildings in Europe, but evidence suggests that the recent rates of retrofits have not made a significant dent on emissions (Kerr and Winskel 2020; Corrado and Ballarini 2016). Green building retrofit policies in China too have been relatively ineffective to date (Liu et al. 2020b,a). Still, one major global factor driving down energy intensities has been the global transition from inefficient coal and biomass use in buildings for heating and cooking, towards natural gas and electricity, in part led by concerted policy action in Asian countries (Kerimray et al. 2017; Thoday et al. 2018; Ürge-Vorsatz et al. 2015).

Overall, emissions from the building sector are expected to continue rising, especially in much of the Global South as housing gaps are filled and demand for floor area increases. As developing countries construct new buildings, there is sizable potential to reduce and use less carbon-intensive building materials and adopt building designs and standards that lower life cycle buildings energy use and allow for passive comfort. A significant shift from the use of solid heating and cooking fuels to gas and electricity in recent years is a trend that will continue and help reduce emissions. However, increasing appliance penetration in regions just gaining access to electricity will increase electricity-related emissions from the building sector, unless accompanied by improved standards, labelling, and the decarbonisation of the electricity sector. Within the Global North, significant untapped potential for increasing heating, building fabric and material efficiency exists, as do behavioural shifts towards low-carbon lifestyles (Creutzig et al. 2016b). Further promising mitigation options are low-carbon building materials and construction and maximising the potential for buildings to produce electricity onsite (Climate Action Tracker 2020), (ClimateWorks Australia 2020), (Falk et al. 2020), (Pauliuk et al. 2020), (Ürge-Vorsatz et al. 2020).

2.4.2.4 Transport Sector

Global transport GHG emissions reached 8.5 $GtCO_2eq$ in 2018 and accounted for 14% of all direct and indirect emissions (Lamb et al, forthcoming). Road transport passenger and freight emissions represent by far the largest component and source of this growth (6.2 $GtCO_2eq$, 73% of total emissions), followed by international shipping (0.7 $GtCO_2eq$, 8%) and international aviation (0.6 $GtCO_2eq$, 7%). National plus international shipping and aviation emissions together account for 1.8 $GtCO_2eq$ or 21% of the sector total.

Since 1990, global transport emissions have grown at a constant rate of about 2% per year (Figure 2.24). The road subsector accounted for most growth since 2010 (+0.9 $GtCO_2eq$, at 1.9% per year), but domestic and international aviation were the fastest growing subsectors. North America, Europe and Eastern Asia stand out as the main regional contributors to global transport emissions and together account for 60% of the total.

The proportion of total final energy used in transport (28%) and its fast expansion over time weighs heavily on climate mitigation efforts as 92% of transport energy comes from oil based-fuels (IEA 2020). These trends situate transport as one of the most challenging sectors for climate change mitigation - even wealthier countries have so far been unable to realise significant emissions reductions in the sector.

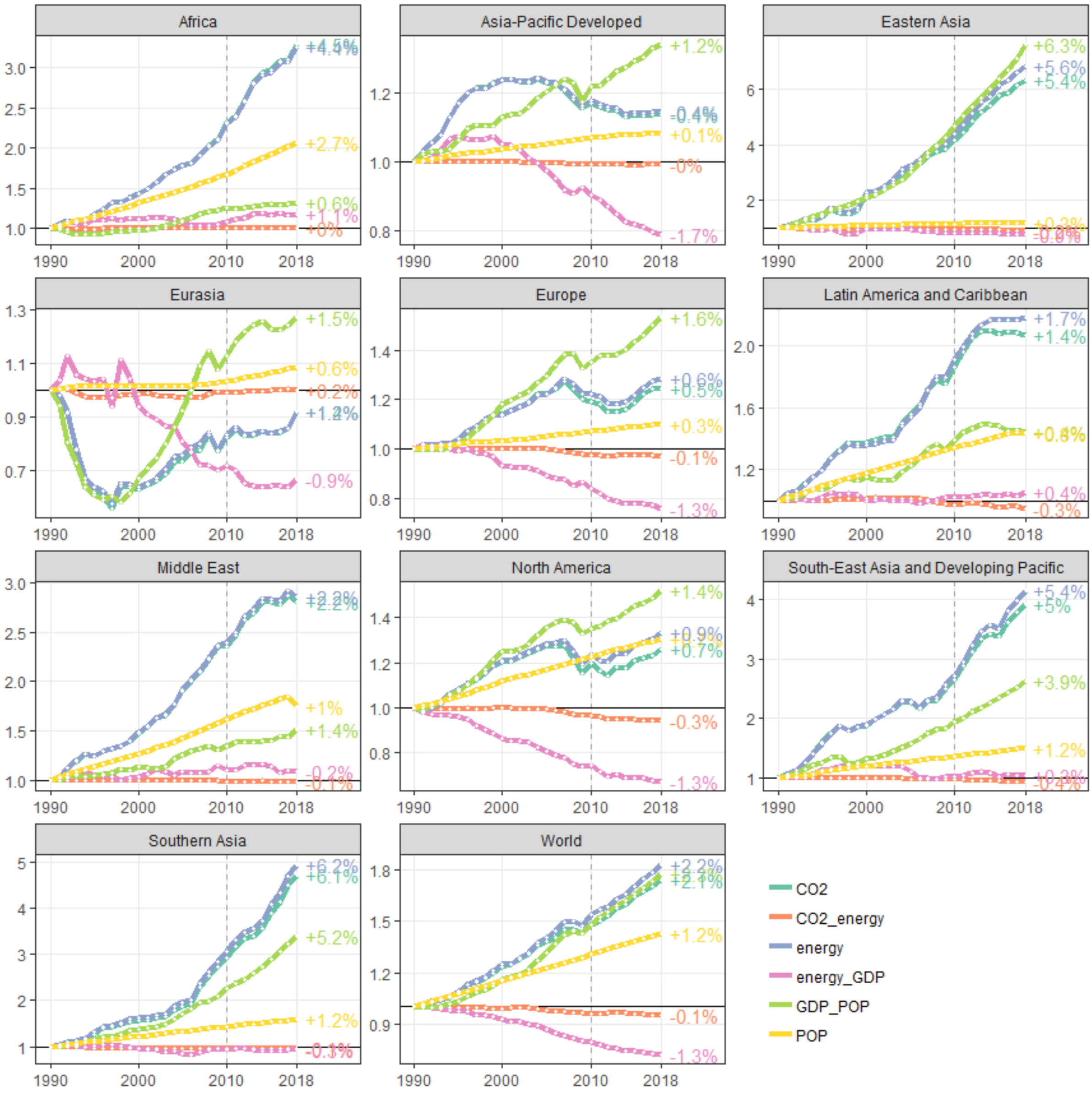


Figure 2.24: Kaya decomposition of CO_2 emissions drivers for the transport sector (Lamb et al, forthcoming). The indicated, annual growth rates are averaged across the years 2010-2018.

More so than any other sector, transport energy use has closely tracked GDP per capita growth (Figure 2.24). Developments since 1990 continue a historical trend of increasing travel distances and a shift from low- to high-speed transport modes that goes along with GDP growth (Schäfer et al. 2009; Gota et al. 2019). Only modest improvements in energy efficiency have been realised, averaging 1.3% per year globally, while carbon intensities have remained stable (Figure 2.24). Overall, global increases in passenger and freight travel activity levels have outpaced energy efficiency and fuel economy improvements, continuing a long-term trend for the transport sector (Grübler 2015; Gucwa and Schäfer 2013; McKinnon 2016).

While global passenger activity has expanded in all world regions, great disparities exist between low and high income regions, and within countries between urban and rural areas (ITF 2019). While private car use is dominant in OECD countries (EC 2019), the growth of passenger-km has considerably slowed there, down to an increase of just 1% between 2000 and 2017 (SLoCaT 2018) (Chapter 10 of this report). Meanwhile, emerging countries in the global South are becoming more car dependent, with rapidly growing motorisation and urban sprawl, and the emergence of local automotive production, while public transport struggles to provide adequate service (Dargay et al. 2007; Hansen and Nielsen 2017; Pojani and Stead 2017). Between 2000 and 2017 global passenger travel increased in non-OECD countries by 169%, starting from a low baseline (SLoCaT 2018).

Freight travel activity grew across the globe by 68% in the last two decades driven by global GDP increases, together with the proliferation of online commerce and rapid (i.e. same-day and next-day) delivery (SLoCaT 2018). Growth has been particularly rapid in heavy-duty road freight transport.

The transport sector global energy intensity dropped by an average of 1.3% per year between 2010 and 2018, primarily driven by wealthier regions, but was relatively level or increasing in all other regions (Figure 2.24). Despite some policy achievements (Chapter 6), energy use in the global transport system remains to the present deeply rooted in fossil fuels (IEA 2019c; Figueroa et al. 2014). The carbon intensity of the transport sector has therefore remained unchanged between 2010 and 2018 in all world regions (Figure 2.24). In part this is due to the increasing adoption of larger, heavier combustion-based vehicles in some regions, which have tended to far outpace electric and hybrid vehicle sales (Chapter 10 of this report). Yet, stringent material efficiency and light-weight design of passenger vehicles alone could cut cumulative global GHG emissions until 2060 by 16-39 $GtCO_2eq$ (Pauliuk et al. 2020).

While accounting for a small share of total GHG emissions, national and international aviation and shipping play a fast-growing role, with annual growth rates of +4.2% and +3.1% respectively between 1990 and 2018. Energy efficiency improvements in aviation were considerably larger than in road transport, but were outpaced by even larger increases in activity levels (Lee et al. 2021; SLoCaT 2018) (Chapter 6 of this report).

Overall, transport trends reveal a steady increase of emissions, overwhelmingly driven by growing motorisation and road transport activity. This global trend is opposite to what is needed and poses a significant mitigation challenge going forward. Despite electrified motorisation becoming increasingly popular (IEA 2019d) (Taiebat and Xu 2019) (Chapter 10 of this report), its impact has been hardly visible in the period up to 2018, and it is in danger of being offset by growing levels of travel activity and countervailing trends such as increasing vehicle size and weight. This suggests a key role for more stringent policies, as well as demand management policies to complement technological innovation, including remote working and meetings, mass transit and active transport (walking and cycling) (Creutzig et al. 2018; Milovanoff et al. 2020), (Creutzig et al. 2016b), (Climate Action Tracker 2020), (ClimateWorks Australia 2020), (Falk et al. 2020). Demand management is even more crucial for subsectors like aviation, where demand is on a rapid upward trend and technological options for decarbonisation are currently very limited.

2.4.2.5 AFOLU Sector

GHG emissions from agriculture, forestry and land use continued to increase by 1% per year on average since 2010 and reached 12.6 $GtCO_2eq$ globally in 2018 (Figure 2.25). Overall, the AFOLU sector accounts for almost one quarter (24%) of total global GHG emissions, and in several regions - Africa, Latin America and South-East Asia - it is the single largest emitting sector. CO_2 emissions from land-use change and CH_4 emissions from enteric fermentation together account for almost 70% of sector-wide greenhouse gases (Lamb et al, forthcoming).

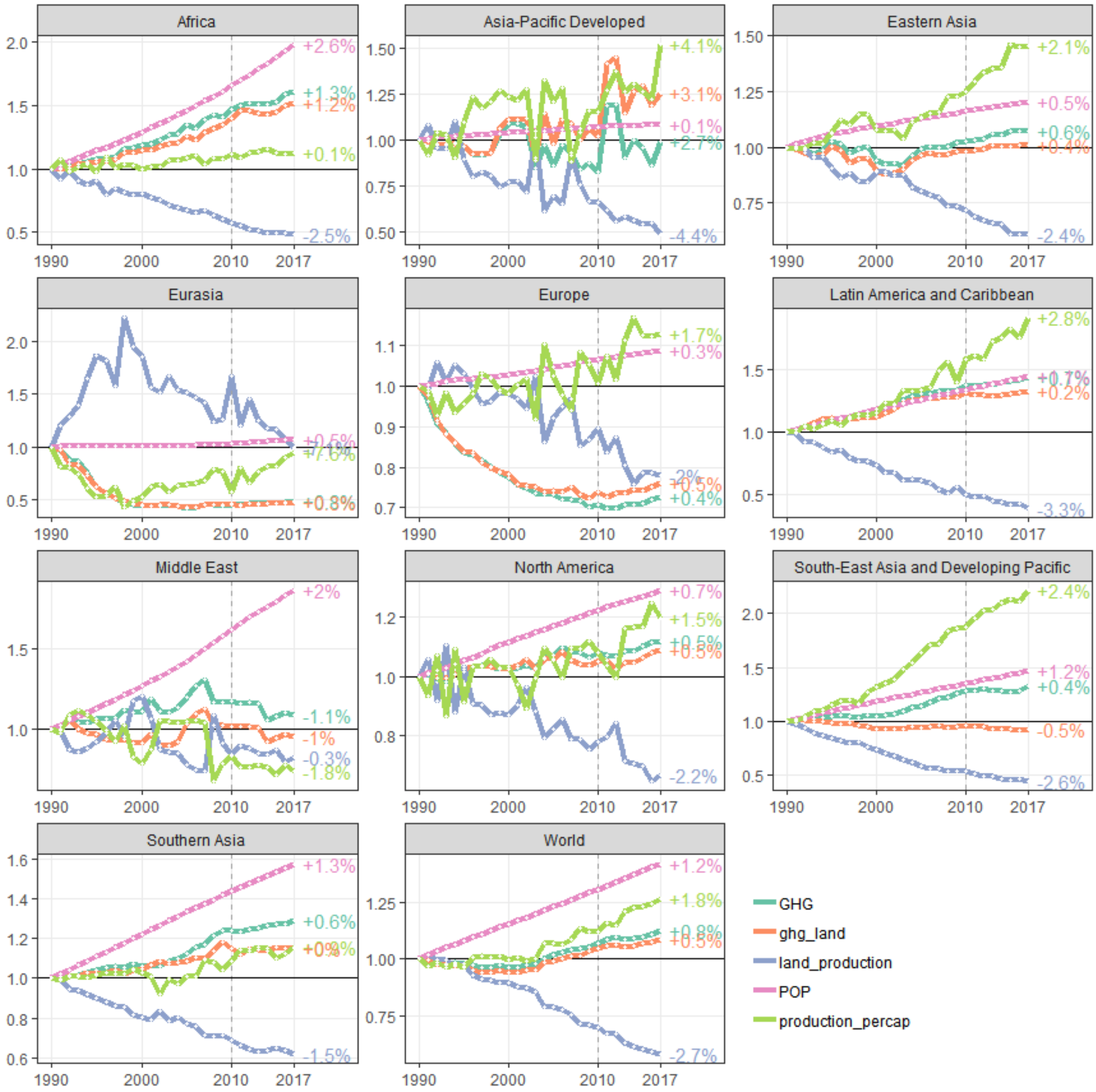


Figure 2.25: Kaya decomposition of GHG emissions drivers for the AFOLU sector (Lamb et al, forthcoming). The indicated, annual growth rates are averaged across the years 2010-2018.

Unlike all other sectors, AFOLU emissions are typically higher in developing compared to developed regions. In Africa, Latin America and South East Asia, CO_2 emissions associated with land-use change and management predominate, dwarfing other AFOLU and non-AFOLU sources, and making AFOLU the single largest sector at more than 50% of emissions in these regions. Land-use and management emissions here is associated with the expansion of agriculture into carbon-dense tropical forest areas, where vast quantities of CO_2 emissions result from the removal and burning of biomass and draining of carbon rich soils (IPCC 2018; Pearson et al. 2017; Hong et al. 2021). Livestock rearing takes place on vast tracts of pasture land worldwide, contributing to large quantities of CH_4 emissions from enteric fermentation in Latin America (0.9 Gt CO_2eq in 2018), Southern Asia (0.7 GtCO_2eq) and Africa (0.6 GtCO_2eq), while also playing a sizable role in the total AFOLU emissions of most other regions.

Trends in AFOLU emissions from 2010-2017 have been driven by increases in population, in particular in Africa, the Middle East, Southern Asia and South East Asia and Developing Pacific, increases in agricultural production per capita in all regions but the Middle East, and increases in emissions per unit of land area. The main downward driver was reductions in the amount of land required for agricultural and forestry production in all regions (-2.7%/yr globally), reflecting agricultural intensification and technological progress (Figure 2.25). Overall, AFOLU emissions are not convincingly decreasing in any region.

The AFOLU sector and its emissions impacts are closely tied to global supply chains with countries in Latin America and South-East Asia using large portions of their land for agricultural and forestry products exported to other countries (Chapter 7 of this report). The strong increases in production per capita and associated GHG emissions seen in these regions are at least partly attributable to growing exports and not national dietary changes. At the same time, efforts to promote environmental sustainability in regions like the EU and the US (but also fast-growing emerging economies such as China) can take place at the cost of increasing land displacement elsewhere to meet their own demand (Meyfroidt et al. 2010; Yu et al. 2013), Creutzig et al. (2019).

Global diets are a key driver of production per capita, and thus land pressure and AFOLU emissions (Chapter 7 of this report). As per-capita incomes rise and populations urbanise, traditional diets that emphasise starchy foods, legumes and vegetables transition towards energy-intensive products such as refined sugars and fats, oils and meat (Tilman and Clark 2014). At a certain point in national development, diets thus override population growth as the main driver of AFOLU emissions (Kastner et al. 2012). Over the last few decades, low- and middle-income countries such as India, Brazil, Egypt, Mexico and South Africa have experienced such a rapid dietary "westernisation" (Popkin 2015; Pathak et al. 2010; De Carvalho et al. 2013; Vermeulen et al. 2012). Another driver of higher food requirements per capita is food waste, the amounts of which increased more or less continuously since the 1960s in all regions but Europe (Porter and Reay 2016; IPCC 2018).

Due to its significance, the Paris Agreement cannot be reached without sustained mitigation in the AFOLU sector. The increasing emissions trends in tropical regions, particularly in Latin America and Southeast Asia, and clearly linked to global supply chains, do not appear to be stabilising, underlining the urgency of interventions at all scales. Per-capita emissions have also not fallen below 0.5 tCO_2eq in any region (Hong et al. 2021), suggesting a current frontier of mitigation efforts. The main mitigation options include in the sector include plant-based diets, reduced food loss and waste, enteric fermentation mitigation, grazing and pasture management, sustainable agricultural practices (incl. improved rice cultivation), fertiliser management, on-farm energy efficiency and renewables as well as nature-based solutions and sinks, such as forest protection, peatland protection and restoration and improved forest management (ClimateWorks Australia 2020), (Falk et al. 2020). If there is a residual of AFOLU emissions that cannot be eliminated, carbon dioxide removal methods such as re/afforestation and biomass plantations with carbon capture and storage would be required to meet stringent climate targets, further putting pressure on global land resources (IPCC 2018).

2.4.3 Poverty and inequality as drivers of GHG emissions

Increasing economic inequality globally has given rise to concern that unequal societies may be more likely to pollute and degrade their environments. The nature of this relationship has important implications for the design of income redistribution policies in efforts to reduce inequalities. The relationship between income and environmental intensity of consumption differs between rich and poor and depends on the level of income (see also Section 2.3 on decoupling). This implies that income inequality and carbon intensity of consumption also differs for different sets of countries and individuals (Baležentis et al. 2020). Reduced income inequality between nations can reduce emissions intensity of global income growth, if energy intensity reductions from income growth in some nations offset increases in energy and emissions from higher growth in other nations (Rao and Min 2018). Increasing income and expenditure inequality between individuals can translate into larger energy and emissions inequality if higher incomes are spent on more energy-intensive consumption and affluent lifestyles (Oswald et al. 2020; Wiedmann et al. 2020b).

Several studies suggest that more equitable distributions of income can improve environmental quality, but the nature of this relationship can vary by level of income and development (Knight et al. 2017; Chen et al. 2020; Hailemariam et al. 2020; Huang and Duan 2020; Uddin et al. 2020; Rojas-Vallejos and Lastuka 2020; Liobikienė and Rimkuvienė 2020). For low and middle-income economies, higher income inequality is shown to be associated with lower carbon emissions, while in upper middle-income and high-income economies, higher income inequality can increase per-capita emissions (Grunewald et al. 2017; Jorgenson et al. 2016). There is also evidence to suggest that more equal societies are more likely to place a higher value on environmental public goods (Baumgärtner et al. 2017; Drupp et al. 2018). Additional research shows that reducing top income inequality in OECD countries can reduce carbon emissions and improve environmental quality (Hailemariam et al. 2019) and that the effect of wealth inequality, measured as the wealth share of the top decile, on per-capita emissions in high-income countries is positive (Knight et al. 2017). Evidence from 40 low-income sub-Saharan African countries also suggests that a rise in income inequality contributed to increasing CO_2 emissions between 2010 and 2016, controlling for other important drivers (Baloch et al. 2020).

Changing income distributions at the lower end, i.e. among the poor, are of particular interest, as development efforts are focused on alleviating poverty. Eradicating extreme poverty (Hubacek et al. 2017b; Chakravarty and Tavoni 2013; Malerba 2020) and providing universal access to modern energy services to poor populations (Pachauri et al. 2018, 2013; Singh et al. 2017; Pachauri 2014) have been shown to have a negligible impact on carbon emissions. Further efforts to bring people out of poverty by providing them decent living standards and high human development, however, may require increased mitigation efforts, though in the case of some nations the additional energy demands are within bounds of projections under climate stabilisation scenarios (Rao et al. 2019; Hubacek et al. 2017a,b; Pascale et al. 2020). Recent research suggests that extending decent living standards universally can be achieved with 13-40GJ/capita, much less than the current world average energy consumption (Millward-Hopkins et al. 2020). The emissions consequences of poverty alleviation and decent living depend also on whether improvements in wellbeing occur via energy- and carbon-intensive industrialisation or low-carbon development (Semieniuk and Yakovenko 2020; Fu et al. 2021; Huang and Tian 2021)

Studies for individual nations are less consistent in their findings on the relationship between inequality and emissions and understanding of causal mechanisms by which inequality may affect emissions remains limited. In addition, exploring the effects of social cohesion on environmental stewardship are still largely unexplored (Cushing et al. 2015) (see also Section 2.6). Research on these relationships is hindered by the fact that longitudinal effects are hard to estimate since inequality changes only slowly over time, and the fact that non-linear effects seem to matter for these relationships. Further analysis of causal pathways can provide important insights for how public policy might address potential trade-offs or synergies through redistributive measures, especially in developing countries and among the poor.

2.4.4 Rapid urbanisation as a driver of GHG emissions

Economic growth and urbanisation go hand in hand and are both influencing GHG emissions. However, the exact role of urban development in driving emissions is multi-facetted and heterogeneous, depending on development status and other regional factors (Jorgenson et al. 2014), (Lamb et al. 2014), (Liddle and Lung 2014), (Creutzig et al. 2015a), (Pincetl 2017), (Azizalrahman and Hasyimi 2019), (Muñoz et al. 2020). This calls for a differentiated assessment. This section assesses the process of rapid urban growth in developing countries and how production- and consumption-based emissions (PBE/CBE) change over time when cities *grow rapidly*, i.e. when urban populations and infrastructure expand significantly. In contrast, Section 2.6 deals with the carbon footprint of urban lifestyles and the difference in emissions profiles between already urbanised and less urbanised areas.

Urban development is most significant and rapid in developing and transition countries, accompanied by a substantial migration of rural populations to urban areas (Apergis and Li 2016), (Azizalrahman and Hasyimi 2019), (Wang et al. 2019e). If the trend of developing countries following infrastructure stock patterns in industrialised nations continues until 2050, this could cause approximately 350 $GtCO_2$ from the production of materials, which is about 35-60% of the remaining carbon budget available for a 2°C global warming target (Müller et al. 2013). In many low and middle-income countries across the world, the process of urban expansion leads to higher per-capita CBE (Jorgenson et al. 2014), (Yao et al. 2015), (Zhang et al. 2016), (Moran et al. 2018), (Muñoz et al. 2020). The high disparity between rural and urban personal carbon footprints in these countries (Wiedenhofer et al. 2017) (see Section 2.6) means that migration to urban areas increases overall emissions as levels of income and expenditure rise, leading to further economic growth and infrastructure development in urban areas (Müller et al. 2013), (Li et al. 2015), (Wang and Yang 2016), (Zhang et al. 2016), (Wiedenhofer et al. 2017), (Cetin and Bakirtas 2019), (Fan et al. 2019b), (Li and Zhou 2019), (Xia et al. 2019), (Sarkodie et al. 2020).

Over the last two to three decades to around the early 2010s, China experienced very rapid urbanisation leading to significant increases in urban affluence and associated per-capita CO_2 emissions, both for direct emissions from private fossil fuel use (Bai et al. 2019) as well as for indirect emissions embodied in purchased goods and services (Zhang et al. 2017), (Shao et al. 2019). At the same time there were significant decreases in CO_2 emissions intensities per $ in China (Apergis and Li 2016), (Ma et al. 2016), (Wang and Yang 2016), (Chen and Chen 2017), (Hu et al. 2017), (Wei et al. 2017), (Dong et al. 2018), (Chen and Zhu 2019), (Fan et al. 2019a), (Fan et al. 2019b), resulting in a slowing of growth of urban emissions. For example Beijing's PBE grew slower between 2010 and 2015 than prior to 2010 (Liu et al. 2019b); its total CBE are thought to have peaked around 2010 (Chen and Chen 2017). Since 2010, changes in production or industrial structure has become a more important downward driver of cities' PBE and CBE of Chinese cities (Chen and Chen 2017), (Wang et al. 2019d).

For total PBE in general, urbanisation is thought to have a smaller effect than changes in population, affluence, energy and emissions intensities, which are all more influential (Lin et al. 2017). Specific emission drivers, however, depend on city- and place-specific circumstances such as income, household size, density or local climate (Baiocchi et al. 2015). Geographic factors, urban form and transport/fuel costs are dependent on each other and, together with economic activity, have been found to explain 37% of urban direct energy use and 88% of urban transport energy use in a global sample of 274 cities (Creutzig et al. 2015a). Mitigation measure therefore need to be specific to each type of human settlement and socio-demographic group (Baiocchi et al. 2015), (Muñiz and Dominguez 2020). During early phases of rapid urban development there are significant opportunities for mitigation by designing higher-density urban forms and by increasing fuel prices for individual transport, which have a particular strong influence on travel behaviour, choice of work place and car ownership (Creutzig et al. 2015a).

2.4.5 Trade as a driver of global GHG emissions

This section assesses how trade openness and liberalisation may have *changed* the *global* level GHG of emissions. It does not describe whether trade *has shifted* emissions between countries (transfer of embodied emissions) or has changed the level of emissions in individual countries (this is described in Section 2.3.). The effect of international emissions trading schemes, mechanisms and policies are described in Sections 2.8 and 14.4, respectively.

It has been stated that international trade has led to significant net growth of global CO_2 emissions. (Jiang and Guan 2017). This happens if countries with relatively less carbon-intensive production increasingly import from countries where production is more carbon intensive (Jiborn et al. 2018) (see

Section 2.3). However, the question whether international trade drives increases or decreases in global GHG emissions is difficult to answer since it does not only depend on the emissions intensity of traded products, but also on the synergistic influence of trade on economic growth, income, consumption patterns and the diffusion of low-carbon technology or practices. All of these in turn are drivers of GHG emissions and the counterfactual question to answer is (Jakob and Marschinski 2013): What would happen without trade? Trade also affects emissions through enhancing innovation and exchanging technologies between trading partners. These complex interactions are currently not fully understood (Cherniwchan et al. 2017). Consumption-based accounting (Section 2.3) alone is therefore not suited to assess whether or not trade is driving GHG emissions (Jakob and Marschinski 2013), (Kander et al. 2015).

Studies investigating global CO_2 emissions changes between 1995 and 2007/08 found that the contribution of trade was moderately (+18% (Hoekstra et al. 2016)) to very moderately positive (+6.7% (Arto and Dietzenbacher 2014)) whereas increases in overall (+172% (Hoekstra et al. 2016)) and per-capita consumption levels (+157% (Arto and Dietzenbacher 2014)) contributed much more strongly to the increase, while improved technology had a significant decreasing effect (-90% (Hoekstra et al. 2016), -94% (Arto and Dietzenbacher 2014)). (Lin et al. 2019) investigated different scenarios on trade restrictions and found that a scenario with significant trade barriers based on additional 25% of tariffs would reduce global CO_2 emissions by 6.3% and gross domestic product by 9.0%. On the other hand, free trade scenario would increase global export volume by 5.4% and global CO_2 emissions by 1.2% for the base year of 2014 because of enhanced global production, especially in developing regions with high emissions intensities (Lin et al. 2019). It seems, however, that increased global GHG emissions only occur when the free trade agreements are between developed and developing countries (Nemati et al. 2019), because emissions reductions for high income countries are counteracted with higher increases in low and middle income countries (Yao et al. 2019). There is no significant change if such agreements are reached within either only developed or only developing countries (Nemati et al. 2019).

In contrast, one study suggests that international trade avoided 15 Gt of CO_2 emissions globally between 1995 and 2009, when compared to a hypothetical situation without trade (López et al. 2018). (Zhu and Jiang 2019) found that the recent slowdown in globalisation from 2012 to 2016 did not lower but instead increased global CO_2 emissions by 202 Mt. This is because the consumption of domestic products increased in many countries, in particular in China and India, leading to increased domestic and therefore global CO_2 emissions. Partly, this is due to the fact that non-OECD countries have a higher emissions intensity than OECD economies. Scenario modelling of the US-China trade war in 2018-2019s showed an increases in global CO_2 emissions, despite a decrease in global economic output (Lu et al. 2020). This was because, as an indirect consequence of the trade war, some countries will increase emission, of which those from land-use changes in Brazil and Argentina far exceed the emission reductions due to reduced global production.

In summary, there is medium agreement but limited evidence that international trade is a moderate upward driver of global GHG emissions. Trade liberalisation tends to relocate production to countries where labour and resource costs are lowest, irrespective of the carbon intensity of production. If shifts in production are accompanied by large-scale transfers of and investment in low-carbon and renewable energy technologies in carbon-intensive countries, the effects of trade on emissions can be mitigated (Jiang and Green 2017), (Gozgor et al. 2020). While such investments and knowledge transfers need to come from net importing nations leading in low-carbon technology, net exporters can help by targeting carbon-intensive export industries with additional mitigation measures (Liu et al. 2015b), (Ren et al. 2014), (Ji et al. 2017). In general, policies focused at mitigating national, territorial emissions alone, without considering trade-embodied emissions, might miss out on important drivers and mitigation opportunities (Zhang et al. 2019), (Jiborn et al. 2018), (Meng et al. 2018b), (Wood et al. 2019b), (Jiang and Green 2017), (Zhong et al. 2018).

2.5 Technological change is key to reducing emissions

Technological change has reduced emissions over the long term and is central to efforts to achieving climate goals (*high confidence*). Technological change has accelerated since AR5 (*high confidence*); multiple low-carbon technologies are improving quickly, adoption has reached substantial shares, and small-scale technologies are particularly promising on both. These recent improvements have enabled faster adoption and continued progress can play a crucial role in accelerating the energy transition. However the historical pace of technological change is insufficient to catalyse a complete transition to a low-carbon energy system; technological change needs to accelerate (*high confidence*). Technological change for climate change mitigation involves improvement in and adoption of technologies, primarily those associated with energy production and use. This section thus assesses the role of technological change in driving emissions reductions and the factors that drive technological change, with an emphasis on the speed of transitions. Incentives and support for technological change affect technology outcomes (Wilson et al. 2020; Sivaram et al. 2018). Work since AR5 has focused on evaluating the effectiveness of policies, both those that accelerate technological change by enhancing knowledge—technology push—and those that increase market opportunities for successful technologies—demand pull (Nemet 2013), as well as the importance of tailoring support to country contexts (Rosenbloom et al. 2020; Barido et al. 2020), including the limits of policies to date that price carbon (Lilliestam et al. 2020). Section 2.8 and Chapter 13 describe how these polices affect emissions and Chapter 16 provides a more detailed assessment of the evolution and mitigation impacts of technology development, innovation and transfer.

2.5.1 Technological Change has reduced emissions

Technological change that facilitates efficient energy utilisation from production to its final conversion into end-use services is a critical driver to reducing carbon emissions. Previous IPCC assessments have acknowledged the role of technological change in the efforts for addressing climate change mitigation (IPCC 2007, 2014), focusing on what drives technological change, analysing the roles played by governments, and distinguishing technological push and demand-pull policy instruments types. AR5 considered whether technological change necessarily is a driver of mitigation or whether it also might contribute to emissions. The evidence shows that both are possible; technological changes can facilitate stringent mitigation, but it also can generate an unintended rebound effect (see Chapter 16) through which new services and cost-saving innovations promote more energy consumption increasing emissions and offsetting some of the progress gained in mitigation (IPCC 2014). The literature on technological change as a driver of mitigation has considerably expanded since AR5 and consequently AR6 includes an entire chapter on innovation, technology development, and transfer (Chapter 16). Here, the focus is on assessing the latest empirical data and the links to past and future emissions reductions, with cross references to Chapter 16 for more detail. A recurring consideration in this section is the extent to which aligned, credible, and durable policies can accelerate technological change factors to put emissions reductions on a trajectory compatible with reaching UNFCCC goals.

Technological change has facilitated the provision of more diverse and efficient energy services (heating, cooling, lighting, and mobility) while generating fewer emissions per unit of service. As seen in section 2.4, in Kaya identity terms (Lima et al. 2016) (see Glossary): population and economic growth are factors that have increased emissions, while technological change has reduced emissions (Peters et al. 2017b). As shown in Figure 2.26, the carbon intensity (CI) of energy supply (MT CO_2/EJ) has fallen by nearly one third over the past 100 years due in part to: the shift from carbon intensive fuels like coal to oil, gas, nuclear, and more recently renewables. Since AR5, there has been a modest but increasingly important process of decarbonisation of energy supply. These Kaya statistics show that while technological change can facilitate the transition to a low-carbon economy, **it** needs to proceed at a much faster pace than historical trends (Peters et al. 2017b). As Figure 2.26 shows, continuing a linear projection of the historical trend over the next three decades will not be sufficient to put us on track to a near zero-carbon energy system by mid-century. Climate stabilisation requires faster technological change in energy.

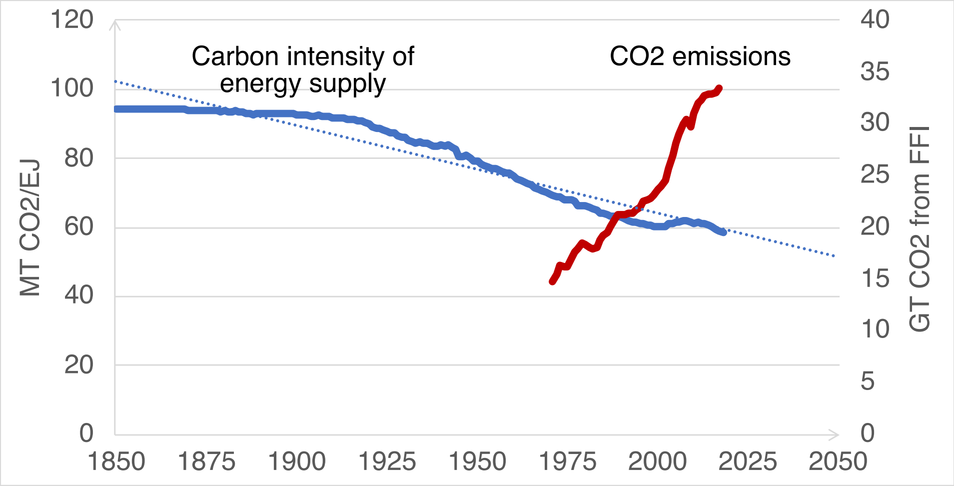


Figure 2.26 Change in carbon intensity of energy supply and CO_2 emissions from fuel and industry (FFI).

Multiple challenges exist in accelerating the past rate of technological change to be compatible with UNFCCC goals First, an array of physical assets in the energy system are long lived and thus involve substantial committed carbon (see section 2.7) (Knapp 1999; Cui et al. 2019). A process of "exnovation," accelerating the phase-out of incumbent technology through intentional policy (e.g. by pricing carbon), provides an avenue to address long lifetimes (Davidson 2019; Rosenbloom and Rinscheid 2020). Second, countries may not have the capacity to absorb the flows of ideas and research results from international knowledge spill-overs due to weak infrastructure, limited research capacity, lack of credit facilities (see Chapter 15, section 15.5), and other barriers to technology transfer (Adenle et al. 2015). In a developing country context, processes of innovation and diffusion need to include competence-building systems (Lema et al. 2015; Perrot and Sanni 2018; Stender et al. 2020). Third, public policy is central to stimulating technological change to reduce emissions; policy depends on creating credible expectations of future market opportunities (Alkemade and Suurs 2012), but the historical evidence shows that policies related to energy and climate over the long term have tended to change (Nemet et al. 2013; Taylor 2012; Koch et al. 2016). Bolstering the credibility and durability of policies related to low-carbon technology are crucial to accelerating technological change and inducing the private sector investment required (Helm et al. 2003; Habermacher et al. 2020). Robust policies and climate finance are especially important in the rapidly growing economies of Asia and Africa, which are on the brink of making major decisions about the type of infrastructure they build as they grow, develop, and industrialise (Nemet et al. 2017; Steckel et al. 2019). Overlooking this transition opportunity would be costly as it can risks locking in high-carbon infrastructure (see Chapter 12) which would jeopardise 2°C temperature targets.

2.5.2 A low-carbon energy transition needs to occur faster than previous transitions

An illuminating debate on the possibility of faster transitions has emerged since AR5—with diverging assumptions about future technological change at the core of the discourse (Bazilian et al. 2020)(Lu and Nemet 2021). Table 2.8 summarises these arguments. A net-zero energy system will require changes in energy technologies to catalyse an "energy transition," (Chapter 6) (Fouquet and Pearson 2012; Smil 2010). Drawing evidence from history, scholars through AR5 emphasised that higher initial prices, integration with supporting infrastructures, rent-seeking incumbents, and risk averse adopters all have made previous transitions slow (Grubler 1990; O'Neill et al. 2003; Araújo 2014; Kramer and Haigh

2009). The urgency of climate goals has raised questions as to whether the low-carbon transition can occur faster than previous transitions, which have taken 5-7 decades (Grubler 2012).

2.5.2.1 Energy transitions can occur faster than in the past

Recent studies have identified conditions and examples of fast energy transitions (Sovacool 2016; Bond et al. 2019; Reed et al. 2019). One describes five rapid national-scale transitions in end-use technologies that support this accelerated perspective including: lighting in Sweden, cook-stoves in China, liquefied petroleum gas stoves in Indonesia, ethanol vehicles in Brazil, and air conditioning in the United States (Sovacool 2016). Adoption of electric vehicles in Norway and China have also been rapid (Li et al. 2020; Rietmann and Lieven 2019). Fast transitions have also occurred in energy supply, including energy modernisation in Kuwait, natural gas in the Netherlands, nuclear electricity in France and Sweden, combined heat and power in Denmark, renewable energy in Uruguay, electric cars in Norway, and coal retirements in Ontario, Canada (Qvist and Brook 2015). Reasons that these exemplars could be applied more broadly in the future include: growing urgency on climate change, shifting motivation from price response to proactive resource scarcity, and an increase in the likelihood of technological breakthroughs (Sovacool 2016; Bazilian et al. 2020). The emergence of smaller unit scale, "granular" technologies also creates the potential for faster system change (Trancik 2006; Grubler et al. 2018; Wilson et al. 2020). Growth also impacts transitions, with one historical analysis showing that when the economy grows quickly, an energy transition is likely to be led by changes in demand, while when the economy is steady, the supply-side matters more (Fouquet 2016); both phenomena can be seen as the micro levels as well (Foell 2019). Prices of energy services and government actions that affect demand are critical to the speed and extent of energy transitions (Kramer and Haigh 2009). (Kern and Rogge 2016) point to the following reasons to expect a fast transition: intentional policy and alignment with goals; globalisation which diversifies sources and integrates supply chains; collective action, via the Paris Agreement; as well as bottom-up grassroots movements and private sector initiatives. Political support for change can also speed transitions (Stokes and Breetz 2018; Burke and Stephens 2017), as can the credibility of transition related targets (Li and Pye 2018; Rogge and Dütschke 2018).

The important role of leader countries is often missed when looking only at global aggregates (Meckling and Hughes 2018); leaders accumulate important knowledge, provide scaled market, and set positive examples for followers (Schwerhoff 2016; Buchholz et al. 2019). In recent years, the conception of where leadership, climate-relevant innovation, and technology transfer originate has shifted to now more meaningfully consider South-South and South-North forms of technology transfer, flows of capital, drivers for market access, origins of innovation, and other forms of cooperation (Urban 2018; Köhler et al. 2019). Recent evidence shows South-South trade is enabling clean technology (Gosens 2020). Leaders can initiate a process of "catalytic cooperation," in which they overcome collective action problems and stimulate rapid change (Hale 2018). Similarly, "sensitive intervention points,"—targeted support of social movements, technologies, or policies themselves—can lead to rapid and self-sustaining change (Farmer et al. 2019), such as support for photovoltaics in Germany in the 2000s and student climate activism in Europe in 2019. The focus on leadership, catalysts, and intervention points reflects a systemic view of transitions that emphasises interactions and interdependence (Geels 2018a; Meckling and Hughes 2018). Technological change has been at the core of transitions, but is best understood as part of system in which social aspects are crucial (Overland and Sovacool 2020; Cherp et al. 2018; Köhler et al. 2019). One additional difference is that the global energy system is now more diverse than in previous energy transitions (Figure 2.27). This staring point is distinct from previous transitions and provides the possibility of a faster low-carbon transition driven by multiple simultaneous transitions, for example in multiple low-carbon supply technologies, transportation, as well as end use.

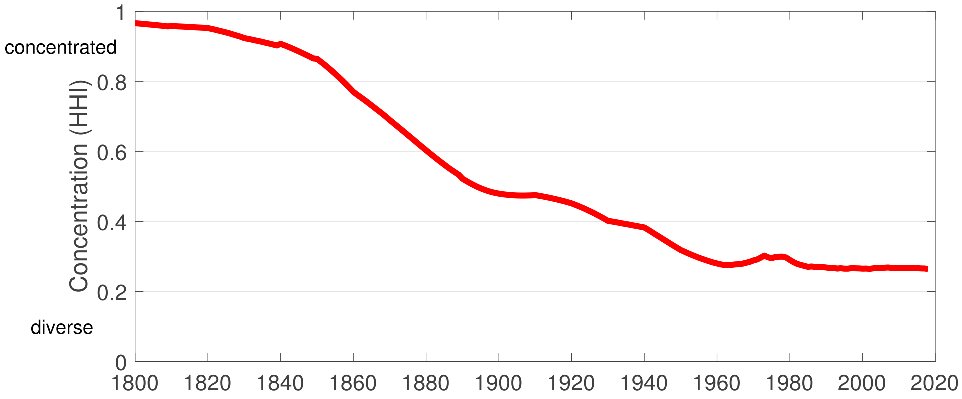


Figure 2.27 Diversification of the global energy system. Hirschman-Herfindahl index sums squares of the shares of each energy carrier (1=concentrated, 0=diverse). Diversity has been stable over past 50 years.

2.5.2.2 Reasons that transitions will occur at historical rates of change

Recent work has also reasserted previous claims that the speed of a low carbon transition will continue historical patterns. Broad transitions involve technological complexity, time-consuming technological development, risk averse adopters, high up-front costs, and low immediate individual adoption benefits, attributes which are not all present in the examples of rapid change described above (Grubler et al. 2016). Additional factors that slow transitions include: the need for the transition to occur globally, thus requiring nations with unequal economic resources and development circumstances to engage in near universal participation; slow progress in recent decades; intermittence of renewables and the time involved in building supporting infrastructure (Smil 2016); difficulty in decarbonising transportation and industry (Rissman et al. 2020); and material resource constraints (Davidsson et al. 2014).

Table 2.8 Reasons to expect a fast energy transition and reasons to expect a slow transition

	Fast transition	Slow transition
Evidentiary basis	**Tech. and country cases over 50 years**	**Historical global system over 200 years**
Systems	**Complementary technologies enable integration**	**Difficult integration with existing infrastructure**
Economics	**Falling costs of nascent technology**	**Mature incumbent technologies**
		Up-front costs and capital constraints
Technology	**Digitalisation and global supply chains**	**Long lifetimes of capital stock**
	More abundant innovation	**Difficult to decarbonise sectors**
	Granular technology	
Actors	**Proactive efforts for transition**	**Risk averse adopters**
	Bottom up public concern	**Attributes do not appeal to consumers**
	Mobilised low-C interest groups	**Rent-seeking by powerful incumbents**
Governance	**Leaders catalyse faster change**	**Collective action problems**

2.5.3 Improvements in technologies enable faster adoption

Since AR5, multiple low-carbon technologies have shown dramatic improvement, particularly solar PV, wind, and batteries. The observed pace of these changes and the likelihood of their continuation supports the arguments in the previous section that future energy transitions are likely to occur more quickly than in the past.

2.5.3.1 Technological change has produced dramatic cost reductions

A wide array of technologies shows long term improvements in performance, efficiency, and cost. Among the most notable are solar photovoltaics, wind power, and batteries. PV's dynamics are the most impressive, having fallen in cost by a factor of 10,000 from the first commercial application on a satellite in 1958 (Maycock and Wakefield 1975) to power purchase agreements signed in 2019 (IRENA 2020). Wind has been on a nearly as steep trajectory (Wiser and Bolinger 2019) as are lithium-ion battery packs for electric vehicles (Service 2019; Nykvist and Nilsson 2015). The future potential for PV and batteries seems especially promising given that neither industry has yet begun to adopt alternative materials with attractive properties as the cost reductions and performance improvements associated with the current generation of each technology continue (Kwade et al. 2018). For wind, future cost reductions are expected from continued up-scaling of turbines, which is enabled by the transition to offshore and its better wind resources. These cost reductions have made renewables competitive with fossil electricity in many places (IRENA 2020). In a developing country technology adoption context, the costs of financing are of crucial importance and can be much higher than in developed country contexts (Schmidt 2019; Creutzig et al. 2017). A key challenge is improving access to finance.

2.5.3.2 Technological change has accelerated since AR5.

In Figure 2.28 we see changes in the costs of 4 dynamic energy technologies. One can see rapid changes since AR5, cost data for which ended in 2012. Solar PV is by far the most dynamic technology, and since AR5 has continued on its steep decline at about the same rate of change as before AR5, but now costs are well within the range of fossil fuels. Very few CSP plants had been built between the 1980s and 2012. Since AR5, 4 GW have been built and costs have fallen by half. On-shore wind has continued its pace of costs reductions such that it is well within the range of fossil. Offshore wind has changed the most since AR5. Whereas costs were increasing before AR5, they have decreased by 25% since. None of these technologies shows indications of reaching a limit in their cost reductions. Crucial to their impact will be extending these gains in the electricity and transportation sectors to the industrial sector (Davis et al. 2018b).

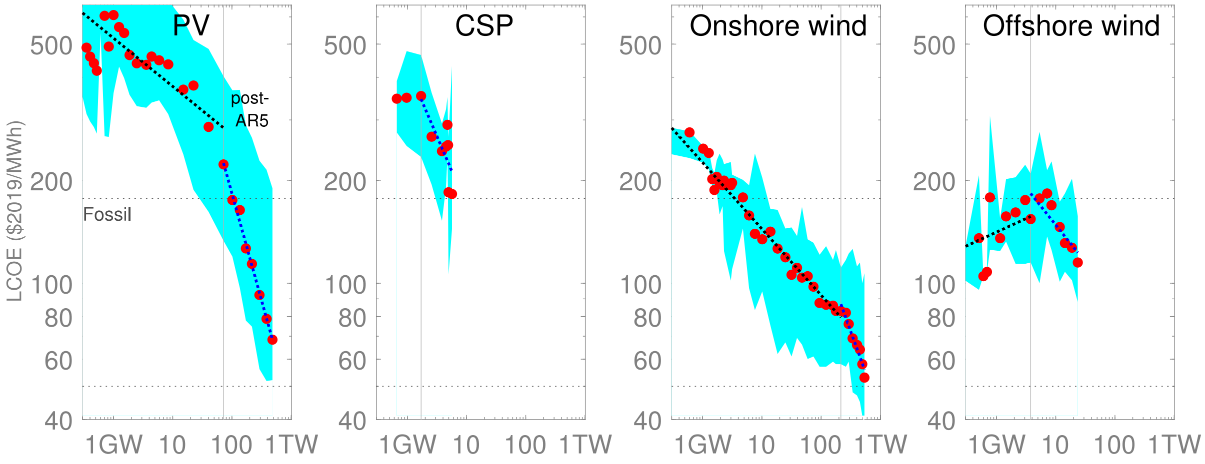


Figure 2.28 Learning curves for renewable energy technologies 2000-2019. Range of fossil fuel LCOE indicated as dashed lines $50-177/MWh. Dashed lines are power functions fit to data for AR4-AR5 and

for post-AR5 (2012). Blue area shows the range between the 10th and 90th percentile in each year. Data: (IRENA 2020; Nemet 2019).

2.5.3.3 Granular technologies improve faster

The array of evidence of technology learning that has accumulated both before and since AR5 has prompted investigations about the factors that enable rapid technology learning. From the wide variety of factors considered, unit size has generated the strongest and most robust results. Smaller unit sizes, sometimes referred to as 'granularity', tend to be associated with faster learning rates (Sweerts et al. 2020; Wilson et al. 2020). The explanatory mechanisms for these observations are manifold and well-established: more iterations are available with which to make improvements (Trancik 2006); mass production can be more powerful than economies of scale (Dahlgren et al. 2013); project management is simpler and less risky (Wilson et al. 2020); the ease of pre-mature scrapping can enable risk-taking for innovative designs (Sweerts et al. 2020); and they tend to be less complicated (Malhotra and Schmidt 2020; Wilson et al. 2020). Small technologies often involve iterative production processes with many opportunities for learning by doing and have much of the most advanced technology in the production equipment than in the product itself. In contrast, large unit scale technologies—such as full-scale nuclear power, carbon capture at power plants (CCS), low-carbon steel making, and negative emissions technologies such as bioenergy with carbon capture and sequestration (BECCS)—are often primarily built on-site and include thousands to millions of parts such that complexity and system integration issues are paramount (Nemet 2019). Despite the accumulating evidence of the benefits of granularity, these studies are careful to acknowledge the role of other factors in explaining learning. In a study of 41 energy technologies (Figure 2.29), unit size explained 22% of the variation in learning rates (Sweerts et al. 2020) and a study of 31 low-carbon technologies showed unit size explained 33% (Wilson et al. 2020). While attributing that amount of variation to a single factor is rare in studies of technological change, the large residual leads studies to find that small-scale technologies provide opportunities for rapid change, but they do not make rapid change inevitable; a supportive context, including supportive policy, and complementary technologies can stimulate more favourable technology outcomes. Those outcomes can themselves support the faster transitions discussed above by promoting rapid technology adoption. They also lead to efforts to take advantage of these effects, for example via shifting from large-scale to small-scale nuclear reactors and direct air capture technology (Morgan et al. 2018; Breyer et al. 2019).

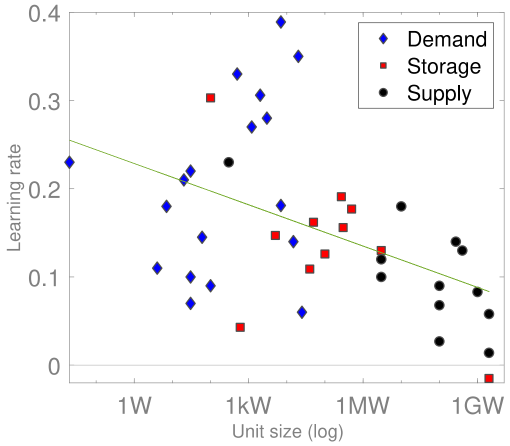


Figure 2.29 Learning rates for 41 energy demand, supply, and storage for renewable energy technologies (Sweerts et al. 2020).

We also see evidence that small technologies not only learn but get adopted faster than large technologies (Wilson et al. 2020). Some of the mechanisms related to the adoption rate difference are related to those for cost reductions; for example, smaller, less lumpy investments involve lower risk for adopters (Dahlgren et al. 2013; Wilson et al. 2020). The shorter lifetimes of small technologies allow users to take advantage of new performance improvements (Knapp 1999) and access a large set of small adopters (Finger et al. 2019). Other mechanisms for faster adoption are distinctly related to markets: modular technologies can address a wide variety of niche markets (Geels 2018b) with different willingness to pay (Nemet 2019) and strategically find protected niches while technology is maturing (Coles et al. 2018).

2.5.4 Rapid adoption accelerates energy transitions

The transition to a more sustainable energy system depends not just on improvement in technologies, but also on widespread adoption of them. Work since AR5 has also substantiated the bi-directional causal link between technology improvement and adoption. Cost reductions facilitate adoption, which generates opportunities for further cost reductions through a process of learning by doing. The rate of adoption is thus closely related to the speed at which an energy transition is possible.

Results of integrated assessment models show that scale-up needs are massive for 2-degree scenarios. These adoption rates of 20% annual growth in the 2020s and 2030s are in line with recent adoption of wind and solar. However, it is important to realise that integrated assessment models include faster adoption rates for some mitigation technologies than for others (Peters et al. 2017b; Müller-Hansen et al. 2020). Average growth rates in IAMs for large scale CCS—biomass, coal, and gas—are between 15 and 20% (Figure 2.30). So few plants have been built that there is little historical data to which to compare this expected growth; with only 2 full scale CCS power plants built and a 7% growth rate if including industrial CCS. In contrast, the set of technologies that has been growing fastest in recent years (wind and solar) is assumed to slow to much lower rates of growth in future years.

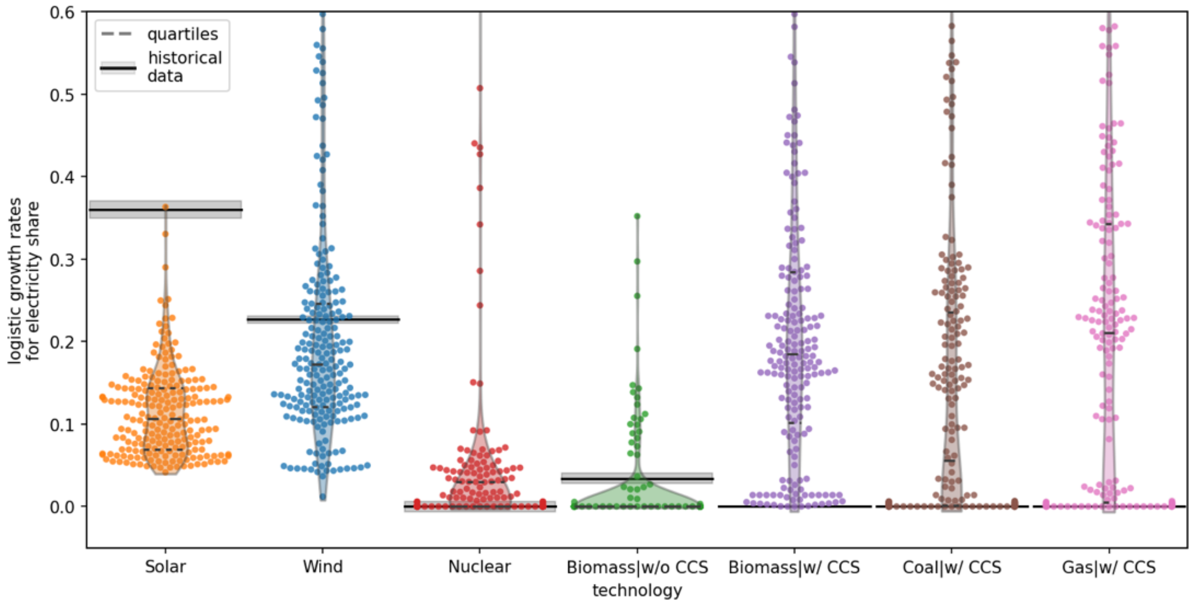


Figure 2.30 Growth of key technologies (2020-2040) in Paris-consistent mitigation scenarios compared to historical growth. Comparisons of historical growth (grey regions) to mitigation scenarios (dots). Data from (Müller-Hansen et al. 2020)

The overall pattern that emerges shows that IAMs expect growth in small-scale renewables to fall to less than half of their recent pace and large-scale CCS to more than double from the limited deployment we can assess. The emerging work since AR5 showing the rapid adoption and faster learning in small scale technologies should prompt a keener focus on what technologies we can depend on to scale up quickly. In any case, the scenario results make quite clear that climate stabilisation depends on rapid adoption of low-carbon technologies throughout the 2020-40 period.

2.6 Behavioural Choices and Lifestyles

2.6.1 Introduction

This section synthesises how behavioural choices, lifestyles, and consumption preferences affect energy use and emissions. Household consumption constitute the largest component of a country's gross domestic product (GDP) and the main contributor to greenhouse gas emissions through direct energy consumption for heating and cooling or driving and indirectly through carbon emitted during production of final consumption items. There is great variation in individual, groups and household behaviour and consumption patterns within and between countries and over time. A number of factors socio-demographics, socio-economic status, infrastructure and access to public services; the regulatory frame; availability, affordability and accessibility of more or less sustainable choices on markets; individual values and preferences are affecting people's consumption patterns and associated carbon emissions (Dietz et al. 2009). Due to the differences that shape individuals' consumption patterns there are enormous differences in carbon footprints associated with income being one of the most important predictors. Globally, households with income in the top 10% are responsible for 36% to 45% of GHG emissions, while those in the bottom 50% are responsible for only 13-15% of emissions depending on the study (Hubacek et al., 2017) (Chancel et al., 2015) (Oxfam, 2020) (Figure 2.31). The average carbon footprint of the high household incomes is more than an order of magnitudes larger than that of the lowest expenditure group (Feng and Hubacek 2019). For example, (Zhang et al., 2017) analysed the impact of household consumption across different income households on the whole CO_2 emissions in China and concluded that the impact on CO_2 emissions generated by urban households' consumption are 1.8 times as much as that of rural ones. High-income households have higher emission related to transport and entertainment, such as recreational expenditure, travel, and eating out, than low-income households. Low-income households tend to have a larger share on necessities (Kerkhof et al. 2009). Also, financial credit (such as mortgages and credit cards) is positively related to household emissions (Xu and Han 2017).

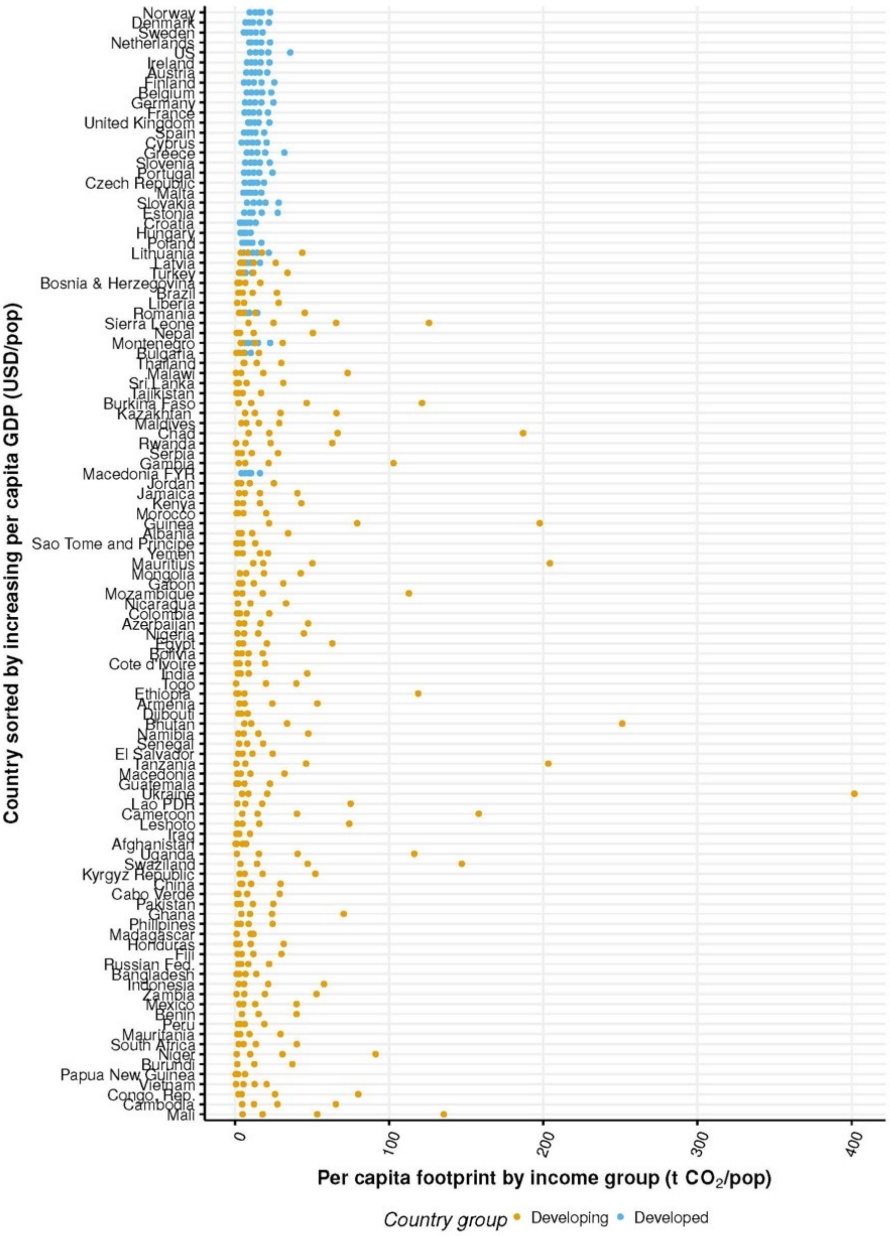


Figure 2.31 Carbon footprints per capita income and expenditure category for 112 countries ranked by per capita income (consumption-based emissions). Notes: Blue dots are for the developing country group provided by the World Bank for 4 expenditure categories and purple dots represent income quintiles of EU countries and the United States. Countries are ranked from the lowest per capita income (Mali) to the left to highest income (Norway) to the right (Hubacek et al. 2017a).

Carbon footprints vary between and within countries and show an uneven distribution because of differences in development levels, economic structure, economic cycle, available public infrastructure, climate and residential lifestyles. For example, Canada's per capita household emissions in 2007 were 7.4 times the emissions of Chinese households in 2011, and 1.6 times of the average UK's household in 2011 (Maraseni et al. 2015).. Similar emission characteristics can also be found within a country. See, for example for China (Feng et al. 2013), for the US (Pizer et al. 2010; Wang et al. 2018; Miehe et al. 2016; Hubacek et al. 2017a; Feng et al. 2013) for Brazil (Sanches-Peirera et al. 2016), for Latin American countries (Zhong et al. 2020).

In western countries, the largest contribution to the household carbon footprint is from transportation, housing, and consumption of food (Druckman and Jackson 2015)(Hubacek et al. 2017). These three items' joint contribution varies in different countries dependent on consumption pattern and account for 58.5% on average in EU 25 countries. (Tukker and Jansen 2006). However, different countries and even regions within countries may have different emission patterns due to differences in income, lifestyles, geography, infrastructure, political and economic situation. For example, the main contributors to the average US household private transport (19.6%), followed by electricity (14.8%) and meat (5.2%) (Jones and Kammen 2011), while the UK households have 24.6% emissions on energy and housing, 13.7% emissions on food, and 12.2% emissions on consumables (Gough et al. 2011). A study of 49 Japanese cities found that energy (31%), food (27%), and accommodation (15%) were the largest sources of household emissions (Long et al. 2017). An overview investigation of Japan's household emissions found that energy, food, and utility are the three main emissions sources, but their shares are dependent on age (Shigetomi et al. 2014a).

In terms of rapidly growing economies, China is the most extensively researched country China's household emissions were primarily derived from electricity and coal consumption, as well as residents' consumption of emission-intensive products, such as housing (33.4%), food (23.6%), private transportation and communications (14.8%)(Wang et al. 2018). Space heating was the largest contributor among various daily energy uses in northern cities (Yang and Liu 2017). In comparison, Indonesian rural households have a larger emission share on foods and a much smaller share on services and recreation than urban households (Irfany and Klasen 2017). Urban Indonesian households have a much larger share of transport related emissions (Irfany and Klasen 2017). Analysis from the Philippines shows that on average households in urban areas emit twice as much as rural ones because of much lower direct energy use in homes and for transport in rural areas (Serino 2017). In other emerging economies, like India, Brazil, Turkey and South Africa as well, a high share of transport related carbon emissions among urban middle- and high-income households is evident (Huang and Tian 2021).

2.6.2 Factors affecting household consumption patterns and behavioural choices

Households' carbon emissions are closely linked to activities and consumption patterns of individuals and group members in households. Individual and group behaviour, in turn, is shaped by economic, technological, and psychological factors, social contexts (such as family ties, friends and peer-pressure) and cultural contexts (social identity, status, and norms) as well as the natural environment (number of heating and cooling days) and physical infrastructure, or geography (Jorgenson et al., 2019). For example, a city with an excellent bicycle infrastructure will make it safer and easier for citizens to become highly mobile by using their bikes; a city that has less density and is dominated by automobile infrastructure induces more people to travel by car (see Chapter 8 and 10). As a consequence, many climate relevant consumption acts are not consciously decided upon or deliberately made part of a lifestyle but are strongly influenced by social norms, access, ease, comfort, and availability (Reisch and Zhao 2017), ethnicity, education, employment, location, or family status (Baiocchi, Minx, & Hubacek, 2010), historical, cultural, geographic, political and social-structural factors (Jorgenson et al. 2019).

Demographic characteristics such as age, sex, and education constitute an important set of determinants influencing emissions patterns. People of different genders have different consumption patterns. For example, men tend to consume more food (especially meat) than women, leading to higher food-related emissions. Also, men spend more money on vehicles and driving (Wang et al. 2018). Similar evidence has been found in Germany, Greece, Norway, and Sweden, where men's energy use is 8%, 39%, 6%, and 22% higher than women's, respectively (Räty and Carlsson-Kanyama 2010).

Age. The effect of population ageing on emissions is contested in literature. Ageing when accompanied by shrinking household size and more energy-intensive consumption and activity patterns results in increased emissions. However, an ageing labour force can also dampen economic growth and result in less energy-intensive activity like driving, which has a negative effect on emissions (Liddle 2011; Liddle and Lung 2010). An ageing of the population characterises the demographic transition in both developed and developing countries. The implications of ageing for emissions depend on labour force participation of the elderly and difference in the consumption and investment patterns of different age groups(O'Neill et al. 2012). Analysis using panel macro data from OECD countries suggest that shifts in age and cohort composition have contributed to rising GHG emissions since the 1960s (Menz and Welsch 2012)(Nassen 2014). Evidence from household-level data over time for the US provides evidence that residential energy consumption increases over the lifetime of household members, largely also due to accompanying changes in household size (Estiri and Zagheni 2019). Similar insights emerge from Japan, where analysis shows that those in their 70s or older, a group that is growing in size in Japan, have higher emissions than other age groups (Shigetomi et al. 2014b, 2019, 2018). Recent analysis from China suggests that the shift to smaller and ageing households is resulting in higher carbon emissions because of the accompanying time-use and consumption shifts (Li and Zhou 2019)(Yu et al. 2018). An increase in the dependency ratio, i.e. the proportion of children under 15 and people over 65 in relation to the working-age population, in other analysis, has been shown to lead to reduced CO_2 emissions in China (Li and Zhou 2019; Wei et al. 2018). Implications of the nature of this relationship are important to policy discussions of working hours and retirement age that are likely to have an influence on emissions. For example, children and youth tend to emit more education related emissions than adults (Xu and Han, 2015). Older people tend to have higher emissions related to heating and cooling being more sensitive to temperature (Meier and Rehdanz 2010).

Household size. Per capita emissions tend to decrease with family size as living together becomes more energy efficient (Qu et al. 2013). The household size in most countries is decreasing (Liu et al. 2011), but the decrease rate differs across countries and show, for example, higher decrease rate in China than Canada and UK (Maraseni et al. 2015). The evidence shows that shifts to smaller households are associated with larger per-capita footprints (Liddle 2014a)(Underwood and Zahran 2015)(Wiedenhofer et al. 2018a)(Ivanova et al. 2017), at least in developed countries (Meangbua et al. 2019).

Urban Living. The carbon footprint of individuals and households is also significantly influenced by urban-rural differences (Ivanova et al. 2018)(Wiedenhofer et al. 2018b). In some part, the difference can be explained by the effect of locational and spatial configuration characteristics such as levels of compactness/density, centrality, proximity and ease of access to services. In all these parameters, urban areas score higher as compared with rural or peri-urban (outlying and suburban) areas, thus influencing household emissions in different ways. Urban households tend to have higher emissions than rural households (Liu et al. 2011; O'Neill et al. 2010), but with different energy and consumption structure. For example, electricity contributes the highest share of direct emissions in China's urban households, whereas rural households have more diverse energy inputs, such as biomass, biogas, solar, wind, small hydro and geothermal in addition to coal (Maraseni et al. 2016).

In terms of indirect emissions, urban households have more service related emissions, such as from education and entertainment than rural households, while rural households tend to have higher emissions related to food consumption or transportation (Büchs and Schnepf 2013; Maraseni et al. 2016) but this is strongly dependent on specific situation of the respective country as in poorer regions rural transport might be mainly based on public transport with lower carbon emissions per capita. Centrality and location also place a role on the level of urban household emissions. Studies on US households found that residents in the urban core have 20% lower household emissions than residents in outlying suburbs, which show a large range of household emissions (from -50% to +60%) (Kahn 2000; Jones and Kammen 2014). Population density may have different effect for different countries.

From a global average perspective, higher population density is associated with lower emissions (Liddle 2014b)(Y. Liu et al., 2017).

Location choices are a significant contributor to household emissions. Suburbanites generally purchase large, spacious homes with larger heating and cooling requirements. Commuting distance and access to public transportation, recreation areas, city centres, public services, and shops are other important neighbourhood-specific determinants of carbon emissions (Baiocchi et al. 2010) (see more on this in urban and the transport chapters 8 and 10).

Time Use. A study on the emissions implications of time use (Wiedenhofer et al. 2018b) found that the most carbon intensive activities are personal care, eating and drinking and commuting. Indirect emissions are also high for repairs and gardening. In contrast, home-based activities such as sleep and resting, cleaning and socialising at home have low carbon intensities per hour of time use. The same study also found that households in cities and with higher incomes tend to substitute personal activities for contracted services, thus shifting away from households to the service sector (Wiedenhofer et al. 2018b). Improvements in the efficiency of time or resource use are diminished by rebound effects which have been shown to reduce emissions savings by 20-40% on average (Gillingham et al. 2015), while other authors argue that potentially the size of the rebound effect could be larger (Saunders 2015) (see more coverage of the rebound effect in Chapter 16). Lifestyle shifts brought about by using information technologies and socio-technological changes are inducing alterations in people's daily activities and time-use patterns.

The reduction of working hours is increasingly discussed as an approach to improve well-being and reduce emissions (Wiedenhofer et al. 2018b)(Fitzgerald et al. 2015)(Fitzgerald et al. 2018a)(Melo et al. 2018)(Smetschka et al. 2019). For instance, analysis of differences in working hours across US states for the period 2007-2013 shows that there is a strong positive relationship between carbon emissions and working hours, which holds even after controlling for other differences in political, demographic and economic drivers of emissions (Fitzgerald et al. 2018b). In other analysis, this relationship is seen to hold in both developed and developing countries (Fitzgerald et al. 2015). One recent study, however, finds evidence of nonlinear relationships between working time and environmental pressure in EU-15 countries between 1970 and 2010, in cases where non-work time is spent instead in carbon-intensive leisure activities (Shao and Shen 2017).

Social Norms. New technologies make it possible to make consumption more transparent and provide the opportunity to harness social norms to affect energy consumption. Evidence from experiments in the US shows that social norms can not only help in reducing a household's absolute level of electricity use but also shift the time of use to periods when more renewable electricity is in the system (Horne and Kennedy 2017). Analysis from Sweden shows that adoption of sustainable innovations like solar panels is influenced by perceived behaviour and expectations of others (Palm 2017). Similar conclusions emerge from analysis in the Netherlands on the adoption of electric vehicles and smart energy systems (Noppers et al. 2019).

Broader contextual factors and cultural trends towards consumerism, individualisation and defining self-worth through conspicuous consumption can drive emissions up (Chancel and Piketty 2015). However, cohort and generational shifts can drive emissions down. For instance, evidence, from millennials in the OECD shows that fewer younger people have driving licenses compared to older generations (Kuhnimhof et al. 2012). Similar, findings are evident from analysis for the US, where changing attitudes, decreased employment and rising virtual mobility explain decreased travel by Millennials (McDonald 2015). Analysis for France shows that baby boomers are higher emitters than other generations (Chancel 2014).

Education & Environmental Knowledge. Environmental knowledge plays a role in behavioural choices related to carbon emissions. (Polonsky et al., 2012) evaluated the impact of general and carbon-related environmental knowledge on attitudes and behaviour of US consumers. A positive relationship was found between general and carbon-specific knowledge and the attitude towards carbon-specific behaviours. One example, pertaining to students, found that the gain of environmental knowledge resulted in more environmentally favourable attitude among these high school students (Bradely et al., 1999). A comparison across states in the USA, for example, shows that environmental awareness can be a mitigating factor of territorial GHG emissions (Dietz et al. 2015). A 1% increase in 'environmentalism' – defined as the "environmental voting record of the state's Congressional delegation" (Dietz et al. 2015) – leads to a 0.45% decrease in emissions.

Environmental knowledge is not always directly translating into decreased ecological footprint (Csutora, 2012). While pro-environmental action is lagging behind, research is shows that, this is not caused by people undervaluing the environment but rather by people structurally underestimating how much others care (Bouman and Steg, 2019). Other evidence shows that there are multiple causal pathways through which a more educated population can effect emissions, some of which may be positive and others negative (Lutz et al. 2019). A more educated population is more productive and can drive higher economic growth and therefore emissions (Lenzen and Cummins 2013). Moreover, education that is designed to specifically inform decisionmakers of the impacts of their decisions and provide behavioural nudges can be a way to reduce emissions (Duarte et al. 2016).

Status Competition. As part of a larger consumer society and consumer culture, based on consumer-oriented lifestyles, products frequently provide a source for identity and fulfilment (Baudrillard, 2017) (Jorgenson et al., 2019) (Stearns, 2001). People pursue cultural constructs such as status, comfort, convenience, hygiene, nutrition, and necessity. Consumption is, by and large, not an end in itself but a means to achieve some other end, and those ends are diverse and not necessarily connected to one another (Wilk, 2010). This shows that consumption patterns cannot be sufficiently understood without also considering the context, for example the cultural and social contexts leading to status competition and status-related consumption (Ehrhardt-Martinez, 2015) (Wilk, 2017)(Veblen, 2009). Status seeking can work to reduce emissions when 'green products' such as an electric car or photovoltaics on the roof become a sign for high-status (Griskevicus, Tybur, & Van Den Bergh, 2010). It also can work to increase emissions through visible and high-carbon intensive consumption items such a larger homes, fuel-inefficient SUVs cars, and long-distance vacations (Schor, 1998), driven by a notion of having 'to keep up with the Joneses' (Hamilton, 2011). This can lead to formation of new habits and needs, where products and services become normalised and are quickly perceived as needed, reinforced through social networks and advertisement, making it psychologically easy to convert a luxury item to a perceived necessity (Assadour, 2012). For example, the share of adults who consider a microwave a necessity was about one third in 1996 but had increased to more than two thirds in 2006, but retreated in importance during the recession years (Pew Research Center, 2009). Similar ups and downs have been observed for television sets, air conditioning, dishwasher or the clothes dryer. 2002; Jackson, 2009). What is considered a basic need and what is a luxury is subject to change over one's lifetime and in relation to others (Horowitz, 1988). This shows that the boundaries of public's luxury-versus-necessity perceptions are malleable (Morin & Taylor, 2009).

Inequality. The trends over the last two decades of falling income inequality among nations, and of growing inequality within nations (Alvaredo et al. 2018), has impacted the increase of global emissions in this period. The rise of middle-class income countries, mostly in Asia, eg. China, India, Indonesia and Vietnam, and the stagnating incomes of the middle classes in developed economies have reduced between countries income differences; meanwhile the population under extreme poverty (threshold of 1.9 USD per person/day) is now concentrated in Sub-Saharan Africa and South Asia (Milanović 2016). A significant pulling apart between top and bottom incomes has occurred during this same period within countries. Since 1980, the top 1% richest individuals in the world captured twice as much growth as the bottom 50% individuals (Friedman and Savage 2017)(Alvaredo et al. 2018).

The influence of these dual inequality trends on lifestyles and carbon emissions at regional and global scale are large. Matching the rebalancing decadal trend of between countries income distribution (Milanović 2016), it has taken place the fastest growth of global carbon emissions that can be observed in fast emerging economies during this period (see section 2.2. and 2.3). Within countries, inequalities have increased for both income and carbon emissions. Globally, emissions remain highly concentrated, with top 10% per capita emitters contributing to between 35-45% of global emissions, while bottom 50% emitters contribute to 13-15% of global emissions; and furthermore, the top 10% emitters living in all continents, and one third of them living in emerging countries (Hubacek, Baiocchi, Feng, & Patwardhan, 2017)(Chancel & Piketty, 2015)(Oxfam 2020).

The critical question raised by scholars is how can short and future developments advances toward a more equitable world follow pathways that minimise their impacts to climate change (Baek and Gweisah 2013)(Hao et al. 2016)(Grunewald et al. 2017)(Berthe and Elie 2015). Different mechanisms and effects come into play between inequality of income and emissions (Berthe and Elie 2015); at lower levels of income higher income inequality reduces emissions while at higher levels of income, the effect is reversed (Grunewald et al. 2017).

Inequality trends have a scale impact driven by massive adoption of lifestyles changes influencing the increase of global emissions. An expanding global middle income population emulating high-carbon emissions intensive lifestyle of the wealthy (Gough 2017), strongly drives emissions growth; decoupling of energy use and emissions from income growth and, the decarbonisation of energy services have not counteracted these trends (see 2.4.1). Scholars are strongly advocating for the need to try an alternative option for sharing global carbon emissions among high emitters (Chakravarty et al. 2009)(Chakravarty and Tavoni 2013). Also for addressing the discourse of income distribution and the carbon intensity of lifestyles given that the top 10% global income earners are responsible for 36% of the current carbon footprint of households (Hubacek et al. 2017b). Growing inequality within countries may make re-composition of emission intensive consumption more difficult and, it may also exacerbate redistribution and social cohesion dilemmas (Gough 2017)(Römpke et al. 2019). Climate mitigation action has different motivational departures in unequal context. Inequality may affect the willingness of rich and poor to pay for environmental goods or accept policies to protect the environment (Baumgärtner et al. 2017). Unequal departure for action is strongly manifested in cities of all sizes in developing countries. There, conditions impacting hardest low-income urban residents constitute lock-in situations such as lack of access to transportation and jobs (Altshuler 2013)(Mattioli 2017), lack of green spaces (Joassart-Marcelli et al. 2011), poor access to waste collection (King and Gutberlet 2013) and to energy and clean water provision. These conditions constraint the feasibility for achieving emissions reductions through lifestyle or behavioural changes alone (Oxfam 2015)(Baiocchi et al. 2010). High inequality limits mitigation efforts, and conversely advancing mitigation should not contribute to deepen existing inequalities (Rao and Min 2018)(Saheb et al. 2019). Accounting for varying demands and affordability across heterogeneous household groups in policy setting is critically important for inclusion of low income and energy poor population groups (Pachauri et al. 2013). Also, the implementation of social policy-- quality education, health, access to decent jobs and services-, that is not just concerned with equity and distributive issues, but, that recomposes consumption and seeks to balance societal trade-offs, as well as, the inequalities and capabilities people have to live the lives they value (Sen 1999)(Gough et al. 2011)(Gough, 2017(Aranoff et al. 2019).

Box 2.2 Sharing Economy

One significant development since AR5 IPCC report, with potential to affect a household's carbon footprint is the rapid growth of the sharing economy, in which consumers share or borrow goods from other consumers. When applied to under-utilised goods sharing could in principle reduce the total amount of consumer goods needed to meet specific needs without reducing consumer welfare and, smart apps can facilitate seamless sharing of resources even when they are coming with environmental problems of their own (OECD, 2009; Ropke et al., 2010). The growth of the sharing economy parallels the spread of information and telecommunication services, online platforms such as eBay and Amazon that encouraged bargain-seeking behaviour by consumers (Ertz et al. 2017) and, the strong penetration rates of multi-purpose mobile computing and internet access devices, of increasing availability even in low-income countries, though at unequal quality of access and reliability. Shared mobility is the most rapidly growing sector of the sharing economy (Greenblatt & Shaheen, 2015), therefore is the focus of this box. Shared mobility has emerged as a potential way to positively affect transport opportunities, mostly in urban settings where modal shift is needed to reduce car use (Cuenot et al. 2012)(Figueroa et al. 2013)(Fishman et al, 2014). Research using large dataset found that gasoline prices significantly increase bikeshare trip frequency and duration in the four largest U.S. metropolises, excluding D.C., (He et al., 2020) and Dockless Scooter-share and Station-based Bike-share in Washington, D.C., (Younes et al., 2020). The literature on shared mobility is expanding rapidly and still debating how much it contributes to decarbonisation or to make it worse as it takes away riders from public transit (ITF, 2018). Limited and mixed evidence exists of environmental impacts. The bike-sharing scheme in Shanghai (BSS) was shown to have reduced emission in 2015 and 2016 (Qiu and He 2018) (Zhang and Mi, 2018). Teixeira et al. (2020) argue that these estimates are overly optimistic because they are based on extremely high and unrealistic car replacing rates. Evaluating BSS operations in London, Brisbane, Melbourne, Minnesota, and Washington D.C., Fishman et al. (2014) found that sharing trips replace mostly public transport and walking trip, and that once heavy fuel consuming rebalancing trucks are included, needed to relocate vehicles to stations with shortages, environmental impacts can be negative for some implementations. Accurate data on actual modal shift patterns and detailed information on rebalancing management and the lifespan of the hardware, including batteries when used are needed. This type of information is not being released by companies. Car sharing has been shown to have about 1.4 lower emissions per passenger-on kilometre than standard taxis because of shorter idle distance and longer delivery distance (Sui et al., 2019). The evidence on environmental impacts of different forms of sharing evidence is mixed and dependent upon the type of sharing and where it is implemented. The potential positive impacts of shared mobility with pooled rides in lowering travel costs, abating congestion, and reduced GHG emissions have not materialised to date (Merlin, 2019). A favourable assessment depends not only on more people traveling in a single vehicle in key geographies, but also what modes have been substituted and if new rides that would not have been otherwise made are created; also feasibility of public ride pooling acceptance (Spurlock et al. 2019). Estimates show that less than 10% of trips honoured by transportation network companies offering pooled rides (i.e., Uber Pool and Lyft Shared) are currently pooled (Henao and Marshall, 2018). Rayle et al. (2016) found that for some specific areas of San Francisco, while ride--hailing trips do seem to replace taxi trips, at least half of the trips replaced other modes such as walking, biking and the use of public transit which make environmental gains negative. Several studies find that ride-hailing likely increases vehicle miles travelled and can contribute to increase congestion through the common practice of moving around waiting for business opportunities, though estimates remain uncertain (Committee for Review of Innovative Urban Mobility Services, 2016) (Clewlow and Mishra, 2017; Rodier, 2018; Schaller, 2018; Henao and Marshall, 2018). A full evaluation of the sustainability of sharing schemes should include indirect emissions and rebound effects. For example, sharing could lead to lower fares due to cuts in the cumulative time travel or trip length and potentially higher demand in trips depending on the elasticity of demand through the substitution effect and added emissions from increased consumption through the income effect which is difficult to evaluate as it depends on the goods or services consumed with the additional income increase (Lopez et al. 2014). Policy measures to avoid rebound would need to be considered and documented. Bike-sharing has positive health co-benefits (Woodcock, et al., 2014), though the diffusion of transportation options that no longer require physical activity (e-bikes, e-scooters) might exacerbate more negative effects. Other indirect benefits include the potential faster uptake of new and cleaner technologies. Lower income groups, women, less educated and ethnic minorities and socially disadvantaged groups in major metropolises are systematically found to be underrepresented among bike sharing users (Ogilvie and Goodman, 2012; Goodman and Cheshire, 2014)(Ursaki and Aultman-(Hall 2016)(McNeil, Broach, and Dill 2018). One of the major causes of inequity seems to be access to BSS location, usually limited to city centres, and the need of credit/debit cards and smart phones (Goodman and Cheshire, 2014; McNeil et al., 2018; F. Ogilvie and Goodman, 2012; Ursaki and Aultman- Hall, 2016). Duran-Rodas et al. (2020) found that access to BSS is greater in areas with higher concentration of young, white, highly educated people. Women have been found to have lower overall use, particularly at night in peripheral areas of the city (Pellicer-Chenoll et al. 2020). Cultural lock in effects of viewing bicycles as the "poor man's" mode of transportation, as opposed to cars, perceived as a symbol of success have been discussed in Mexico City (von Ritter Figueres 2017). Successful car and bike sharing have rapidly expanded in middle income countries such as China, Indonesia, Mexico, Brazil and Turkey. Technology and data advances are currently barriers to spreading of sharing in low- and lower middle-income cities but the potential offered by these technologies to allow poor countries to leapfrog to more integrated, efficient, multimodal transport systems is important (Yanocha et al. 2020).

2.7 Emissions associated with existing and planned long-lived infrastructure

2.7.1 Introduction: clarification of concepts

Emissions accounting focuses on the annual fluxes of CO_2 to the atmosphere. The CO_2 fluxes are directly or indirectly related to physical infrastructures like coal or gas power plants, mines, roads, buildings or industrial plants (Müller et al. 2013). Such historically long-lived infrastructures may lock societies into carbon-intensive lifestyles and practices for many decades and have been discussed as bottlenecks to climate change mitigation (Unruh 2000, 2002; Unruh and Carrillo-Hermosilla 2006; Seto et al. 2016; Sovacool 2016; Grubler 2012): how fast emissions can be reduced in the future, and therefore how difficult it may be to stay within certain carbon budgets, is closely related to how quickly existing fossil fuel-based infrastructures can be replaced by low- or no-carbon ones and whether plans for new infrastructures are realised or not (Tong et al. 2019a; Fofrich et al. 2020; Edenhofer et al. 2018b; Luderer et al. 2018). Infrastructure stock evolution depends not only on technological and economic factors but also on the institutional context that can contribute to infrastructure lock-in or lock-out (Seto et al. 2016). Technological, institutional and behavioural lock-ins are often mutually reinforcing. That is, physical infrastructures such as the built environment of urban districts can shape behaviour and practices of daily life, which in turn change the demand for infrastructure and can lock in energy demand (Seto et al. 2016; Creutzig et al. 2016a; Makido et al. 2012; Banister et al. 1997; Shove and Trentmann 2018).

There is a broad literature on carbon lock-in related to infrastructure that has analysed different geographical scales and sectors, with a strong focus on power sector (Figure 2.32). Available quantifications differ in the time frames of analysis that can be classified as backward-looking, static for a given year, or forward-looking using scenarios (Fisch et al. 2020). Quantifications also differ in the indicators used to quantify carbon-lock in. Literature has assessed, depending on the short-term climate ambition, the evolution of high-carbon infrastructures stock in the short term (Bertram et al. 2015; McGlade et al. 2018; Kefford et al. 2018) and the overall mitigation costs (Luderer et al. 2016; Riahi et al. 2015). Another literature strand has quantified transition risks induced by infrastructure inertia as the amount of stranded assets risks which are premature retirements/retrofitting or underutilisation of existing assets (Luderer et al. 2016; Kefford et al. 2018; Iyer et al. 2015; van Soest et al. 2017; Lane et al. 2016; Farfan and Breyer 2017; Cui et al. 2019; Fofrich et al. 2020; Malik et al. 2020; Wang et al. 2020a; Johnson et al. 2015). In this regard, it is important to note that stranded assets that could occur from climate policy – and related the economic assessment of committed emissions - highly depend on investors and to which extent they already anticipate climate policy (Rozenberg et al. 2020; van der Ploeg and Rezai 2020). From an economic perspective, stranded assets can further occur when policy makers are time-inconsistent (Kalkuhl et al. 2020), or if capital depreciation rates are too low in the light of increasing carbon prices (Baldwin et al. 2020). Few authors in the literature on carbon lock-in have relied on indicators related to institutional and political factors such as technology scale or employment (Erickson et al. 2015; Spencer et al. 2018).

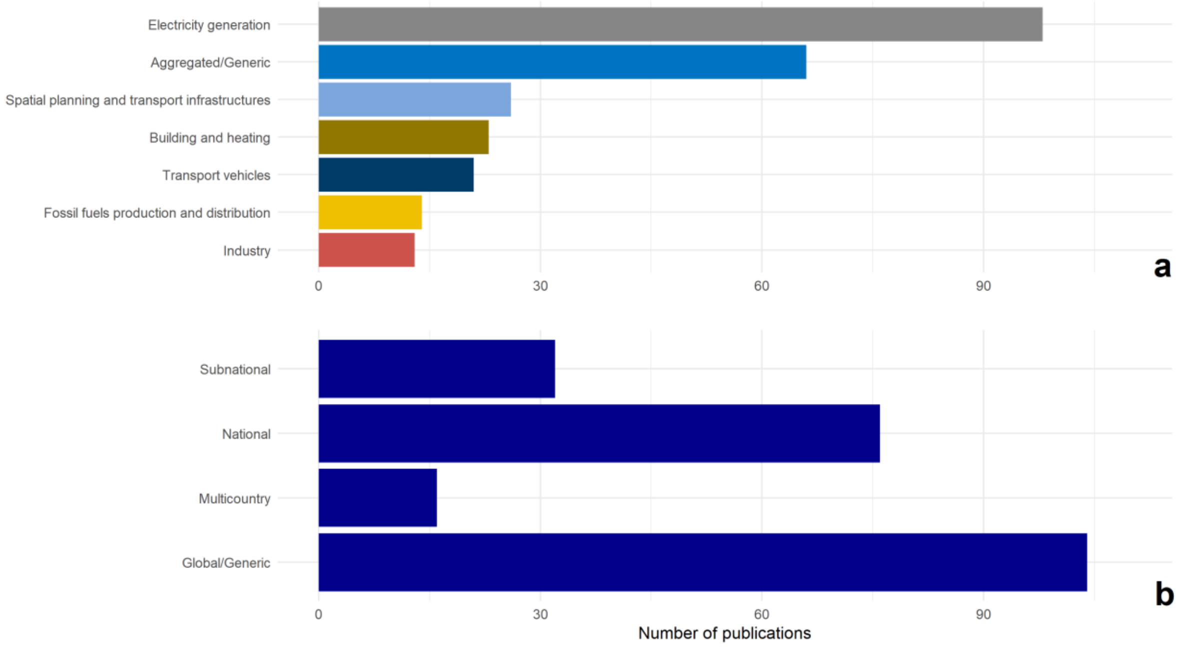


Figure 2.32 - The literature on carbon lock-in from infrastructures by scale, regions and sectors (Fisch et al. 2020)

A separate accounting literature has also contributed to our understanding of future CO_2 emissions from existing and planned infrastructures (see Davis et al. 2010; Davis and Socolow 2014). Traditional emissions accounting relates CO_2 emission fluxes from a particular infrastructure like a coal-fired power plant to the year in which emissions occur. If a lifetime (and capacity utilisation) is assumed, it is equally possible to assign all fossil energy use and related CO_2 emissions occurring across such a plant's entire operation to the year when it starts operating. This has been termed "commitment accounting" and the cumulative lifetime emissions "committed emissions" (Davis and Socolow 2014).

There are two complementary approaches to commitment accounting: first, as infrastructure lifetimes and utilisation rates are policy variables of interest themselves, a complementary literature tries to understand carbon commitments dynamically as a function of policy stringency within a scenario framework. In particular, cumulative, gross residual CO_2 emissions from fossil fuels and industry are assessed within a global, multi-sector energy systems model for alternative climate policy pathways, especially with different levels of near-term policy ambition (Minx et al. 2020a; Luderer et al. 2018; Kriegler et al. 2015, 2018b). Second, another complementary literature has provided a supply side perspective and quantified the embedded emissions in fossil fuel reserves and resources (McGlade and Ekins 2015; Heede and Oreskes 2016; Bauer et al. 2016).

2.7.2 Estimates of committed emissions

There is a limited literature with quantitative estimates of future CO_2 commitments that are global in scope and are based on committed carbon accounting (Davis et al. 2010; Davis and Socolow 2014; Pfeiffer et al. 2016; Edenhofer et al. 2018b; Pfeiffer et al. 2018; Smith et al. 2019; Tong et al. 2019a; Erickson et al. 2015; Rozenberg et al. 2015; Pearson et al. 2018; Cui et al. 2019). Estimates from eight studies are summarised in Table 2.9. Differences between studies arise in the scope of the energy infrastructure covered (incl. resolution), the inclusion of new infrastructure proposals, the exact estimation methodology applied as well as their assessments of uncertainties. A few studies have quantified committed emissions at finer scales (regional or national) focusing on the power sector (e.g. Shearer et al. 2017, 2020; Tao et al. 2020; González-Mahecha et al. 2019; Grubert 2020) or the shipping sector (Bullock et al. 2020).

Table 2.9 Comparing carbon commitments. Comparison of committed emissions by sector estimated in different studies. Carbon commitments are reported from the "year of dataset". Note that in some cases, the totals may not correspond to the sum of underlying sectors due to rounding (see Tong et al. 2019a)

		Davis et al. (2010)		**Davis and Socolow (2014)**		**Rozenberg et al (2015)**		**Edenhofer et al. (2018)**		**Pfeiffer et al. (2018)**		**Smith et al. (2019)**		**Tong et al. (2019)**		**Cui et al. (2019)**	
		GtCO$_2$	Year of dataset	GtCO$_2$	Year of dataset	Gt CO$_2$	Year of dataset	GtCO$_2$	Year of dataset	GtCO$_2$	Year of dataset	GtCO$_2$	Year of dataset	GtCO$_2$	Year of dataset	Gt CO$_2$	Year of dataset
Existing	Electricity	224	2009	307	2012	-	-	-	-	308	2016	345 (261-451)	2009*	358 (240-493)	2018	-	-
	Coal		2009	206	2012	-	-	190	2016	220	2016	-	-	260 (175-358)	2018	336	2017
	Gas, oil, and other fuels		2009	100	2012	-	-	-	-	88	2016	-	-	98 (65-135)	2018	-	-
	Industry	104	2009			-	-	-	-	-	-	154 (117-191)	2009	162 (110-219)	2017	-	-
	Transport	116	2009			-	-	-	-	-	-	92 (73-110)	2017	64 (53-75)	2017	-	-
	Residential, commercial, and other energy	53	2009			-	-	-	-	-	-	121 (91-158)	2009*	74 (52-105)	2018	-	-
	All Sectors	**496** **(282-701)**				**661** **(365-889)**	2013	-	-	-	-	**715** **(546-909)**	-	**658** **(455-892)**	-	-	-
Proposed	Electricity					-	-	-	-	270	2016	-	-	188 (142-234)	2018	-	-
	Coal					-	-	150	2016	211	2016	-	-	97 (74-121)	2018	178	2017

	Gas, oil, and other fuels					-	-	-	-	59	2016	-	-	91 (68-113)	2018	-	-
All Sectors + Proposed Electricity														**846** **(597-1,126)**			

There are three studies that provide original and comprehensive estimates of committed CO_2 emissions from existing energy infrastructures across all sectors – electricity, industry, transport as well as residential, commercial, and other energy. Most recent studies by Smith et al. (2019) and Tong et al. (Tong et al. 2019a) evaluate future CO_2 commitments at 715 (546-909) $GtCO_2$ and 658 (455-892) $GtCO_2$ respectively. Note that early estimates by Davis et al. (2010) are considerably lower at 496 (282-701) $GtCO_2$ with the central estimate being just inside (Tong et al. 2019a) or outside (Smith et al. 2019) the uncertainty range of more recent studies. These lower estimates are due to substantial commissioning of new fossil energy infrastructure covered by more recent data. The earlier estimates are therefore not further considered in discussions here.

50% of future commitments related to current energy infrastructure. Central estimates across studies in the energy sector vary between 310 and 360 $GtCO_2$ as shown in Table 2.9. The share of coal power plants within these are about 70% ranging 190 and 260 $GtCO_2$ across studies. Commitments from coal gas and other fuels vary between 90 and 100 $GtCO_2$. Coal power infrastructure is especially critical due to its high carbon intensity. Roughly 1 Gt of future CO_2 emissions are committed for every 6 GW of new coal-fired generating capacity or every 12 GW of gas-fired generating capacity (Davis et al. 2010).

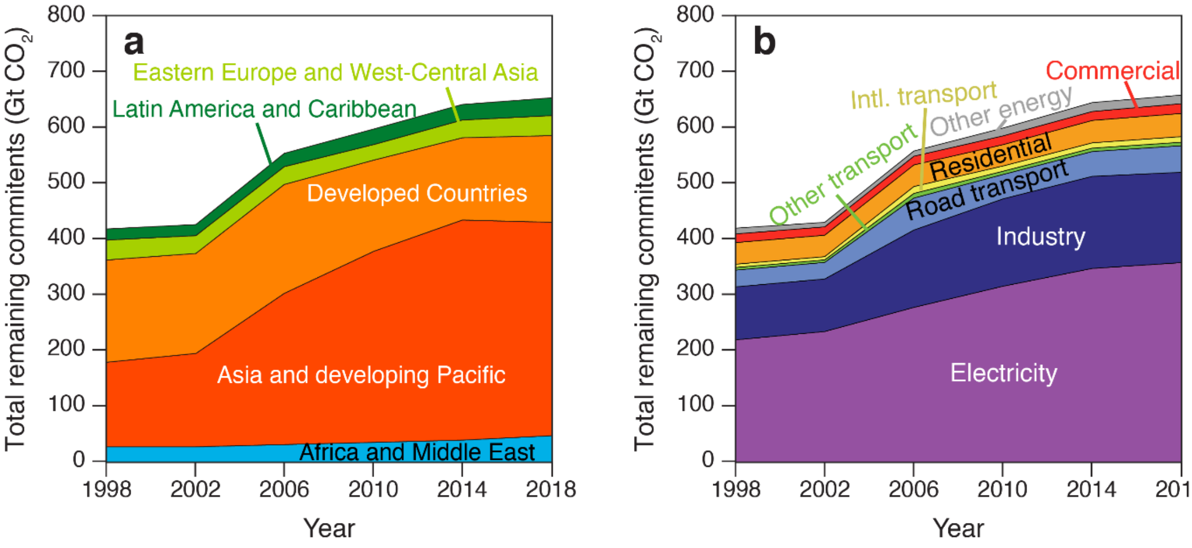


Figure 2.33 Changes in remaining commitments every four years from 1998-2018 (1998, 2002, 2006, 2010, 2014, and 2018). Based on Tong et al. (2019b).

Like global annual CO_2 emissions (Peters et al. 2019; Friedlingstein et al. 2019a), future CO_2 emissions from fossil-fuel infrastructures have failed to peak (Figure 2.33) and continued to rise despite countries' efforts to organise mitigation action around the globe (Le Quere et al. 2019; Rogelj et al. 2016; den Elzen et al. 2019; Höhne et al. 2020). Hence, every tonne of committed CO_2 "saved" from decommissioning of energy infrastructure is over-compensated by additional carbon commitments from newly-built infrastructure (Davis and Socolow 2014; Tong et al. 2019a). This can be seen as evidence for further inertia added to the system that makes a transformation harder and may require early retirement of additional assets for meeting the climate goals. Further discussions on stranded assets can be found in chapter 6 of this report.

Future CO_2 commitments from *proposed infrastructure* focus on the power sector only due to data availability (Table 2.9). Infrastructure proposals can be at various stages of development involving very different probabilities of implementation. Studies tend to include all these stages, but differ in their level of reporting. Pfeiffer et al. (2018) and Tong et al. (Tong et al. 2019a) assess the committed CO_2 emissions from the power sector at 270 $GtCO_2$ and 188 $GtCO_2$ respectively. The role of coal in these future plans varies between 50% and 80% across these studies-in absolute terms between 97 and 211 GtCO$_2$. The differences of 80 GtCO$_2$ is caused by substantially higher estimates of future coal commitments (210 vs 100 GtCO$_2$), while commitments from other fuels are slightly lower than in Tong et al. (Tong et al. 2019a). Estimates of committed CO$_2$ emissions from development plans in coal power provided by Edenhofer et al. (2018b) and Cui et al. (2019) lie well within that range at 150 and 178 GtCO$_2$ and show that only about a quarter of these commitments relate to projects that are already under construction, while the rest is still at planning stage.

Table 2.10 Plans in coal power development and their implementation between 2009 and 2017 (in GW) (Hannam et al. 2020)

[GW coal]	**Proposals**					**Cancellations**		**Commissioning**		**Retirements**
Region	*in 2009*	*2009-14*	*in 2015*	*2015-19*	*in 2019*	*2009-14*	*2015-19*	*2009-14*	*2015-19*	*Pre-2009 capacity retired after 2009*
OECD-1990	104	41	55	16	26	56	35	35	10	-135
EIT	51	23	47	6	22	22	22	6	9	-3
LAM	23	7	13	3	7	12	8	5	1	-1
MAF	33	23	41	21	31	14	24	0	8	-1
ASIA	701	976	1098	216	323	160	698	419	294	-42
World	913	1071	1254	264	409	264	786	465	322	-182

Proposals to add new coal power capacity increased between 2009 and 2014 from about 910 to about 1250 GW in total, but dropped subsequently to about 410 GW by 2019 (Table 2.10). While a lot of plans to build coal power stations were scrapped, the total commissioned capacity also dropped from about 470 GW (~50% of the proposed capacity in 2009) for 2009-2014 to about 320 GW (~25% of the proposed capacity in 2015) for 2014-2019 (Hannam et al. 2020). This could provide evidence for a shift in expectations and attitudes over future infrastructure developments since the establishment of the Paris Agreement.

Estimates of committed CO$_2$ emissions from *current* fossil fuel infrastructures of 715 (546-909) GtCO$_2$ (Smith et al. 2019) and 658 (455-892) (Tong et al. 2019b) – as shown in Figure 2.34 - already exceed considerably the remaining carbon budget for keeping global warming well below 1.5°C with a 66% (50%) probability of 310 (390) ± 250 GtCO$_2$ and exhausts at least 68% (58%) of the remaining carbon budget of 960 (1140) GtCO$_2$ for staying well below 2°C with an at least 66% (50%) probability. The only available estimate of committed CO$_2$ emissions from current and planned fossil-fuel infrastructures by Tong et al. (2019a) tracks at 846 (597-1126) GtCO$_2$. This is a lower bound estimated, because it does not include infrastructure proposals from industry, buildings and transportation due to a lack of data availability. Hence, estimates of committed emissions from *current and proposed* infrastructure are well beyond the 1.5°C CO$_2$ budget. The upper end of the uncertainty range suggests that this could also already exhaust the 2°C budget.

Hence, this line of evidence suggests that the Paris climate goals could move out of reach unless there are substantial decreases in historical lifetimes or utilisation rates of existing fossil fuel infrastructures, large-scale retrofits with CCS, or large-scale CO$_2$ removal from the atmosphere (Smith et al. 2019; Tong et al. 2019a). As shown in Figure 2.35, corresponding scenario evidence suggests that average lifetimes of coal and gas power infrastructure would need to be drastically reduced to 9 (5-20) and 12 (9-14) years to keep warming below 1.5°C and 16 (6-28) and 17 (10-25) years to keep warming below 2°C. Given current average lifetimes of 39 and 36 years for coal and gas power plants, this implies retiring 23 (11-33) and 19 (11-16) year earlier when following 1.5°C pathways and 23 (11-33) and 19 (11-16) when following a 2°C pathway (Fofrich et al. 2020; Cui et al. 2019). Lifetimes are further reduced if plants under construction come online and if all proposed projects are built (Cui et al. 2019). Premature retirement of power plants pledged by PPCA members would cut emissions by 1.6 $GtCO_2$, which is 150 times less than globally committed emissions from existing coal power plants (Jewell et al. 2019).

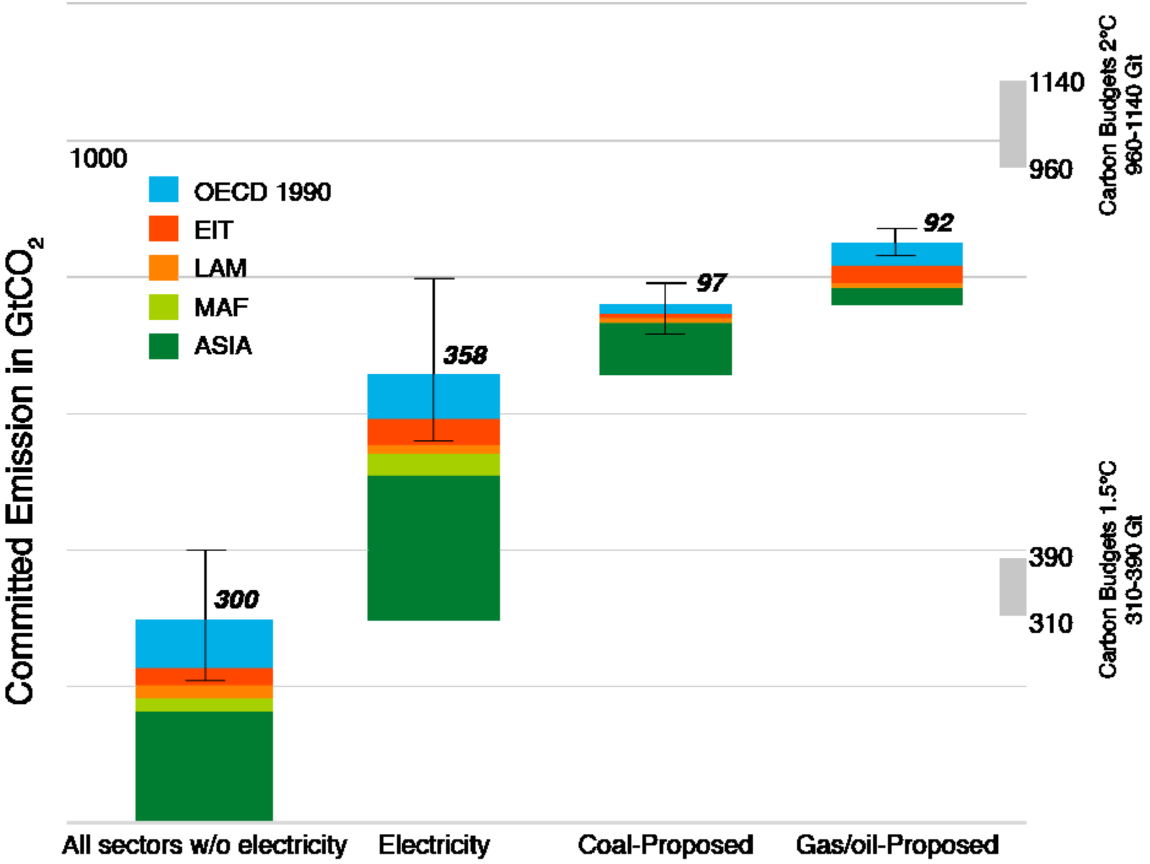


Figure 2.34 Committed carbon from existing and proposed energy infrastructure in the context of Paris carbon budgets. Based on (Tong et al. 2019a) and (Edenhofer et al. 2018b).

There are other estimates of future emissions from infrastructures. Quantifications of carbon lock-ins, e.g. stemming from urban form, are difficult, in part because they also relate to behaviours that are closely tied to routines and norms that co-evolve with "hard infrastructures" and technologies, as well as "soft infrastructure" such as social networks and markets. There are some notable exceptions (Guivarch and Hallegatte 2011; Lucon et al. 2014; Erickson and Tempest 2015; Creutzig et al. 2016a; Driscoll 2014; IPCC 2014b). Given estimates of 210 Gt commitments from existing urban infrastructure and 495 Gt for new infrastructures for the period 2010-2050 (Erickson and Tempest (2015); Creutzig et al. (2016a)), Creutzig et al. (2016a) suggest that 10-26% of carbon commitments from existing urban infrastructures and 45-68% from new built infrastructure could be avoided through various infrastructure solutions (not including conventional technological decarbonisation options). Also the development of these urban infrastructures themselves can be associated with large quantities of CO_2 emissions heavily relying on cement, steel and other carbon-intensive input. Embodied emission from building urban infrastructures could add 350-550 $GtCO_2$ by 2050 without additional mitigation actions (Krausmann et al. 2017; Müller et al. 2013).

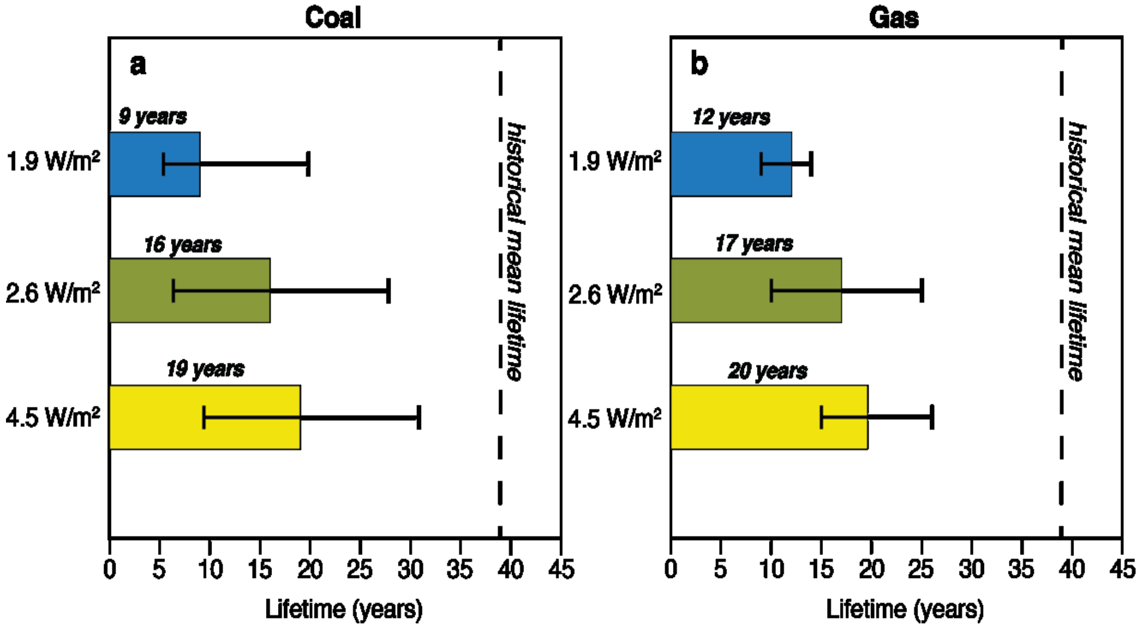


Figure 2.35 - Maximum power plant lifetime under different electricity-emission scenarios. Under ambitious climate change scenarios, fossil powered electricity generating infrastructure retire much earlier than they have historically. Here we present the maximum obtainable lifetime under different electricity demand scenarios for three levels of radiative forcing (radiative forcing 1.9, 2.6, and 4.5 W m^{-2}). Error bars show the full range of power retirements under different capacity factor assumptions. Source: (Fofrich et al. 2020)

Finally, a complementary approach to estimating committed emissions from the demand for fossil fuel infrastructure is to estimate the embedded emissions in the world's fossil fuel reserves (and resources). A broad literature confirms that the amount of carbon embedded in the world's fossil fuel reserves by far exceeds the carbon budget (McCollum et al. 2014; Jewell et al. 2013; Bauer et al. 2016). Estimates vary depending on the methodology used. Using a model based approach based on IPCC AR5 scenarios McGlade and Ekins (2015) estimate that about 2,900 Gt (11,000 Gt) CO_2 are embedded in the world's fossil fuel reserves (resources). Heede and Oreskes (2016) provide a different estimate looking into companies and government-run industries that own fossil fuels and have the technological and financial capacity to develop the reserves in the short – to medium term. They find that those emissions will result in emissions of 1600 Gt CO_2, of which 90% reserves are owned by state-owned entities and states.

2.7.3 Synthesis - Estimates of residual fossil fuel emissions

A strand of literature providing a complementary perspective on carbon lock-in are transformation scenarios from Integrated Assessment Modelling (IAMs) as they endogenously determine trade-off such alternative ways to mitigate lock-in. IAMs can be used to assess the gross amount of remaining, freely emitting fossil fuel related CO_2 emissions across decarbonisation pathways that are not removed from the system even under strong (short- and long-term) climate policy ambition. This can be considered the amount of unabated CO_2 that cannot be easily removed during a global transition that is consistent with limiting warming to well-below 2°C despite considerations of a comprehensive set of mitigation options. This literature indicates that such a minimum amount of unabated residual CO_2 emissions that cannot be removed from the system may be around 600-700 $GtCO_2$ (Kriegler et al. 2018b; Minx et al. 2020a). This budget increases to 650-1800 $GtCO_2$ (Figure 2.36 and Table 2.11) as soon as a broader set of policy assumptions are considered including delayed action in scenarios that limit warming to 1.5°C and 2°C respectively (Luderer et al. 2018).

Notably, the lower end of residual fossil fuel emissions in IAM scenarios (Luderer et al., 2018) is remarkably similar to global estimates from committed carbon accounting as shown in Table 2.11. Yet, there are important conceptual and interpretative differences that are also reflected in the very different distribution of reported carbon commitments (Table 2.11 and Figure 2.36). As a consequence, highest carbon commitments are reported for the power sector in accounting studies, scenario studies highlight the transport and industry sectors as major bottlenecks. This is explained by the conceptual differences explained above: fossil-fuel infrastructures can be much more easily pre-maturely retired in sectors, where there are many competitive alternatives that are readily available and is much more difficult where there are fewer and more costly alternatives. For instance, IAM scenarios in line with the Paris targets retire coal plants one to three decades earlier than historically observed (Fofrich et al. 2020; Cui et al. 2019), because there are many competitive decarbonisation options (Clarke et al. 2014). Therefore, residual fossil emissions from power supply estimated by IAMs tend to be substantially lower than committed emissions derived from bottom-up studies assuming operation until the end of the technical lifetime. IAMs further account for continued investments into fossil-based energy technologies in areas with limited decarbonisation potential, such as some areas of transportation (in particular aviation, shipping and road-based freight) or some industrial processes (such as cement production or feedstocks for chemicals). This explains higher residual fossil emissions from non-electric energy uses in IAM studies compared to bottom-up commitment accounting.

Similar variations can be found in the regional distributions of CO_2 commitments (see also Wang et al. 2020a; Malik et al. 2020). With their stronger focus on the power sector accounting studies emphasise the role of Asia and Developing Pacific, where the average plant age is lower and more expansion plans for fossil fuel infrastructures still exist. However, if industry and transportation sectors remain the real climate change mitigation bottlenecks (Creutzig et al. 2015b) as highlighted by scenario studies (Clarke et al. 2014; Luderer et al. 2018; Cui et al. 2019), developed countries play a much more important role.

Bringing these two lines of evidence together might therefore strongly emphasises that particularly current CO_2 commitments from the power sector need to be substantially reduced through premature retirements or CCS retrofits in order to limit warming well below 2°C. This is the bottom-line of a growing scenario evidence that has become available (Luderer et al. 2018; Kriegler et al. 2018b; Minx et al. 2020a; Cui et al. 2019; Fofrich et al. 2020). This is important as the power sector is comparatively easy to decarbonise (IPCC 2014a; Krey et al. 2014) and it is crucial to leave space within the carbon budget for residual emissions from non-electric energy end uses that are particularly hard to mitigate. Moreover, any further delay in climate policy substantially increases the carbon commitments. Achieving the Paris climate goals increasingly depends on the availability of carbon dioxide removal technologies as the carbon commitments increase (Minx et al. 2020a; Kriegler et al. 2018b; Luderer et al. 2018).

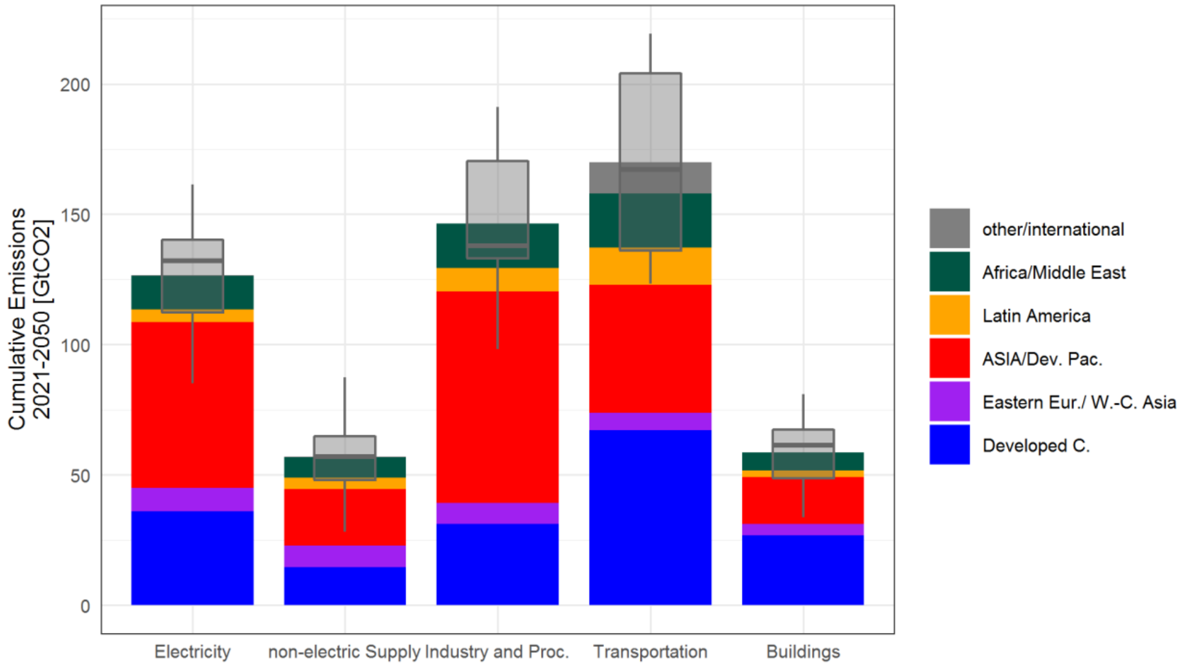


Figure 2.36 Cumulative residual (gross) fossil fuel emissions (GtCO$_2$) sectors and regions for the period 2021-2050 from scenarios that limit warming below 1.5°C. Stacked bars show mean cumulative, residual fossil fuel emission budgets across seven participating models: AIM/CGE, GCAM, IMAGE, MESSAGES, POLES, REMIND, WITCH. Grey box plots indicate the median and 16th–84th percentile range; whiskers indicate full spread. Colours indicate regions: Asian and Developing Pacific (red), Latin America and Caribbean (orange), Africa and Middle East (green), Developed Countries (blue), Eastern Europe and West-Central Asia (purple). Each bar represents one sector: electricity, non-electric energy supply, industry, transportation and building. Scenario design prescribes a harmonised, global carbon price in line with long-term carbon budget. Delay scenarios follow the same price trajectory, but 10 years later. Carbon dioxide removal requirements represent ex-post calculations that subtract gross fossil fuel emissions from the carbon budget associated with the respective long-term warming limit. Hence, CDR requirements reflect a minimum amount of CDR for a given mitigation trajectory. Results are reported at 2 significant digits. Analysis is based on Luderer et al. (2018).

Table 2.11 Residual (gross) fossil fuel emissions (GtCO$_2$) in climate change mitigation scenarios strengthening mitigation action after 2020 ("early strengthening"), compared to scenarios that keep NDC ambition level until 2030 and only strengthen thereafter. Cumulative emission budgets for 2021-2050 are given in terms of the mean as well as minimum and maximum (in parentheses) across seven participating models: AIM/CGE, GCAM, IMAGE, MESSAGES, POLES, REMIND, WITCH. Scenario design prescribes a harmonised, global carbon price in line with long-term carbon budget. Delay scenarios follow the same price trajectory, but 10 years later. Carbon dioxide removal requirements represent ex-post calculations that subtract gross fossil fuel emissions from the carbon budget associated with the respective long-term warming limit. Hence, carbon dioxide removal (CDR) requirements reflect a minimum amount of CDR for a given mitigation trajectory. Results are reported at 2 significant digits. Sources: (Minx et al. 2020a; Luderer et al. 2018)

Committed emission accounting			
		Tong et al. (2019)	
		GtCO$_2$	Year
Existing AND proposed	Electricity	546 (382-727)	2018
	Non-electric supply		
Existing	Industry	162 (110-219)	2017
	Transportation	64 (53-75)	2017
	Buildings	74 (52-105)	2018
	All sectors and proposed electricity	846 (597-1,126)	

Residual fossil fuel emissions - cumulative gross CO$_2$ emissions from fossil fuel and industry 2021-2050 (in GtCO$_2$)					
		Early strengthening from (2020)		*Delayed strengthening from 2030*	
		Well below 2°C	Below 1.5°C in 2100	Well below 2°C	Below 1.5°C in 2100
Existing AND future instalments	Electricity	190 (130 - 280)	130 (85 - 160)	250 (220 - 310)	210 (190 - 230)
	Non-electric supply	71 (37 - 84)	57 (28 - 87)	83 (49 - 110)	74 (41 - 100)
	Industry	190 (130 - 260)	150 (98 - 190)	230 (160 - 270)	200 (140 - 250)
	Transportation	210 (140 - 250)	170 (120 - 220)	230 (170 - 270)	200 (150 - 240)
	Buildings	77 (62 - 89)	59 (34 - 81)	85 (67 - 100)	70 (49 - 91)
	All sectors (2021-2050)	740 (590 - 880)	560 (440 - 640)	870 (750 - 940)	750 (610 - 860)
	All sectors (2021-2100)	1300 (970 - 1500)	850 (650 - 1100)	1400 (1200 - 1600)	1000 (860 - 1300)
	Implied minimum requirement for carbon dioxide removal	170	570	270	620

2.8 Climate and non-climate policies and measures and their impacts on emissions

2.8.1 Introduction

The key to achieving climate change mitigation targets is crafting environmentally effective, economically efficient and socially equitable policies. This section presents succinct assessments of the outcomes and effectiveness of climate policies applied in the last two decades (Section 2.8.2.). Detailed evaluation of climate policies is presented in Chapter 13. Furthermore, GHG emissions are also affected by policies enacted in various economic sectors to pursue non-climatic objectives. They are discussed in Section 2.8.3. A short summary is provided in Section 2.8.4. [6]

It is rather difficult, though not impossible, to discern the genuine impacts of climate or non-climate policies on GHG emissions. Most of current and past policies cover only a small part of global emissions in a limited geographical area and/or a small number of economic sectors. However, in addition to the targeted region or sector, policies and measures tend to affect GHG emissions in other parts of the world. Emissions leakage is the key channel by which such phenomena and complex interactions occur.[7] Uncertainties in impacts, synergies and trade-offs between policies and measures also complicate the evaluation of emissions impacts. These makes it challenging to identify the impacts of any specific policy or measure on emissions of any specific region or sector. Rigorous statistical analyses are necessary for building strong empirical evidence, but the experience to date of climate related policy experiments is limited.

National climate policy is complex and difficult. This is clearly demonstrated by Figure 2.37, which shows a cluster analysis combining climate policy success indicators (climate law adoption, fossil subsidy levels, per capita emissions levels) with political economy indicators, such as the strength of certain interest groups (e.g. oil & gas rents), state institutions and capabilities (e.g. control of corruption) and social factors (e.g. social trust and climate awareness) (Lamb and Minx 2020). Countries around the world thus face widely varying contexts and levels of hinderance in adopting climate policies and ensuring their effectiveness. The figure provides a useful backdrop to assessing the impacts of policies and measures discussed in the rest of this section.

FOOTNOTE: [6] This section only reviews emission impacts of policy instruments. Other important aspects such as equity and cost-effectiveness will be dealt with in Chapter 13 that is dedicated for the comprehensive evaluations of policies and measures.

FOOTNOTE:[7] Refer to Chapter 13 on policies and institutions for detailed discussion of emissions leakages and complex interactions from policy mixes.

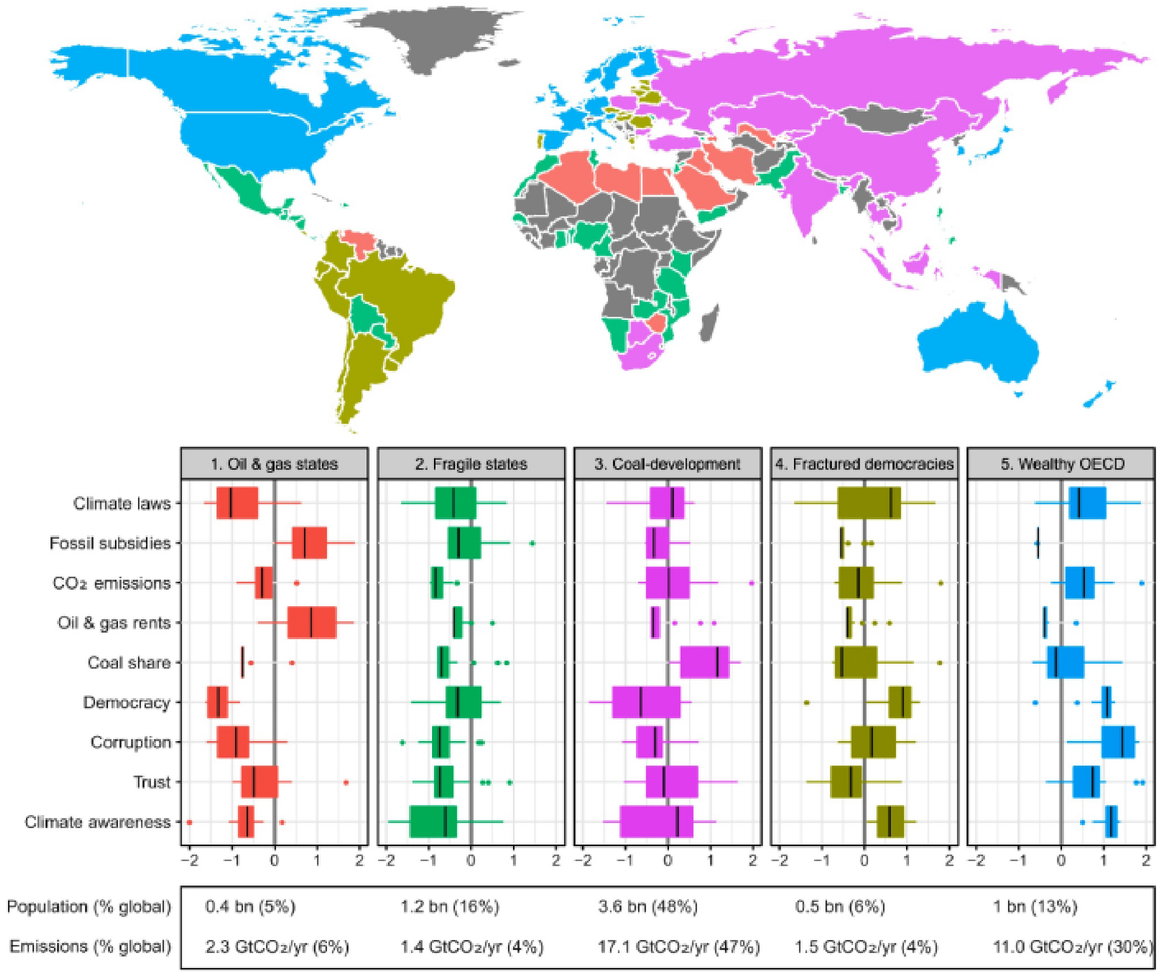


Figure 2.37 A typology of countries based on factors that hinder climate policy adoption and effectiveness. Countries are grouped using a kmeans algorithm on 12 variables of climate policy progress and political economic constraints (shown in the central panel as boxplots). (Lamb and Minx 2020).

2.8.2 Emissions impacts of climate policies

2.8.2.1 Comprehensive multinational assessments

Comprehensive multinational evaluations with wider regional and sectoral coverage enable us to assess emissions impacts without distortions from emissions leakage. Among the wide range of climate policy instruments, pricing carbon, such as a carbon tax or an emissions trading system, has been the one of the most popular and effective options to reduce GHG emissions. In a comparison of 142 countries with and without carbon pricing policies, countries with a carbon price showed an annual CO_2 emission growth rates 2 %p lower than countries without such policies, with an additional euro per tonne of CO_2 in carbon price being associated with a reduction in annual emissions growth rate of approximately 0.3 %p. (Best et al. 2020). A more comprehensive evaluation of carbon prices, using effective carbon rates, which encompasses both explicit and implicit carbon prices, shows that countries with a lower carbon pricing gap (a higher carbon price) tend to be more carbon-efficient, i.e., they have a lower carbon intensity of GDP (OECD 2018).[8] However, there is no empirical evidence so far of the effectiveness of

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FOOTNOTE: [8] (OECD 2018) measures carbon prices using the *effective carbon rate* (ECR), which is the sum of three components: specific taxes on fossil fuels, carbon taxes and prices of tradable emissions permits, for 42 such pricing policies in promoting technological change at the rate necessary for full decarbonisation (Lilliestam et al. 2020). In contrast, an empirical analysis on the effects of environmental regulation and innovation on the carbon emissions of OECD countries during the period 1999-2014 indicates that a 1% increase in environmentally friendly patents reduced carbon emissions by 0.017%, and a 1% increase in environmental tax revenue per capita reduced carbon emissions by 0.03% (Hashmi and Alam 2019).

Domestic as well as international climate legislation have contributed to the reduction of GHG emissions so far. An empirical analysis of legislative activity in 133 countries over the period 1999–2016 based on panel data indicated that each new law reduced annual carbon dioxide (CO_2) emissions per unit of GDP by 0.78% nationally in the short term (during the first three years) and by 1.79% in the long term (beyond three years). Additionally, current climate laws as of 2016 were associated with an annual reduction in global CO_2 emissions of 5.9 $GtCO_2$ (more than the US CO_2 emissions that year), and cumulative CO_2 emissions savings from 1999 amounting to 38 $GtCO_2$ (one year's worth of global CO_2 output) (Eskander and Fankhauser 2020). It is notable that 36 countries that accepted legally binding targets under the Kyoto Protocol all complied. On the domestic level, among the 36 countries, nine countries emitted higher levels of GHGs than committed and but finally complied the Kyoto Protocol by way of buying credits from abroad using flexibility mechanisms. Therefore, after the use of flexibility mechanisms, all Annex B Parties are in compliance (Shishlov et al. 2016).[9] It is impossible to disentangle precisely the contribution of overt domestic emission reduction (and land-use policy changes) to realised net emissions, but it is clear that the participating countries, especially those in the OECD, did make substantial policy efforts with material impact (Grubb 2016). The drivers of decreasing CO_2 emissions in a group of 18 developed economies that have decarbonised over the period 2005–2015 has been shown to be the displacement of fossil fuels by renewable energy and decreases in energy use (Le Quere et al. 2019).

2.8.2.2 Regional or national climate policies

Carbon pricing, carbon taxes and GHG emissions trading, has become the most popular climate policy instrument across the globe. As of May 2020, there are 61 carbon pricing initiatives in place or scheduled for implementation, consisting of 31 ETSs and 30 carbon taxes, covering 12 $GtCO_2eq$ or about 22% of global GHG emissions (World Bank 2020). Aside from the theoretic efficiency, the performance of carbon pricing in practice varies by countries and sector, and depends on policy environment, such as energy taxes and renewable energy incentives, and external factors, such as economic recessions, energy prices, and natural disasters.

The European Union Emissions Trading Scheme (EU ETS) is the most pronounced regional climate policy to date. The literature is in broad agreement that emissions have been abated as a result of the carbon price associated with the EU ETS though the estimates of the rate of abatement vary by study, by country and by sector; the full range is between 3% and 28% (Arlinghaus 2015; Ellerman et al. 2010; Anderson and Di Maria 2011; Egenhofer, Christian, Alessi Monica, Georgiev Anton 2011; Martin et al. 2016; Petrick and Wagner 2014; Abrell et al. 2011; McGuinness and Ellerman 2008). Though EU-25 countries achieved significant emissions reductions, a majority of emissions reductions occurred as a result of the economic crisis, and only about 11 ~ 13% of the total reduction can be attributed to the EU

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countries (OECD plus G20 countries) for six economic sectors (industry, electricity, residential and commercial, road transport, off-road transport, and agriculture and fisheries). The *carbon pricing gap* measures the difference between actual ECRs and benchmark rates. The report considers two benchmark rates: EUR 30, a low-end estimate of carbon costs today; and EUR 60, a midpoint estimate of the carbon cost in 2020 and a low-end estimate for 2030. The carbon pricing gap indicates the extent to which polluters do not pay for the damage from carbon emissions.

FOOTNOTE: [9] Overall, the countries party to the Protocol surpassed their aggregate commitment by an average 2.4 $GtCO_2eq\ yr^{-1}$. Of the possible explanations for this overachievement, 'hot-air' was estimated at 2.2 $GtCO_2eq\ yr^{-1}$, while accounting rules for land use, land-use change and forestry (LULUCF) further removed 0.4 $GtCO_2eq\ yr^{-1}$ from the net result excluding LULUCF (Shishlov et al. 2016).

ETS (Bel and Joseph 2015). Renewable energy policies both at the EU and Member States level, and other non-climate policies such as the Landfill Directive, the Large Combustion Plant Directive, the Nitrates Directive and other agricultural policies, have played an essential role in abating GHG emissions, especially non-CO_2 emissions during the 1995~2012 period (ICF International 2016). The EU ETS saved about 1.2 billion tons of CO_2 between 2008 and 2016 (3.8%) relative to a world without carbon markets, or almost half of what EU governments promised to reduce under their Kyoto Protocol commitments (Bayer and Aklin 2020).

China's emission trading pilots have resulted in a significant decline in the carbon intensity in the pilot provinces, by way of adjusting the industrial structure, but energy structure and energy intensity channels have not yet been realised (Zhou et al. 2019). The Regional Greenhouse Gas Initiative (RGGI) in the USA has induced leakage in emissions, through increases in electricity generation in surrounding non-RGGI areas, but it has led to the reduction of emissions at the aggregate level by way of changes in the fuel mix from coal to gas (Fell and Maniloff 2018). The environmental effectiveness of the Tokyo ETS has not been assessed, but the advisory aspects of the Tokyo ETS, such as monitoring and information sharing, has been effective in encouraging energy savings (Wakabayashi and Kimura 2018). Actual emissions declined for six of the ten ETSs where data is available, while at the same time the 2009 recession, changes in the relative prices of coal and natural gas, renewable energy and energy efficiency initiatives, and the nuclear plant shutdown following the great east Japan earthquake and tsunami have had significant impacts on the emissions covered by several of the ETSs (Haites et al. 2018).

The evidence of environmental effectiveness of carbon taxes in Western European countries is varied depending on country and study. A significant impact is found in Finland but insignificant impacts is found in Denmark and Netherlands, and there are mixed results for Sweden (Lin and Li 2011; Brännlund et al. 2014) . Only six of the 17 taxes, where data are available, have reduced actual emissions subject to the tax—Denmark (duty on CO_2), Japan, Slovenia (fluorinated gases), Sweden, Switzerland and the UK. Tax rates, with the exception of Sweden and Switzerland, are probably too low to materially affect emissions by most taxed sources and in most jurisdictions. In addition, the scale and frequency of the rate changes has not been sufficient to stimulate further emissions reductions (Haites et al. 2018).

An assessment of the performance of 17 carbon taxes and 10 ETSs with respect to environmental effectiveness suggests that both instruments reduce emissions, but ETSs have performed better than carbon taxes on the principal criteria of environmental effectiveness and cost-effectiveness (Haites et al. 2018).

2.8.2.3 Sectoral climate policies

Many governments have implemented sector-specific policies, in addition to nationwide measures, to reduce GHG emissions. Examples of sectoral climate policies includes carbon taxes on transportation fuels, low carbon fuel standards, and regulation of coal power generation.

The implementation of a carbon tax and value-added tax on gasoline and diesel in Sweden resulted in significant reductions of CO_2 emissions in the transportation sector (Andersson 2019; Shmelev and Speck 2018). An assessment of a variety of carbon tax schemas across various sectors in the European Union show a negative relationship between CO_2 emissions and a CO_2 tax (Hájek et al. 2019). In British Columbia, the carbon tax resulted in a decrease in demand for gasoline and a reduction in total greenhouse gas emissions (not exclusive to the transportation sector) estimated to be between 5-15% (Murray and Rivers 2015; Rivers and Schaufele 2015). Modelling studies show that carbon pricing can induce mode switching in international transportation as well (Avetisyan 2018). Low Carbon Fuel Standards in California have contributed to reducing carbon emissions in the transportation sector by approximately 9.85% ~ 13.28% during 1997~2014 (Huseynov and Palma 2018).

The power sector typically accounts for a large portion of countries' CO_2 emissions. Market-based regulation and government subsidies in China contributed to improving operational efficiency and reducing emissions, but command and control regulations, such as emission or technology standards, failed to show any statistically significant impacts on reducing emissions of China's power plants (Zhao et al. 2015). Mandatory climate and energy policies, including California Global Warming Solutions Act (AB32), reduced CO_2 emissions by 2.7 ~ 25% of average state-level annual emissions from the power sector over the period 1990-2014 in the USA. Mandatory GHG registry/reporting, electric decoupling and public benefit fund have been effective in further decreasing power sector emissions in the USA (Martin and Saikawa 2017). In the UK electricity sector, a carbon price floor, combined with electricity market reform (competitive auctions for both firm capacity and renewable energy), displaced coal, whose share fell from 46% in 1995 to 7% in 2017, halving CO_2 emissions, while renewables grew from under 4% in 2008 to 22% by 2017 (Grubb and Newbery 2018).

Box 2.3 Emission impacts of carbon pricing: Case of UK Carbon Price Support

The United Kingdom introduced a Carbon Price Support (CPS) in 2013 at GBP 9 per tonne of CO_2 for emissions in the electricity sector. The carbon price support is charged on top of permit prices and was increased to GBP 18 by 1 April 2015. The total effective carbon rate has been slightly over EUR 30 per tonne CO_2 since then.

Emissions from the electricity sector decreased by 58% from 2012, before the CPS was introduced*, to 2016, the first full year for which total effective carbon rates equalled about EUR 30.* The decrease in emissions is explained by a sharp drop in the use of coal for the generation of electricity. Coal use fell by 78% during the same period. Coal was partly replaced by natural gas, which is about half as emissions intensive as coal per unit of energy, and partly by zero-carbon renewables. Overall UK emissions from energy use fell by 25% between 2012 and 2016, of which 19% can be attributed to cleaner electricity generation.

Source: OECD (2018)

2.8.3 Emission impacts of non-climate policies

2.8.3.1 Co-impacts of air quality, sector specific, and energy policies on climate mitigation

Policies other than those intended directly to mitigate GHG emissions can also influence these. Co-impacts of local or regional air pollution abatement policies and measures for climate mitigation are the most studied in literature. Cross-border externalities of air pollution have also made these a focus of several international agreements, with over 60 multilateral treaties and several bilateral protocols enacted since the 1970s (Mitchell et al. 2020). Evaluating the effectiveness of such treaties and policies both for their intended outcomes and other potential co-impacts, including co-benefits or costs, on GHG emissions is difficult because deriving causal inferences and accurate attribution requires accounting for several confounding factors and direct and indirect spill overs (Isaksen 2020). Nevertheless, several studies assess the effectiveness of such treaties and regulations (Li et al. 2017c; Zhao et al. 2015; Li et al. 2017b; Mardones and Cornejo 2020; Wang et al. 2019b; Morgenstern 2018; De Foy et al. 2016). However, there is a greater focus on ex-ante studies rather than ex-post empirical analysis in the literature.

Air pollution control measures can in theory intensify or mitigate climate change. The focus of many air quality policies and regulations is on local pollution from specific sources that can potentially either substitute or complement global GHG emissions in production and generation processes. Moreover, policies that reduce certain air pollutants, such as SO_2, have a positive radiative forcing effect (Navarro et al. 2016). The evidence on the ancillary co-impacts of air pollution control regulation and policies for GHG emissions is therefore mixed. Evidence from the USA suggests that increased stringency of local pollution regulation had no statistically detectable co-benefits or costs on GHG emissions (Brunel and

Johnson 2019). Evidence from China suggests that there have been differences in the effectiveness of policies addressing local point sources as opposed to non-point sources and the co-benefits for climate are mixed (van der A et al. 2017; Yu et al. 2019; Xu et al. 2016; Huang and Wang 2016; Liu et al. 2020e; Dang and Liao 2019; Fang et al. 2019). Legislation to reduce emissions of air pollutants in Europe have significantly improved air quality and health but have had an unintended warming effect on the climate (Turnock et al. 2016).

In many instances, the realisation of potential co-benefits is dependent on the type of pollutant addressed by the specific policy, and whether complementarities between local pollution and global GHG emissions are considered in policy design (Li et al. 2017b; Rafaj et al. 2014). Effective environmental regulations that also deliver co-benefits for climate mitigation require integrated policies (Schmale et al. 2014; Haines et al. 2017). However, the extent of mainstreaming or integration of climate concerns in sectoral plans and policies is often unclear. Moreover, uncoordinated policies can have unintended consequences and even increase emissions (Holland et al. 2015). Pollution control policies and regulations that focus on single pollutants may not deliver benefits for the mitigation of GHG emissions. Many studies suggest that policies that target both local and global environmental benefits simultaneously may be more effective (Klemun et al. 2020). Furthermore, air pollution policies aimed at inducing structural changes, e.g. closure of polluting coal power plants or reducing motorised miles travelled, are more likely to have potential positive spill over effects for climate mitigation, as compared to policies incentivising end-of-pipe controls (Ji et al. 2017).

Other policies that typically have potential co-benefits for climate mitigation include those specific to certain sectors. A detailed discussion of sector specific policies and regulations can be found in chapter 5 and chapters 6-11, and a detailed overview of these is not provided again here. Examples of such policies include for instance, those that encourage active travel modes, which have been found to have ancillary benefits for local air quality, human health and GHG emissions (Fujii et al. 2018). Efforts to support a transition to renewable energy sources are also seen to have important air quality and climate co-benefits (Apergis et al. 2018). Policies to encourage green building design have also been shown to reduce GHG emissions (Eisenstein et al. 2017). Evidence from several countries also show that efforts at replacing polluting solid biomass cooking with cleaner gas-burning or electric alternatives also have strong co-benefits for health, air quality and climate change (Anenberg et al. 2017; Singh et al. 2017; Tao et al. 2018).

Finally, the coronavirus pandemic and subsequent economic and social crises ensuing also offer new opportunities to design reform and recovery packages that also help mitigate climate change. While it is too early to assess the empirical evidence of impacts of such policies, which are still being decided and implemented, an emerging literature is highlighting how policies targeting economic recovery can go hand in hand with reducing GHG emissions (Engström et al. 2020).

2.8.3.2 Policies in the transportation sector

An alternative approach to a carbon tax is an indirect emissions tax on fuels, such as an excise tax, or on vehicles, based on the expected CO_2 intensity of new passenger vehicles. Vehicle purchase taxes can result in a reduction in greenhouse gas emissions through reducing the CO_2 emissions intensity of vehicles, while also discouraging new vehicle purchases (Aydin and Esen 2018). For example, a vehicle tax policy in Norway resulted in a reduction of average CO_2 intensity per kilometre of 7.5gCO_2/km (Ciccone 2018; Steinsland et al. 2018). Despite such evidence, studies of carbon pricing find that additional policies are often needed to stimulate sufficient emissions reductions in transportation (Tvinnereim and Mehling 2018).

Electric vehicles can reduce greenhouse gas emissions and such policies are important for spurring adoption of such vehicles, and greenhouse gas emission reductions (Kumar and Alok 2020; Thiel et al. 2020). The extent to which electric vehicle deployment can decrease emissions by replacing internal-combustion engine based vehicles depends on the generation mix of the electric grid (Choi et al. 2018;

Canals Casals et al. 2016; Nichols et al. 2015; Abdul-Manan 2015; Teixeira and Sodré 2018; Hofmann et al. 2016). The adoption of hybrid electric vehicles and plug-in electric vehicles can result in greenhouse gas reductions, but the magnitude depends on the electricity generation mix (Nanaki and Koroneos 2013). Barriers to electric vehicle adoption include fragmented infrastructure, missing standards, and challenges of adoption among potential adopters (Steinhilber et al. 2013).

Policy incentives for electric vehicle adoption can be an effective mechanism to increase electric vehicle sales (Langbroek et al. 2016) and may include charging discounts, purchase subsidies, regulations, and government leadership (Bakker and Jacob Trip 2013; Qiu et al. 2019; Santos and Davies 2020; Silvia and Krause 2016; Teixeira and Sodré 2018). The presence of charging infrastructure and publicly available charging increases the adoption rate of electric vehicles (Vergis and Chen 2015; Javid et al. 2019). A comparison of electric vehicle adoption rates across 30 countries shows a positive correlation between charging stations and electric vehicle market share (Sierzchula et al. 2014). A rollout of 80,000 DC fast chargers across the United States is estimated to have resulted in a 4% reduction in emissions compared to a baseline of no additional fast chargers (Levinson and West 2018). More recently bans on internal combustion engine vehicles has provided a much more direct approach to stimulating the adoption of EVs and its supporting infrastructure; however the efficacy of such measures depends on enforcement (Plötz et al. 2019).

Public transit can reduce vehicle travel and reduce greenhouse gas emissions by reducing the number of trips taken by private vehicles and the length of those trips. Changes to the operation of public transportation systems (such as density of bus stops, distance from stops to households, duration and frequency of trip times, and lowering ridership costs) can result in a mode shift from private car trips to public transit trips (Choi 2018; Cats et al. 2017; Carroll et al. 2019). These changes in the public transit system operation and network optimisation have been shown to have reduced greenhouse gas emissions in cases such as San Francisco, in which the cost optimisation of the transit network was estimated to decrease emissions by a factor of three (Cheng et al. 2018) and Barcelona, where the optimisation of the urban bus system was estimated to reduce greenhouse gas emissions by 50% (Griswold et al. 2017). For every 1% increase in investment in transit services and transit-oriented design, there is an estimated 0.16% reduction in vehicle kilometres travelled per capita (McIntosh et al. 2014).

Besides rail and busses, bike and car sharing programs can reduce greenhouse gas emissions. A study of eight cities in the United States found that bike share programs contribute to a reduction in greenhouse gas emissions, with larger bike share systems and higher ridership contributing to larger reductions, although the potential of bike share programs to reduce total emissions is limited to <0.1% of total greenhouse gas emissions from the transportation sectors of these cities (Kou et al. 2020). The emission reductions, or lack thereof, associated with car-sharing programs is disputed and depends on the specifics of programs: the mode shift from public transit to car-sharing services can outweigh the decreases in greenhouse gas emissions associated with decreased cars on the road (Jung and Koo 2018), whereas car sharing programs with electric vehicle fleets may reduce greenhouse gas emissions (Luna et al. 2020).

2.8.3.3 Climate impacts of agricultural, forestry and land use policies

Policies on agriculture, forestry and land use have had a long history in many developing and developed countries. Co-impacts of these policies on the climate have been only marginally studied, although the impact might be quite important, given the high part of the AFOLU sector, which is responsible for about one third of total GHG emissions (see Chapter 7 for details of emissions trends and mitigation measures in the AFOLU sector). Moreover, both private and governmental policies can have a major impact on the climate. Experience indicates that "climate proofing" a policy is likely to require some stimulus, resources and expertise from agencies or organisations from outside the country. National governments in developing countries invariably have such wide-ranging demands and constraints on agricultural policy development and implementation that mainstreaming climate change rarely becomes a priority. Stimulus and support for adaptation and mitigation can come from the UN system and from international development institutions (Bockel, L ; Smit 2009).

Forestry case: zero deforestation

Zero-deforestation initiatives generate results at multiple levels (Meijer 2014). Efforts to achieve zero-deforestation (and consequently emissions) are undertaken by NGOs, companies, governments and other stakeholder groups. NGOs engage through their campaigning, but also propose tools and approaches for companies. The extent to which companies can actually monitor actions conducive to zero deforestation pledges depends on their position in the supply chain. Companies at the production end of the supply chain are able to make pledges with tailor-made performance indicators, and to verify compliance with these pledges themselves. Producers, processors and vertically integrated companies control production, or at least have a direct relationship with producers. They can therefore verify compliance with zero-deforestation pledges themselves, instead of having to rely on certification. The companies themselves work to improve corporate policies and achieve compliance with certification standards. However, albeit a useful output that contributes to deforestation reduction, certification is not universally seen as an end in itself: zero deforestation requires substantial improvements to underlying business practices as an outcome. Beyond the business practices of participating companies, achieving long-term positive societal impacts requires upscaling from supply chains towards landscapes, with engagement of all stakeholders, and in particular small producers. The various success indicators for zero deforestation mirror the multiple levels at which such initiatives develop: progress towards certification, improved traceability and legality are apparent output measures, whereas direct-area monitoring and site selection approaches target the business practices themselves. Long-term positive impacts, however, will need to be assessed with hindsight and focus on national and global statistics. Successful initiatives targeting zero deforestation at jurisdictional level would also need to improve the enforcement of forest laws and regulations (EII 2015; Meyer, C; Miller 2015).

Large-scale agribusiness, banks and consumer goods companies dominate supply-chain focused zero deforestation initiatives, but only the producers (TFD 2014), including local communities and smallholders, can change the production circumstances. Private-sector commitments are mostly assumed by large-scale agribusiness, banks and consumer goods companies but their pledges are relevant for their entire supply chains. Producers shoulder much of the burden for meeting environmental requirements of pledges. And local communities and small producers are vulnerable to being cut out when supply chains reorient. The zero-deforestation pledges do not always devise programmes for introducing new sourcing strategies, and this omission needs to be addressed. Governments may have an important contribution to make here, particularly in safeguarding the interests of small producers.

Other than in Brazil, beyond individual supply chains, there is still little evidence on positive results of zero-deforestation commitments, and implementation efforts need to be stepped up. There is too little information available for companies to judge their progress. Moreover, many zero-deforestation pledges set targets to be achieved by 2020 or 2030, and, consequently, many companies have not yet reported publicly on their progress. Similarly, only a few governments have yet shown progress in reducing deforestation, but the New York Declaration on Forests, the SDGs and the Paris Agreement were adopted relatively recently. It seems plausible to conclude that the effectiveness of private-sector zero-deforestation pledges depends on the extent to which they can be supported by governmental action and foster a cooperative environment with the engagement of all stakeholders. Where the pledges are coordinated with regulation, multi-stakeholder dialogues and technical and financial support, a true paradigm shift becomes possible. Many governments are still building the capacity to improve overall forest governance, but implementing ambitious international targets is likely to depend on technical and financial support that has not yet been mobilised.

The zero-deforestation initiatives have created a valuable opportunity to strengthen forest governance through closer collaboration between governments, the private sector and civil society. Sustainable and timely results rely on the capacity of such initiatives to establish collaborative action with multiple stakeholders, recognising their different needs, providing support and feeding back the lessons learned. Whereas the private sector can be a catalyst and should be open to dialogue and collaboration with stakeholders outside a specific supply chain, governments play a fundamental role in providing leadership. They can harness the conditions for halting deforestation, along with the inclusion and upgrading of sustainability standards across commodity value chains. Governments, the private sector and civil society need to work together in multi-stakeholder partnerships to shape good land-use governance and advance sustainable development.

2.8.4 Main Conclusions

The literature is in broad agreement that emissions reduction have taken place as a result of the carbon pricing associated with carbon taxes or emissions trading, as well as other climate policies and legislations, though magnitude of reductions vary by the kind of data and methodology used, by country and by sector (*robust evidence, high agreement*). Climate related policies such as renewable portfolio standards have played a significant role in decreasing GHG emissions in some regions including the EU. Also, domestic and international climate legislation have contributed to reducing GHG emissions globally.

Carbon pricing has been one of the most popular and effective policy instruments. Evidence of successful carbon pricing schemes, especially emission trading schemes in the European Union, have shown their effectiveness in reducing GHG emissions. Also, the sector-specific policies, such as carbon taxes in transportation and market and non-market-based policies in the power sector, showed their effectiveness in reducing GHG emissions in many countries. However, the effectiveness of carbon pricing and climate policies have been varied by country and study, and this indicates that it is important not only to design well-organised carbon pricing or climate policies but also to consider the economic, political, and social grounds of a country or a region.

Moreover, it is necessary to pay more attention to the understanding of the co-benefits of non-climate policies. While it is difficult to derive causality and accurate direct and indirect effects on GHG emissions, an increasing number of studies have been conducted to identify co-benefits, especially of air pollution abatement policies and GHG emissions reductions. The mixed results of co-benefits between climate mitigation and other non-climate policies indicate the importance of understanding and internalising the co-benefits in decision-making processes in order to avoid unintended consequences of increasing GHG emissions and to bring environmental, social, and economic benefits and climate mitigation together.

2.9 Gaps in Knowledge and Data

- Progress has been made on the provision and timely update of territorial GHG emissions, but more work needs to be done in quantifying relevant uncertainties. Such assessment of uncertainties should deploy different methods and not only be carried at the global, but also national, sub-national and sectoral level.

- While the consumption-based CO_2 emissions provide important insights on the emissions and the mitigation opportunities, research gaps are numerous. Prevalence of several different carbon accounting frameworks is making comparison difficult. Many of them are less useful in rapidly developing countries. There is less research on developing countries and emission accounting for cities. Drivers/reasons that caused decoupling in different types of countries need to be further explored. How to achieve decoupling without outsourcing emissions to less developed regions is a key question to address. How will global supply chains change in the post-crisis era and thus impact consumption-based emissions for countries and cities needs future work.

- Understanding the ways to modulate social-economic drivers towards emission mitigation is crucial. Technological improvements (e.g. improved energy or land use intensity of the economy) have persistent pattern over the last few decades but the gains have been outpaced by increases in affluence (GDP per capita) and population growth, leading to continued emissions growth. The main gap in knowledge therefore is how these persistent and powerful drivers that increased emissions can be mitigated by demand management, alternative economic models, population control and rapid technological transition. Linked to this is the question how the physical material throughput of economies can be reduced without jeopardising economic and social wellbeing. More research on decoupling and sustainability transformations is needed to answer these questions. Key knowledge gaps also remain in differentiating the urban mitigation options based on the stage of urban development and how trade could help to reduce global GHG emissions, in particular, how supporting low-carbon technologies in developing and exporting countries can counteract the upward-driving effect of trade.

- Understanding of how inequality affects emissions is in a nascent stage. Not much is known about the causal mechanisms by which different dimensions of inequality affect emissions. In particular, limited knowledge exists on the linkages between dimensions of inequality other than income or wealth and emissions arising from different service demands. Research on how inequalities in living standards relate to emissions and how changes in inequalities between genders, social groups, and other marginalised communities impact emissions trends needs to be deepened.

- Digitalisation of economy are often quoted as providing new opportunities, but the more knowledge and evidences are necessary. Understanding what role can be played by smart apps running on multi sensor devices to facilitate sharing of resources in solving mitigation and other environmental problems are necessary. Transparency and further evidence gathering on the benefit of sharing economy impacts on mitigation are needed. The potentials and influence of disruptive technologies (demand and supply side) on GHG emissions needs more scrutiny.

- Despite growing evidence of technological progress across a variety of mitigation areas and the availability of increasingly precise data sets, knowledge gaps remain on technological change and innovation and evidences on speed of transitions to clarify what would make them fast or slow. Innovation is an inherently uncertain process and there will always be imperfect ex ante knowledge on technological outcomes and their effects on mitigation. The extent to which a low-carbon transition can proceed faster than historical examples is crucial to understand for the mitigation. That depends on a better understanding of the speed of infrastructure build and replacement. Additionally, how and whether financing for low-carbon technology investment in LMI countries can be delivered at low-cost and sustained over time needs further research. The emerging findings that the small-scale technologies learn faster and are adopted more quickly needs to be tested against a broader set of cases and in particular the large dispersion in data and residual needs to be explained. More knowledge is also needed on how important mitigation technologies can grow much faster to be relevant to the urgent mitigation needs.

- Synthetic work is required to bring together assessments of carbon lock-in from the accounting as well as the scenario literature. This requires conceptual work on the relationship between carbon budgets, residual fossil-fuel emissions and carbon dioxide removal on the one hand, and integration of data and modelling approaches on the application side.

- More evidence is needed on the performance of climate and non-climate policies and measures in reducing emissions. More attention needs to be paid to the methodology for comprehensive evaluation of climate policies and measures, such as effective carbon rates and more research is needed on ex-post evaluations on emission impacts of climate and non-climate policies and measures, particularly on the global scale, considering national circumstances and priorities.

Frequently Asked Questions

FAQ 2.1 Is humanity on track to reduce emissions?

Global Greenhouse (GHG) emissions continued to rise and measured at 59±5.9 $GtCO_2eq$ in 2018 although the rate of growth has fallen compared to the previous decade. Still, emissions were higher than at any point in human history before**.** Emissions were 11% (6.0 $GtCO_2eq$) and 51% (20 $GtCO_2eq$) higher than in 2010 and 1990, respectively. Average annual GHG emissions for 2009-2018 were 56±5.6 $GtCO_2eq$ compared to 47±4.7 and 40±4.0 $GtCO_2eq$ for 2000-2009 and 1990-1999, respectively. GHG emissions growth slowed since 2010: while average annual GHG emissions growth was 2.3% between 2000 and 2010, it was only 1.3% for 2010-2018. Emissions and removals of GHGs are weighted by Global Warming Potentials with a 100-year time horizon (GWP100), using values from the Sixth Assessment Report (Section 2.2.1).

FAQ 2.2 Are there countries that have managed to economically grow and reduce emissions at the same time?

There are at least 36 countries that have sustained territorial-based CO_2 and GHG emissions reductions for more than 10 years. While total cumulative GHG reductions of these decarbonising countries are trivial compared to recent global emissions growth, some of them achieved a relative decline of up to 50% in emissions, showing what is possible even under circumstances that were only moderately favourable for climate policies (Section 2.2.3). 43 out of 166 countries have achieved absolute decoupling of consumption-based CO_2 emissions from economic growth in recent years (2010-2015)**.** A group of developed countries, such as some EU countries and the United States of America, and some developing countries, such as Cuba and Iran, have successfully achieved absolute decoupling of consumption-based CO_2 emissions and GDP growth (i.e., experienced GDP growth while their emissions have stabilised or declined). The decoupling has been achieved at various levels of per capita income and per capita emissions (Section 2.3.1).

FAQ 2.3 How much time do we have to act?

If global CO_2 emissions continue to be released at current rates, the remaining carbon budget for keeping warming below both 1.5°C will be exhausted before 2030. Between 1850 and 2018 total cumulative CO_2 emissions from the Fossil Fuel Industry (FFI) and Agriculture, Forestry and Other Land Use (AFOLU) were 2400±390 $GtCO_2$. Of these, about 980±98 $GtCO_2$ were added to the atmosphere since 1990. 330±31 $GtCO_2$ were added since AR5 (2010). This is about the same size as the remaining carbon budget of 310±250 (390, 500) $GtCO_2$ for keeping global warming below 1.5°C and between 2-3 times smaller than the 960±250 (1140, 1390) $GtCO_2$ for keeping warming below 2°C with a probability of 67% (50%, 33%), respectively. At current rates of CO_2 emissions (43±4.1 Gt CO_2 yr^{-1}), these remaining budgets will be exhausted in 7(9,11) and 22 (27, 33) years, respectively, depending on selected probability threshold and how remaining geo-physical uncertainties unfold. Even in the case of global CO_2 emission reductions at 2% or 5% per year, the 1.5°C budget will be exhausted before 2030 highlighting the dependence of 1.5°C pathways on the availability of substantial CO_2 removal capacities (Section 2.2.1).

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