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Drivers, Trends and Mitigation

Coordinating Lead Authors:

Gabriel Blanco (Argentina), Reyer Gerlagh (Netherlands), Sangwon Suh (Republic of Korea/USA)

Lead Authors:

John Barrett (UK), Heleen C. de Coninck (Netherlands), Cristobal Felix Diaz Morejon (Cuba), Ritu Mathur (India), Nebojsa Nakicenovic (IIASA/Austria/Montenegro), Alfred Ofosu Ahenkorah (Ghana), Jiahua Pan (China), Himanshu Pathak (India), Jake Rice (Canada), Richard Richels (USA), Steven J. Smith (USA), David I. Stern (Australia), Ferenc L. Toth (IAEA/Hungary), Peter Zhou (Botswana)

Contributing Authors:

Robert Andres (USA), Giovanni Baiocchi (UK/Italy), William Michael Hanemann (USA), Michael Jakob (Germany), Peter Kolp (IIASA/Austria), Emilio la Rovere (Brazil), Thomas Michielsen (Netherlands/UK), Keisuke Nansai (Japan), Mathis Rogner (Austria), Steven Rose (USA), Estela Santalla (Argentina), Diana Ürge-Vorsatz (Hungary), Tommy Wiedmann (Germany/Australia), Thomas Wilson (USA)

Review Editors:

Marcos Gomes (Brazil), Aviel Verbruggen (Belgium)

Chapter Science Assistants:

Joseph Bergesen (USA), Rahul Madhusudanan (USA)

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Executive Summary

Chapter 5 analyzes the anthropogenic greenhouse gas (GHG) emission trends until the present and the main drivers that explain those trends. The chapter uses different perspectives to analyze past GHG-emissions trends, including aggregate emissions flows and per capita emissions, cumulative emissions, sectoral emissions, and territory-based vs. consumption-based emissions. In all cases, global and regional trends are analyzed. Where appropriate, the emission trends are contextualized with long-term historic developments in GHG emissions extending back to 1750.

GHG-emissions trends

Anthropogenic GHG emissions have increased from 27 (±3.2) to 49 (±4.5) $GtCO_2$eq/yr (+80 %) between 1970 and 2010; GHG emissions during the last decade of this period were the highest in human history *(high confidence)*.[1] GHG emissions grew on average by 1 $GtCO_2$eq (2.2 %) per year between 2000 and 2010, compared to 0.4 $GtCO_2$eq (1.3 %) per year between 1970 and 2000. [Section 5.2.1]

CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78 % of the total GHG emission increase from 1970 to 2010, with similar percentage contribution for the period 2000–2010 (*high confidence*). Fossil fuel-related CO_2 emissions for energy purposes increased consistently over the last 40 years reaching 32 (±2.7) $GtCO_2$/yr, or 69 % of global GHG emissions in 2010.[2] They grew further by about 3 % between 2010 and 2011 and by about 1–2 % between 2011 and 2012. Agriculture, deforestation, and other land use changes have been the second-largest contributors whose emissions, including other GHGs, have reached 12 $GtCO_2$eq/yr (*low confidence*), 24 % of global GHG emissions in 2010. Since 1970, CO_2 emissions increased by about 90 %, and methane (CH_4) and nitrous oxide (N_2O) increased by about 47 % and 43 %, respectively. Fluorinated gases (F-gases) emitted in industrial processes continue to represent less than 2 % of anthropogenic GHG emissions. Of the 49 (±4.5) $GtCO_2$eq/yr in total anthropogenic GHG emissions in 2010, CO_2 remains the major anthropogenic GHG accounting for 76 % (38±3.8 $GtCO_2$eq/yr) of total anthropogenic GHG emissions in 2010. 16 % (7.8±1.6 $GtCO_2$eq/yr) come from methane (CH_4), 6.2 % (3.1±1.9 $GtCO_2$eq/yr) from nitrous oxide (N_2O), and 2.0 % (1.0±0.2 $GtCO_2$eq/yr) from fluorinated gases. [5.2.1]

Over the last four decades GHG emissions have risen in every region other than Economies in Transition, though trends in the different regions have been dissimilar (*high confidence*). In Asia, GHG emissions grew by 330 % reaching 19 $GtCO_2$eq/yr in 2010, in Middle East and Africa (MAF) by 70 %, in Latin America (LAM) by 57 %, in the group of member countries of the Organisation for Economic Co-operation and Development (OECD-1990) by 22 %, and in Economies in Transition (EIT) by 4 %.[3] Although small in absolute terms, GHG emissions from international transportation are growing rapidly. [5.2.1]

Cumulative fossil CO_2 emissions (since 1750) more than tripled from 420 $GtCO_2$ by 1970 to 1300 $GtCO_2$ (±8 %) by 2010 (*high confidence*). Cumulative CO_2 emissions associated with agriculture, deforestation, and other land use change (AFOLU) have increased from about 490 $GtCO_2$ in 1970 to approximately 680 $GtCO_2$ (±45 %) in 2010. Considering cumulative CO_2 emissions from 1750 to 2010, the OECD-1990 region continues to be the major contributor with 42 %; Asia with 22 % is increasing its share. [5.2.1]

In 2010, median per capita emissions for the group of high-income countries (13 tCO_2eq/cap) is almost 10 times that of low-income countries (1.4 tCO_2eq/cap) (*robust evidence, high agreement*). Global average per capita GHG emissions have shown a stable trend over the last 40 years. This global average, however, masks the divergence that exists at the regional level; in 2010 per capita GHG emissions in OECD-1990 and EIT are between 1.9 and 2.7 times higher than per capita GHG emissions in LAM, MAF, and Asia. While per capita GHG emissions in LAM and MAF have been stable over the last four decades, in Asia they have increased by more than 120 %. [5.2.1]

The energy and industry sectors in upper-middle income countries accounted for 60 % of the rise in global GHG emissions between 2000 and 2010 (*high confidence*). From 2000–2010, GHG emissions grew in all sectors, except in AFOLU where positive and negative emission changes are reported across different databases and uncertainties in the data are high: energy supply (+36 %, to 17 $GtCO_2$eq/yr), industry (+39 %, to 10 $GtCO_2$eq/yr), transport (+18 %, to 7.0 $GtCO_2$eq/yr), buildings (+9 %, to 3.2 $GtCO_2$eq/yr), AFOLU (+8 %, to 12 $GtCO_2$eq/yr).[4] Waste GHG emissions increased substantially but remained close to 3 % of global GHG emissions. [5.3.4, 5.3.5]

In the OECD-1990 region, territorial CO_2 emissions slightly decreased between 2000 and 2010, but consumption-based CO_2 emissions increased by 5 % (*robust evidence, high agreement*). In most developed countries, both consumption-related emissions and GDP are growing. There is an emerging gap between territorial,

[1] Values with ± provide uncertainty ranges for a 90 % confidence interval.

[2] Unless stated otherwise, all emission shares are calculated based on global warming potential with a 100-year time horizon. See also Section 3.9.6 for more information on emission metrics.

[3] The country compositions of OECD-1990, EIT, LAM, MAF, and ASIA are defined in Annex II.2 of the report. In Chapter 5, both 'ASIA' and 'Asia' refer to the same group of countries in the geographic region Asia. The region referred to excludes Japan, Australia and New Zealand; the latter countries are included in the OECD-1990 region.

[4] These numbers are from the Emissions Database for Global Atmospheric Research (EDGAR) database (JRC/PBL, 2013). These data have high levels of uncertainty and differences between databases exist.

production-related emissions, and consumption-related emissions that include CO_2 embedded in trade flows. The gap shows that a considerable share of CO2 emissions from fossil fuels combustion in developing countries is released in the production of goods exported to developed countries. By 2010, however, the developing country group has overtaken the developed country group in terms of annual CO_2 emissions from fossil fuel combustion and industrial processes from both production and consumption perspectives. [5.3.3]

The trend of increasing fossil CO_2 emissions is robust (*very high confidence*). Five different fossil fuel CO_2 emissions datasets—harmonized to cover fossil fuel, cement, bunker fuels, and gas flaring—show ±4 % differences over the last three decades. Uncertainties associated with estimates of historic anthropogenic GHG emissions vary by type of gas and decrease with the level of aggregation. Global CO_2 emissions from fossil fuels have relatively low uncertainty, assessed to be ±8 %. Uncertainty in fossil CO_2 emissions at the country level reaches up to 50 %. [5.2.1, 5.2.3]

GHG-emissions drivers

Per capita production and consumption growth is a major driver for worldwide increasing GHG emissions (*robust evidence, high agreement*). Global average economic growth, as measured through GDP per capita, grew by 100 %, from 4800 to 9800 $Int\$_{2005}$/cap yr between 1970 and 2010, outpacing GHG-intensity improvements. At regional level, however, there are large variations. Although different in absolute values, OECD-1990 and LAM showed a stable growth in per capita income of the same order of magnitude as the GHG-intensity improvements. This led to almost constant per capita emissions and an increase in total emissions at the rate of population growth. The EIT showed a decrease in income around 1990 that together with decreasing emissions per output and a very low population growth led to a decrease in overall emissions until 2000. The MAF showed a decrease in GDP per capita, but a high population growth rate led to an increase in overall emissions. Emerging economies in Asia showed very high economic growth rates at aggregate and per capita levels leading to the largest growth in per capita emissions despite also having the highest emissions per output efficiency improvements. [5.3.3]

Reductions in the energy intensity of economic output during the past four decades have not been sufficient to offset the effect of GDP growth (*high confidence*). Energy intensity has declined in all developed and large developing countries due mainly to technology, changes in economic structure, the mix of energy sources, and changes in the participation of inputs such as capital and labour used. At the global level, per capita primary energy consumption rose by 30 % from 1970–2010; due to population growth, total energy use has increased by 130 % over the same period. Countries and regions with higher income per capita tend to have higher energy use per capita; per capita energy use in the developing regions is only about 25 % of that in the developed economies on average. Growth rates in energy use per capita in developing countries, however, are much higher than those in developed countries. [5.3.4]

The decreasing carbon intensity of energy supply has been insufficient to offset the increase in global energy use (*high confidence*). Increased use of coal since 2000 has reversed the slight decarbonization trends exacerbating the burden of energy-related GHG emissions. Estimates indicate that coal, and unconventional gas and oil resources are large, suggesting that decarbonization would not be primarily driven by the exhaustion of fossil fuels, but by economics and technological and socio-political decisions. [5.3.4, 5.8]

Population growth aggravates worldwide growth of GHG emissions (*high confidence*). Global population has increased by 87 % from 1970 reaching 6.9 billion in 2010. The population has increased mainly in Asia, Latin America, and Africa, but the emissions increase for an additional person varies widely, depending on geographical location, income, lifestyle, and the available energy resources and technologies. The gap in per capita emissions between the top and bottom countries exceeds a factor of 50. The effects of demographic changes such as urbanization, ageing, and household size have indirect effects on emissions and smaller than the direct effects of changes in population size. [5.3.2]

Technological innovation and diffusion support overall economic growth, and also determine the energy intensity of economic output and the carbon intensity of energy (*medium confidence*). At the aggregate level, between 1970 and 2010, technological change increased income and resources use, as past technological change has favoured labour-productivity increase over resource efficiency [5.6.1]. Innovations that potentially decrease emissions can trigger behavioural responses that diminish the potential gains from increased efficiency, a phenomenon called the 'rebound effect' [5.6.2]. Trade facilitates the diffusion of productivity-enhancing and emissions-reducing technologies [5.4].

Infrastructural choices have long-lasting effects on emissions and may lock a country in a development path for decades (*medium evidence, medium agreement*). As an example, infrastructure and technology choices made by industrialized countries in the post-World War II period, at low-energy prices, still have an effect on current worldwide GHG emissions. [5.6.3]

Behaviour affects emissions through energy use, technological choices, lifestyles, and consumption preferences (*robust evidence, high agreement*). Behaviour is rooted in individuals' psychological, cultural, and social orientations that lead to different lifestyles and consumption patterns. Across countries, strategies and policies have been used to change individual choices, sometimes through changing the context in which decisions are made; a question remains whether such policies can be scaled up to macro level. [5.5]

Co-benefits may be particularly important for policymakers because the benefits can be realized faster than can benefits from reduced climate change, but they depend on assumptions about future trends (*medium evidence, high agreement*). Policies addressing fossil fuel use may reduce not only CO_2 emissions but also sulphur dioxide (SO_2) emissions and other pollutants that directly affect human health, but this effect interacts with future air pollution policies. Some mitigation policies may also produce adverse side-effects, by promoting energy supply technologies that increase some forms of air pollution. A comprehensive analysis of co-benefits and adverse side-effects is essential to estimate the actual costs of mitigation policies. [5.7]

Policies can be designed to act upon underlying drivers so as to decrease GHG emissions (*limited evidence, medium agreement*). Policies can be designed and implemented to affect underlying drivers. From 1970–2010, in most regions and countries, policies have proved insufficient in influencing infrastructure, technological, or behavioural choices at a scale that curbs the upward GHG-emissions trends. [5.6, 5.8]

5.1 Introduction and overview

The concentration of greenhouse gases, including CO_2 and methane (CH_4), in the atmosphere has been steadily rising since the beginning of the Industrial Revolution (Etheridge et al., 1996, 2002; NRC, 2010). Anthropogenic CO_2 emissions from the combustion of fossil fuels have been the main contributor to rising CO_2-concentration levels in the atmosphere, followed by CO_2 emissions from land use, land use change, and forestry (LULUCF).

Chapter 5 analyzes the anthropogenic greenhouse gas (GHG)-emission trends until the present and the main drivers that explain those trends. This chapter serves as a reference for assessing, in following chapters, the potential future emissions paths, and mitigation measures.

For a systematic assessment of the main drivers of GHG-emission trends, this and subsequent chapters employ a decomposition analysis based on the IPAT and Kaya identities (see Box 5.1).

Chapter 5 first considers the immediate drivers, or factors in the decomposition, of total GHG emissions. For energy, the factors are population, gross domestic product (GDP) (production) and gross national expenditure (GNE) (expenditures) per capita, energy intensity of production and expenditures, and GHG-emissions intensity of energy. For other sectors, the last two factors are combined into GHG-emissions intensity of production or expenditures. Secondly, it considers the underlying drivers defined as the processes, mechanisms, and characteristics of society that influence emissions through the factors, such as fossil fuels endowment and availability, consumption patterns, structural and technological changes, and behavioural choices.

Underlying drivers are subject to policies and measures that can be applied to, and act upon them. Changes in these underlying drivers, in turn, induce changes in the immediate drivers and, eventually, in the GHG-emissions trends.

The effect of immediate drivers on GHG emissions can be quantified through a straight decomposition analysis; the effect of underlying drivers on immediate drivers, however, is not straightforward and, for that reason, difficult to quantify in terms of their ultimate effects on GHG emissions. In addition, sometimes immediate drivers may affect underlying drivers in a reverse direction. Policies and measures in turn affect these interactions. Figure 5.1 reflects the interconnections among GHG emissions, immediate drivers, underlying drivers, and policies and measures as well as the interactions across these three groups through the dotted lines.

Past trends in global and regional GHG emissions from the beginning of the Industrial Revolution are presented in Section 5.2, *Global trends in greenhouse gases and short-lived species*; sectoral breakdowns of emissions trends are introduced later in Section 5.3.4, *Energy demand and supply,* and Section 5.3.5, *Other key sectors,* which includes transport, buildings, industry, forestry, agriculture, and waste sectors.

The decomposition framework and its main results at both global and regional levels are presented in Section 5.3.1, *Drivers of global emissions*. Immediate drivers or factors in the decomposition identity are discussed in Section 5.3.2, *Population and demographic structure*, Section 5.3.3, *Economic growth and development*, and Section 5.3.4, *Energy demand and supply*. Past trends of the immediate drivers are identified and analyzed in these sections.

At a deeper level, the underlying drivers that influence immediate drivers that, in turn, affect GHG emissions trends, are identified and discussed in Section 5.4, *Production and trade patterns*, Section 5.5, *Consumption and behavioural change*, and Section 5.6, *Technological change*. Underlying drivers include individual and societal choices as well as infrastructure and technological changes.

Section 5.7, *Co-benefits and adverse side-effects of mitigation actions,* identifies the effects of mitigation policies, measures or actions on other development aspects such as energy security, and public health.

Section 5.8, *The system perspective: linking sectors, technologies and consumption patterns,* synthesizes the main findings of the chapter and highlights the relevant interactions among and across immediate and underlying drivers that may be key for the design of mitigation policies and measures.

Finally, Section 5.9, *Gaps in knowledge and data,* addresses shortcomings in the dataset that prevent a more thorough analysis or limit the time span of certain variables. The section also discussed the gaps in the knowledge on the linkages among drivers and their effect on GHG emissions.

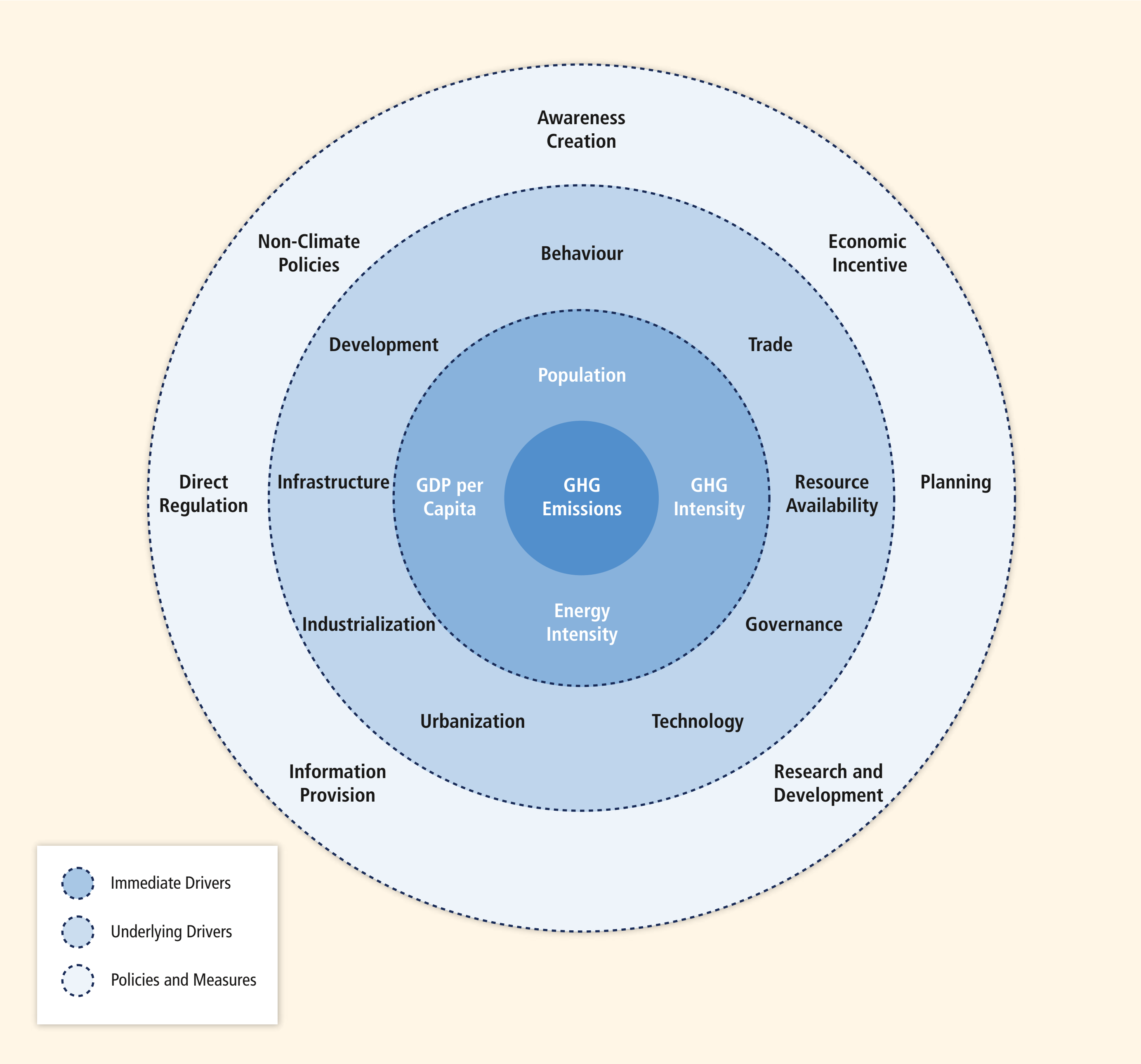


Figure 5.1 | Interconnections among GHG emissions, immediate drivers, underlying drivers, and policies and measures. Immediate drivers comprise the factors in the decomposition of emissions. Underlying drivers refer to the processes, mechanisms, and characteristics that influence emissions through the factors. Policies and measures affect the underlying drivers that, in turn, may change the factors. Immediate and underlying drivers may, in return, influence policies and measures.

5.2 Global trends in stocks and flows of greenhouse gases and short-lived species

5.2.1 Sectoral and regional trends in GHG emissions

Between 1970 and 2010, global warming potential (GWP)-weighted territorial GHG emissions increased from 27 to 49 $GtCO_2eq$, an 80 % increase (Figure 5.2). Total GHG emissions increased by 8 $GtCO_2eq$ over the 1970s, 6 $GtCO_2eq$ over the 1980s, and by 2 $GtCO_2$ over the 1990s, estimated as linear trends. Emissions growth accelerated in the 2000s for an increase of 10 $GtCO_2eq$. The average annual GHG-growth rate over these decadal periods was 2.0 %, 1.4 %, 0.6 %, and 2.2 %.[5] The main regional changes underlying these global trends were the reduction in GHG emissions in the Economies in Transition (EIT) region

[5] Note that there are different methods to calculate the average annual growth rate. Here, for convenience of the reader, we take the simple linear average of the annual growth rates g_t within the period considered.

starting in the 1990s and the rapid increase in GHG emissions in Asia in the 2000s. Emissions values in Section 5.2 are from the Emissions Database for Global Atmospheric Research (EDGAR) (JRC/PBL, 2013) unless otherwise noted. As in previous assessments, the EDGAR inventory is used because it provides the only consistent and comprehensive estimate of global emissions over the last 40 years. The EDGAR emissions estimates for specific compounds are compared to other results in the literature below.

Similar trends were seen for fossil CO_2 emissions, where a longer record exists. The absolute growth rate over the last decade was 8 $GtCO_2$/decade, which was higher than at any point in history (Boden et al., 2012). The relative growth rate for per capita CO_2 emissions over the last decade is still smaller than the per capita growth rates at previous points in history, such as during the post-World War II economic expansion. Absolute rates of CO_2 emissions growth, however, are higher than in the past due to an overall expansion of the global economy due to population growth.

Carbon dioxide (CO_2) is the largest component of anthropogenic GHG emissions (Figure 1.3 in Chapter 1). CO_2 is released during the combustion of fossil fuels such as coal, oil, and gas as well as the production of cement (Houghton, 2007). In 2010, CO_2, including net land-use-change emissions, comprised over 75 % (38±3.8 $GtCO_2$eq/yr) of 100-year GWP-weighted anthropogenic GHG emissions (Figure 1.3). Between 1970–2010, global anthropogenic fossil CO_2 emissions more than doubled, while methane (CH_4) and nitrous oxide (N_2O) each increased by about 45 %, although there is evidence that CH_4 emissions may not have increased over recent decades (see Section 5.2.3). In 2010, their shares in total GHG emissions were 16 % (7.8±1.6 $GtCO_2$eq/yr) and 6.2 % (3.1±1.9 $GtCO_2$eq/yr) respectively. Fluorinated gases, which represented about 0.4 % in 1970, increased to comprise 2 % (1.0±0.2 $GtCO_2$eq/yr) of GHG emissions in 2010. Some anthropogenic influences on climate, such as chlorofluorocarbons and aviation contrails, are not discussed in this section, but are assessed in the Intergovernmental Panel on Climate Change (IPCC) Working Group I (WGI) contribution to the Fifth Assessment Report (AR5) (Boucher and Randall, 2013; Hartmann et al., 2013). Forcing from aerosols and ozone precursor compounds are considered in the next section.

Following general scientific practice, 100-year GWPs from the IPCC Second Assessment Report (SAR) (Schimel et al., 1996) are used as the index for converting GHG emission estimates to common units of CO_2-equivalent emissions in this section (please refer to Annex II.9.1 for the exact values). There is no unique method of comparing trends for different climate-forcing agents (see Sections 1.2.5 and 3.9.6). A change to 20- or 500-year GWP values would change the trends by ±6 %. Similarly, use of updated GWPs from the IPCC Fourth Assessment Report (AR4) or AR5, which change values by a smaller amount, would not change the overall conclusions in this section. The largest absolute

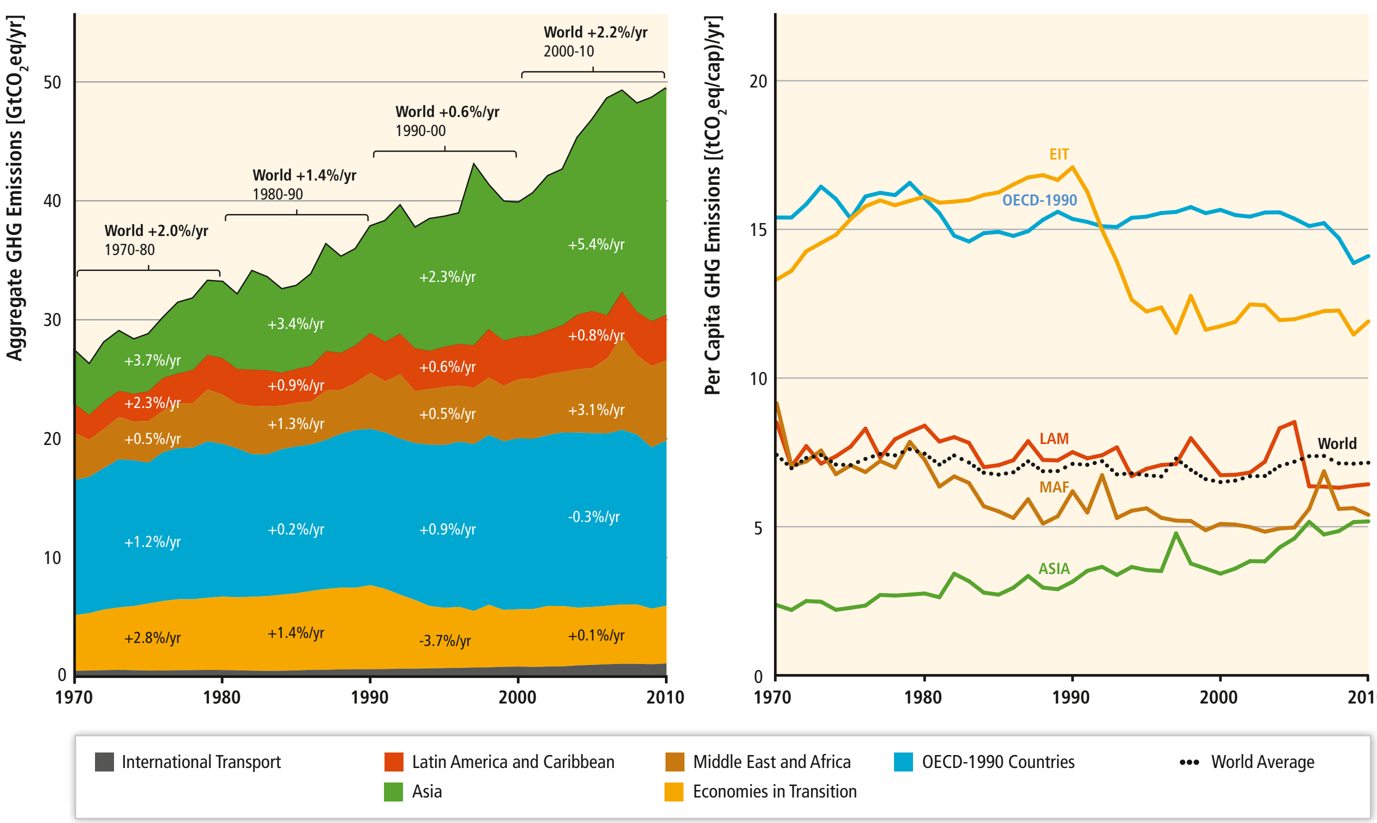


Figure 5.2 | Left panel: GHG emissions per region over 1970 – 2010. Emissions include all sectors, sources and gases, are territorial (see Box 5.2), and aggregated using 100-year GWP values. Right panel: The same data presented as per capita GHG emissions. Data from JRC/PBL (2013) and IEA (2012). Regions are defined in Annex II.2.

impact of a change in index values is on the weight given to methane, whose emission trends are particularly uncertain (Section 5.2.3; Kirschke et al., 2013).

Global per capita GHG emissions (Figure 5.2, right panel) have shown little trend over the last 40 years. The most noticeable regional trend over the last two decades in terms of per capita GHG emissions is the increase in Asia. Per capita emissions in regions other than EIT were fairly flat until the last several years when per capita emissions have decreased slightly in Latin America (LAM) and the group of member countries of the Organisation for Economic Co-operation and Development in 1990 (OECD-1990).

Fossil CO_2 emissions have grown substantially over the past two centuries (Figure 5.3, left panels). Fossil CO_2 emissions over 2002–2011 were estimated at 30 ±8 % $GtCO_2$/yr (Andres et al., 2012), (90 % confidence interval). Emissions in the 2000s as compared to the 1990s were higher in all regions, except for EIT, and the rate of increase was largest in ASIA. The increase in developing countries is due to an industrialization process that historically has been energy-intensive; a pattern similar to what the current OECD countries experienced before 1970. The figure also shows a shift in relative contribution. The OECD-1990 countries contributed most to the pre-1970 emissions, but in 2010 the developing countries and ASIA in particular, make up the major share of emissions.

CO_2 emissions from fossil fuel combustion and industrial processes made up the largest share (78 %) of the total emission increase from 1970 to 2010, with a similar percentage contribution between 2000 and 2010. In 2011, fossil CO_2 emissions were 3 % higher than in 2010, taking the average of estimates from Joint Research Centre (JRC)/ Netherlands Environmental Assessment Agency (PBL) (Olivier et al., 2013), U.S. Energy Information Administration (EIA), and Carbon Dioxide Information Analysis Center (CDIAC) (Macknick, 2011). Preliminary estimates for 2012 indicate that emissions growth has slowed to 1.4 % (Olivier et al., 2013) or 2 % (BP, 2013), as compared to 2012.

Land-use-change (LUC) emissions are highly uncertain, with emissions over 2002–2011 estimated to be 3.3 ±50–75 % $GtCO_2$/yr (Ciais et al., 2013). One estimate of LUC emissions by region is shown in Figure 5.3, left panel (Houghton et al., 2012), disaggregated into sub-regions using Houghton (2008), and extended to 1750 using regional trends from Pongratz et al. (2009). LUC emissions were comparable to or greater than fossil emissions for much of the last two centuries, but are of the order of 10 % of fossil emissions by 2010. LUC emissions appear to be declining over the last decade, with some regions showing net carbon uptake, although estimates do not agree on the rate or magnitude of these changes (Figure 11.6). Uncertainty estimates in Figure 5.3 follow Le Quéré et al.(2012) and WGI (Ciais et al., 2013).

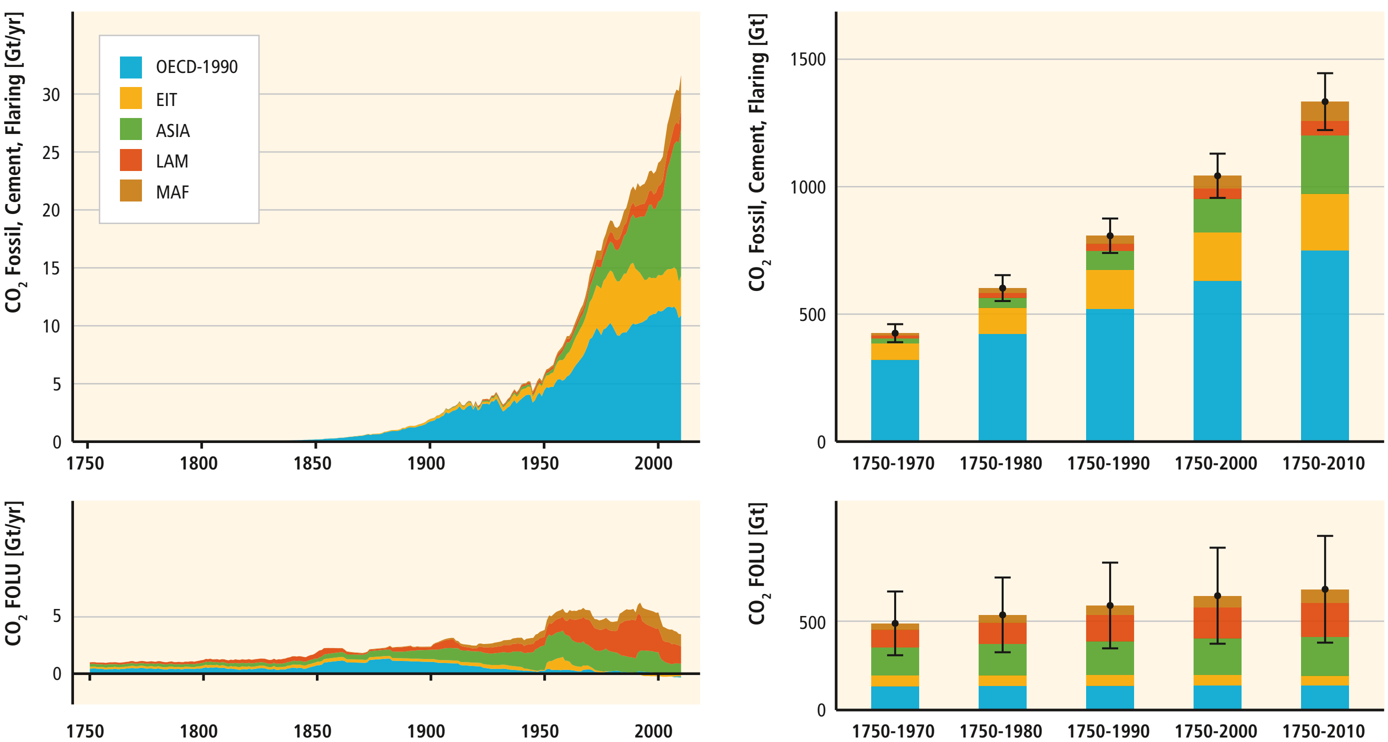


Figure 5.3 | Upper-left panel: CO_2 emissions per region over 1750–2010, including emissions from fossil fuel combustion, cement production, and gas flaring (territorial, Boden et al., 2012). Lower-left panel: an illustrative estimate of CO_2 emissions from AFOLU over 1750–2010 (Houghton e al., 2012). Right panels show cumulative CO_2 emissions over selected time periods by region. Whisker lines give an indication of the range of emission results. Regions are defined in Annex II.2.

Cumulative CO_2 emissions, which are a rough measure of the impact of past emissions on atmospheric concentrations, are also shown in Figure 5.3 (right panels). About half of cumulative fossil CO_2 emissions to 2010 were from the OECD-1990 region, 20 % from the EIT region, 15 % from the ASIA region, and the remainder from LAM, MAF, and international shipping (not shown). The cumulative contribution of LUC emissions was similar to that of fossil fuels until the late 20th century. By 2010, however, cumulative fossil emissions are nearly twice that of cumulative LUC emissions. Note that the figures for LUC are illustrative, and are much more uncertain than the estimates of fossil CO_2 emissions. Cumulative fossil CO_2 emissions to 2011 are estimated to be 1340 ± 110 $GtCO_2$, while cumulative LUC emissions are 680 ± 300 $GtCO_2$ (WGI Table 6.1). Cumulative uncertainties are, conservatively, estimated across time periods with 100 % correlation across years. Cumulative per capita emissions are another method of presenting emissions in the context of examining historical responsibility (see Chapters 3 and 13; Teng et al., 2011).

Methane is the second most important greenhouse gas, although its apparent impact in these figures is sensitive to the index used to convert to CO_2 equivalents (see Section 3.9.6). Methane emissions are due to a wide range of anthropogenic activities including the production and transport of fossil fuels, livestock, and rice cultivation, and the decay of organic waste in solid waste landfills. The 2005 estimate of CH_4 emissions from JRC/PBL (2013) of 7.3 $GtCO_2eq$ is 7 % higher than the 6.8 $GtCO_2eq$ estimates of US EPA (2012) and Höglund-Isaksson et al. (2012), which is well within an estimated 20 % uncertainty (Section 5.2.3).

The third most important anthropogenic greenhouse gas is N_2O, which is emitted during agricultural and industrial activities as well as during combustion and human waste disposal. Current estimates are that about 40 % of total N_20 emissions are anthropogenic. The 2005 estimate of N_2O emissions from JRC/PBL (2013) of 3.0 $GtCO_2eq$ is 12 % lower than the 3.4 $GtCO_2$ estimate of US EPA (2012), which is well within an estimated 30 to 90 % uncertainty (Section 5.2.3).

In addition to CO_2, CH_4, and N_2O, the F-gases are also greenhouse gases, and include hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride. These gases, sometimes referred to as High Global Warming Potential gases ('High GWP gases'), are typically emitted in smaller quantities from a variety of industrial processes. Hydrofluorocarbons are mostly used as substitutes for ozone-depleting substances (i. e., chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and halons). Emissions uncertainty for these gases varies, although for those gases with known atmospheric lifetimes, atmospheric measurements can be inverted to obtain an estimate of total global emissions. Overall, the uncertainty in global F-gas emissions have been estimated to be 20 % (UNEP, 2012, appendix), although atmospheric inversions constrain emissions to lower uncertainty levels in some cases (Section 5.2.3).

Greenhouse gases are emitted from many societal activities, with global emissions from the energy sector consistently increasing the most each decade over the last 40 years (see also Figure 5.18). A notable change over the last decade is high growth in emissions from the industrial sector, the second highest growth by sector over this period. Subsequent sections of this chapter describe the main trends and drivers associated with these activities and prospects for future mitigation options.

5.2.2 Trends in aerosols and aerosol/tropospheric ozone precursors

In addition to GHGs, aerosols and tropospheric ozone also contribute to trends in climate forcing. Because these forcing agents are shorter lived and heterogeneous, their impact on climate is not discussed in terms of concentrations, but instead in terms of radiative forcing, which is the change in the radiative energy budget of the Earth (Myhre et al., 2014). A positive forcing, such as that due to increases in GHGs, tends to warm the system while a negative forcing represents a cooling effect. Trends for the relevant emissions are shown in the Figure 5.4.

Aerosols contribute a net negative, but uncertain, radiative forcing (IPCC, 2007a; Myhre et al., 2014) estimated to total −0.90 W/m^2 (5–95 % range: −1.9 to −0.1 W/m^2). Trends in atmospheric aerosol loading, and the associated radiative forcing, are influenced primarily by trends in primary aerosol, black carbon (BC) and organic carbon (OC), and precursor emissions (primarily sulphur dioxide (SO_2)), although trends in climate and land-use also impact these forcing agents.

Sulphur dioxide is the largest anthropogenic source of aerosols, and is emitted by fossil fuel combustion, metal smelting, and other industrial processes. Global sulphur emissions peaked in the 1970s, and have generally decreased since then. Uncertainty in global SO_2 emissions over this period is estimated to be relatively low (±10 %), although regional uncertainty can be higher (Smith et al., 2011).

A recent update of carbonaceous aerosol emissions trends (BC and OC) found an increase from 1970 through 2000, with a particularly notable increase in BC emissions from 1970 to 1980 (Lamarque et al., 2010). A recent assessment indicates that BC and OC emissions may be underestimated (Bond et al., 2013). These emissions are highly sensitive to combustion conditions, which results in a large uncertainty (+100 %/−50 %; Bond et al., 2007). Global emissions from 2000 to 2010 have not yet been estimated, but will depend on the trends in driving forces such as residential coal and biofuel use, which are poorly quantified, and petroleum consumption for transport, but also changes in technology characteristics and the implementation of emission reduction technologies.

Because of the large uncertainty in aerosol forcing effects, the trend in aerosol forcing over the last two decades is not clear (Shindell et al., 2013).

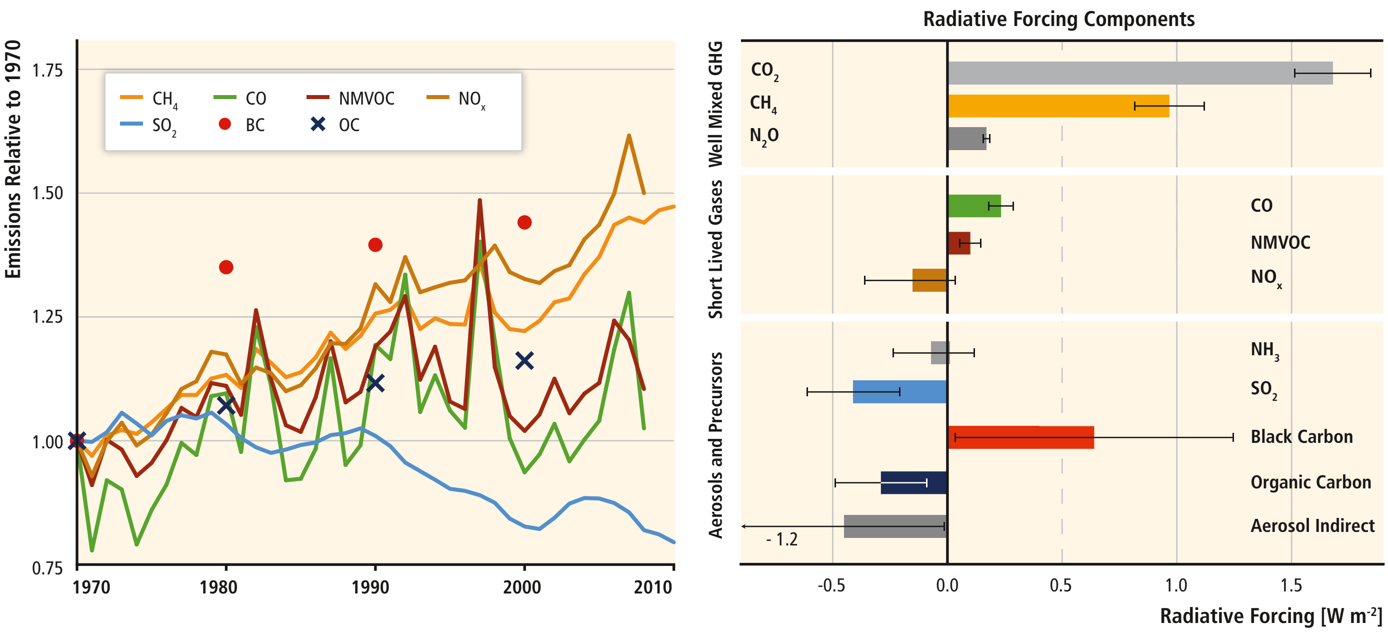


Figure 5.4 | Left panel: Global trends for air pollutant and methane emissions from anthropogenic and open burning, normalized to 1970 values. Short-timescale variability, in carbon monoxide (CO) and non-methane volatile organic compounds (NMVOC) in particular, is due to grassland and forest burning. Data from JRC/PBL (2013), except for SO_2 (Smith et al., 2011; Klimont et al., 2013), and BC/OC (Lamarque et al., 2010). Right panel: contribution of each emission species in terms of top of the atmosphere radiative forcing (adapted from Myhre et al., 2014, Figure 8.17). The aerosol indirect effect is shown separately as there is uncertainty as to the contribution of each species. Species not included in the left panel are shown in grey (included for reference).

Tropospheric ozone contributes a positive forcing and is formed by chemical reactions in the atmosphere. Ozone concentrations are impacted by a variety of emissions, including CH_4, nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic hydrocarbons (VOC) (Myhre et al., 2014). Global emissions of ozone precursor compounds are also thought to have increased over the last four decades. Global uncertainty has not been quantified for these emissions. An uncertainty of 10–20 % for 1990 NO_x emissions has been estimated in various European countries (Schöpp et al., 2005).

5.2.3 Emissions uncertainty

5.2.3.1 Methods for emissions uncertainty estimation

There are multiple methods of estimating emissions uncertainty (Marland et al., 2009), although almost all methods include an element of expert judgement. The traditional uncertainty estimation method, which compares emissions estimates to independent measurements, fails because of a mismatch in spatial and temporal scales. The data required for emission estimates, ranging from emission factors to fuel consumption data, originate from multiple sources that rarely have well characterized uncertainties. A potentially useful input to uncertainty estimates is a comparison of somewhat independent estimates of emissions, ideally over time, although care must be taken to assure that data cover the same source categories (Macknick, 2011; Andres et al., 2012). Formal uncertainty propagation can be useful as well (UNEP, 2012; Elzen et al., 2013) although one poorly constrained element of such analysis is the methodology for aggregating uncertainty between regions. Uncertainties in this section are presented as 5–95 % confidence intervals, with values from the literature converted to this range where necessary assuming a Gaussian uncertainty distribution.

Total GHG emissions from EDGAR as presented here are up to 5–10 % lower over 1970–2004 than the earlier estimates presented in AR4 (IPCC, 2007a). The lower values here are largely due to lower estimates of LUC CO_2 emissions (by 0–50 %) and N_2O emissions (by 20–40 %) and fossil CO_2 emissions (by 0–5 %). These differences in these emissions are within the uncertainty ranges estimated for these emission categories.

5.2.3.2 Fossil carbon dioxide emissions uncertainty

Carbon dioxide emissions from fossil fuels and cement production are considered to have relatively low uncertainty, with global uncertainty recently assessed to be 8 % (Andres et al., 2012). Uncertainties in fossil-fuel CO_2 emissions arise from uncertainty in fuel combustion or other activity data and uncertainties in emission factors, as well as assumptions for combustion completeness and non-combustion uses. Default uncertainty estimates (two standard deviations) suggested by the IPCC (2006) for fossil fuel combustion emission factors are lower for fuels that have relatively uniform properties (−3 %/+5 % for motor gasoline, −2 %/+1 % for gas/diesel oil) and higher for fuels with more diverse properties (–15 %/+18 % petroleum coke, –10 %/+14 % for lignite). Some emissions factors used by country inventories, however, differ from the suggested defaults by amounts that are outside the stated uncertainty range because of local fuel practices (Olivier et al., 2011). In a study examining power plant emissions in the United States, measured CO_2 emissions were an average of 5 % higher than calculated emissions, with larger deviations for individual plants (Ackerman and Sundquist, 2008). A comparison of five different fossil fuel CO_2 emissions datasets, harmonized to cover most of the same sources (fossil fuel, cement, bunker fuels, gas flaring) shows ±4 % differences over the last three decades (Macknick, 2011). Uncertainty in underlying energy production and consumption statistics, which are drawn from similar sources for existing emission estimates, will contribute further to uncertainty (Gregg et al., 2008; Guan et al., 2012).

Uncertainty in fossil CO_2 emissions increases at the country level (Marland et al., 1999; Macknick, 2011; Andres et al., 2012), with differences between estimates of up to 50 %. Figure 5.5 compares five estimates of fossil CO_2 emissions for several countries. For some countries the estimates agree well while for others more substantial differences exist. A high level of agreement between estimates, however, can arise due to similar assumptions and data sources and does not necessarily imply an equally low level of uncertainty. Note that differences in treatment of biofuels and international bunker fuels at the country level can contribute to differences seen in this comparison.

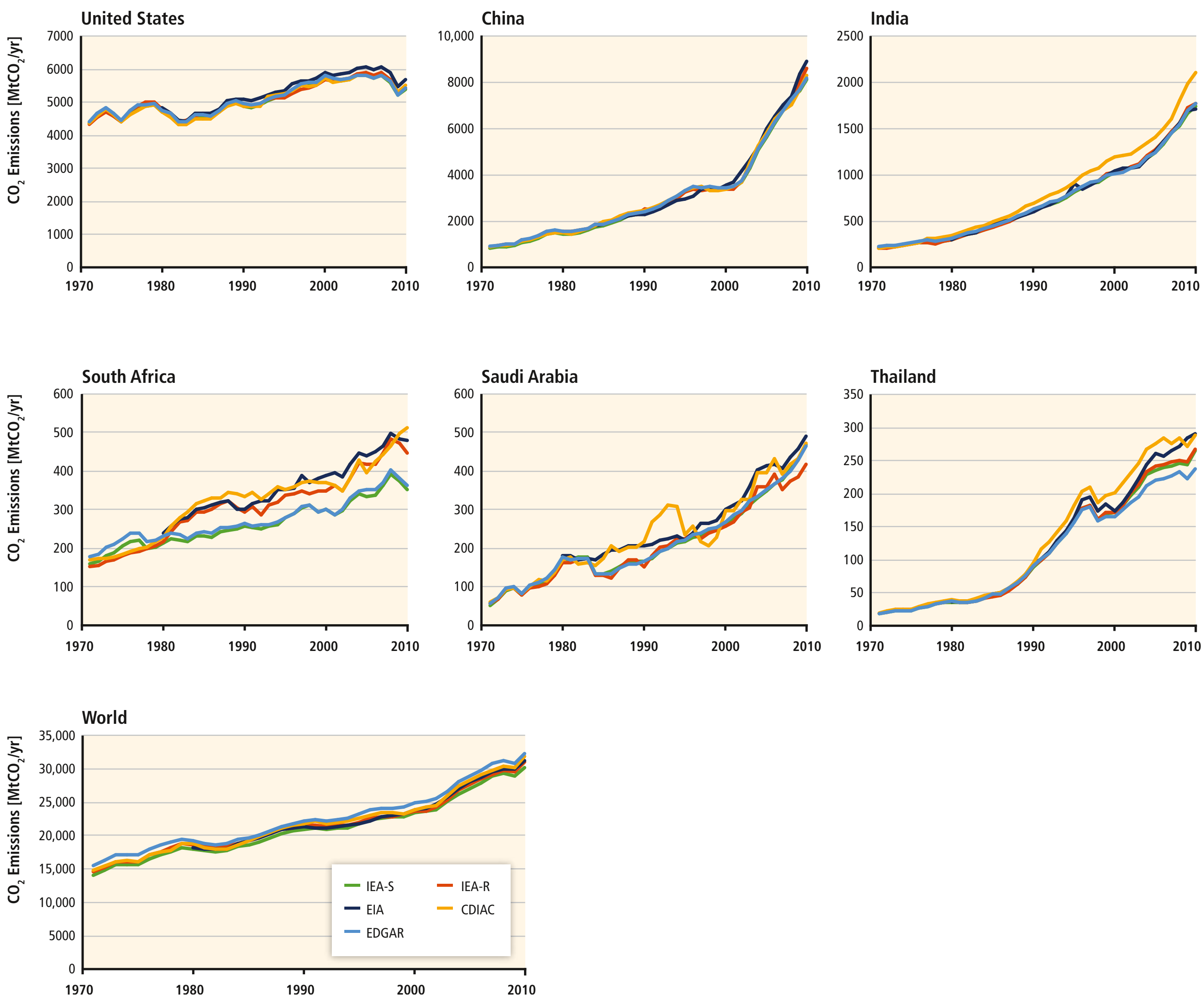


Figure 5.5 | Upper panels: five estimates of CO_2 emissions for the three countries with the largest emissions (and complete time series), including fossil fuel combustion, cement production, and gas flaring. Middle panels: the three countries with the largest percentage variation between estimates. Lower panel: global emissions ($MtCO_2$). Emissions data are harmonized data from Macknick (2011; downloaded Sept 2013), IEA (2012) and JRC / PBL (2013). Note that the vertical scales differ significantly between plots.

5.2.3.3 Other greenhouse gases and non-fossil fuel carbon dioxide

Uncertainty is particularly large for sources without a simple relationship to activity factors, such as emissions from LUC (Houghton et al., 2012; see also Chapter 11 for a comprehensive discussion), fugitive emissions of CH_4 and fluorinated gases (Hayhoe et al., 2002), and biogenic emissions of CH_4 and N_2O, and gas flaring (Macknick, 2011). Formally estimating uncertainty for LUC emissions is difficult because a number of relevant processes are not characterized well enough to be included in estimates (Houghton et al., 2012).

Methane emissions are more uncertain than CO_2, with fewer global estimates (US EPA, 2012; Höglund-Isaksson et al., 2012; JRC/PBL, 2013). The relationship between emissions and activity levels for CH_4 are highly variable, leading to greater uncertainty in emission estimates. Leakage rates, for example, depend on equipment design, environmental conditions, and maintenance procedures. Emissions from anaerobic decomposition (ruminants, rice, landfill) also are dependent on environmental conditions.

Nitrogen oxide emission factors are also heterogeneous, leading to large uncertainty. Bottom-up (inventory) estimates of uncertainty of 25 % (UNEP, 2012) are smaller than the uncertainty of 60 % estimated by constraining emissions with atmospheric concentration observation and estimates of removal rates (Ciais et al., 2013).

Unlike CO_2, CH_4, and N_2O, most fluorinated gases are purely anthropogenic in origin, simplifying estimates. Bottom up emissions, however, depend on assumed rates of leakage, for example, from refrigeration units. Emissions can be estimated using concentration data together with inverse modelling techniques, resulting in global uncertainties of 20–80 % for various perfluorocarbons (Ivy et al., 2012), 8–11 % for sulphur hexafluoride (SF_6) (Rigby et al., 2010), and ±6–11 % for HCFC-22 (Saikawa et al., 2012).[6]

5.2.3.4 Total greenhouse gas uncertainty

Estimated uncertainty ranges for GHGs 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 net LUC CO_2 (50–75 %). Few estimates of total GHG uncertainty exist, and it should be noted that any such estimates are contingent on the index used to convert emissions to CO_2 equivalent values. The uncertainty estimates quoted here are also not time-dependent. In reality, the most recent data is generally more uncertain due to the preliminary nature of much of the information used to calculate estimates. Data for historical periods can also be more uncertain due to less extensive data collection infrastructure and the lack of emission factor measurements for technologies no longer in use. Uncertainty can also change over time due to changes in regional and sector contributions.

An illustrative uncertainty estimate of around 10 % for total GHG emissions can be obtained by combining the uncertainties for each gas assuming complete independence (which may underestimate actual uncertainty). An estimate of 7.5 % (90 percentile range) was provided by the United Nations Environment Programme (UNEP) Gap Report (UNEP, 2012, appendix), which is lower largely due to a lower uncertainty for fossil CO_2.

5.2.3.5 Sulphur dioxide and aerosols

Uncertainties in SO_2 and carbonaceous aerosol (BC and OC) emissions have been estimated by Smith et al. (2011) and Bond et al. (2004, 2007). Sulphur dioxide emissions uncertainty at the global level is relatively low because uncertainties in fuel sulphur content are not well correlated between regions. Uncertainty at the regional level ranges up to 35 %. Uncertainties in carbonaceous aerosol emissions, in contrast, are high at both regional and global scales due to fundamental uncertainty in emission factors. Carbonaceous aerosol emissions are highly state-dependent, with emissions factors that can vary by over an order of magnitude depending on combustion conditions and emission controls. A recent assessment indicated that BC emissions may be substantially underestimated (Bond et al., 2013), supporting the literature estimates of high uncertainty for these emissions.

5.2.3.6 Uncertainties in emission trends

For global fossil CO_2, the increase over the last decade as well as previous decades was larger than estimated uncertainties in annual emissions, meaning that the trend of increasing emissions is robust. Uncertainties can, however, impact the trends of fossil emissions of specific countries if increases are less rapid and uncertainties are sufficiently high.

Quantification of uncertainties is complicated by uncertainties not only in annual uncertainty determinations but also by potential year-to-year uncertainty correlations (Ballantyne et al., 2010, 2012). For fossil CO_2, these correlations are most closely tied to fuel use estimates, an integral part of the fossil CO_2 emission calculation. For other emissions, errors in other drivers or emission factors may have their own temporal trends as well. Without explicit temporal uncertainty considerations, the true emission trends may deviate slightly from the estimated ones.

In contrast to fossil-fuel emissions, uncertainties in global LUC emissions are sufficiently high to make trends over recent decades uncertain in direction and magnitude (see also Chapter 11).

While two global inventories both indicate that anthropogenic methane emissions have increased over the last three decades, a recent

[6] HCFC-22 is regulated under the Montreal Protocol but not included in fluorinated gases totals reported in this chapter as it is not included in the Kyoto Protocol.

assessment combining atmospheric measurements, inventories, and modelling concluded that anthropogenic methane emissions are likely to have been flat or have declined over this period (Kirschke et al., 2013). The EDGAR inventory estimates an 86-Mt-CH_4 (or 30 %) increase over 1980–2010 and the EPA (2012) historical estimate has a 26-Mt-CH_4 increase from 1990–2005 (with a further 18-Mt-CH_4 projected increase to 2010). (Kirschke et al., 2013) derives either a 5-Mt increase or a net 15-Mt decrease over this period, which indicates the inventories may be overestimating the increase in anthropogenic methane emissions. These results suggest that estimates of methane emission uncertainties of 20 % (UNEP, 2012; Kirschke et al., 2013) for anthropogenic emissions may be too low, since the differences in trend between inventories and the inversion synthesis are of this magnitude.

Overall, global SO_2 emissions have decreased over the last two decades, decreasing again in recent years following an increase from about 2000–2005 (Klimont et al., 2013). Global trends in carbonaceous aerosols over the past decade have not been estimated, however, BC and OC emissions from fuel combustion in China and India were estimated to have increased over 2000–2010 (Lu et al., 2011).

5.2.3.7 Uncertainties in consumption-based carbon dioxide emission accounts

Consumption-based CO_2 emission accounts reallocate part of the territorial CO_2 emissions associated with the production of exports to the countries where they are eventually consumed (Peters, 2008; Minx et al., 2009). Different techniques and assumptions have been applied in modelling consumption-based CO_2 emissions including aggregation or disaggregation of production sectors (Lenzen, 2011; Lindner et al., 2012, 2013); consideration of price and deflation effects (Dietzenbacher and Hoen, 1998; Dietzenbacher and Wagener, 1999); use of balancing techniques for data discrepancies (Rey et al., 2004; Lenzen et al., 2009, 2010); simplifying multi-regional input-output models (Nansai et al., 2009a); and use of domestic production structure as a proxy for imports (Suh, 2005). Different models and assumptions result in substantially different estimates of consumption-based CO_2 emissions, but a direct comparison between these remains a gap in the literature.

Uncertainties in consumption-based emission accounts arise from various sources (Lenzen et al., 2010) including (1) uncertainty in the territory-based emission estimates (see previous sections); (2) uncertainties in input-output and international trade statistics (Lenzen et al., 2010); and (3) uncertainties in the definitions, level of aggregation, and assumptions underlying the model (Peters and Solli, 2010; Kanemoto et al., 2012; Andres et al., 2012).

There has been little quantitative analysis of this at the global level, with only a few comparisons across different versions of the same dataset (Andrew and Peters, 2013) and direct comparisons between studies (Andres et al., 2012). However, there have been detailed studies at the country level (Lenzen et al., 2010) and many of the mechanisms of uncertainty are understood.

The few quantitative studies on the uncertainty and model spread in global analyses confirm that the uncertainty in consumption-based emissions are larger than territorial emissions, though trends over time are likely to be robust (Andres et al., 2012). The uncertainty in territorial emission estimates is a key driver for the uncertainty in consumption-based emissions, and differences in definition and system boundaries can lead to important differences (Peters and Solli, 2010). A detailed assessment of the uncertainty due to different supply chain models is lacking, and this remains a large gap in the literature. Based on model comparisons, particularly for large countries or regions, the uncertainties may be less important than the uncertainties in territorial emission estimates used as inputs.

5.3 Key drivers of global change

5.3.1 Drivers of global emissions

This section analyzes drivers of the global trends in GHG emissions that were discussed in Section 5.2. In general, drivers are the elements that directly or indirectly contribute to GHG emissions. While there is no general consensus in the literature, some researchers distinguish proximate versus underlying or ultimate drivers (see e. g., Angel et al., 1998; Geist and Lambin, 2002), where proximate drivers are generally the activities that are directly or closely related to the generation of GHGs and underlying or ultimate drivers are the ones that motivate the proximate drivers.

There is neither a unique method to identify the drivers of climate change, nor can the drivers always be objectively defined: human activities manifest themselves through a complex network of interactions, and isolating a clear cause-and-effect for a certain phenomenon purely through the lens of scientific observation is often difficult. Therefore, the term, 'driver' may not represent an exact *causality* but is used to indicate an *association* to provide insights on what constitutes overall changes in global GHG emissions.

In the literature, studies recognize various factors as main drivers to GHG emissions including consumption (Morioka and Yoshida, 1995; Munksgaard et al., 2001; Wier et al., 2001; Hertwich and Peters, 2009), international trade (Weber and Matthews, 2007; Peters and Hertwich, 2008; Li and Hewitt, 2008; Yunfeng and Laike, 2010; Peters et al., 2011; Jakob and Marschinski, 2013), population growth (Ehrlich and Holdren, 1971; O'Neill et al., 2010), economic growth (Grossman and Krueger, 1994; Arrow et al, 1996; Stern et al., 1996; Lim et al., 2009; Blodgett and Parker, 2010; Carson, 2010), structural change to a service econ-

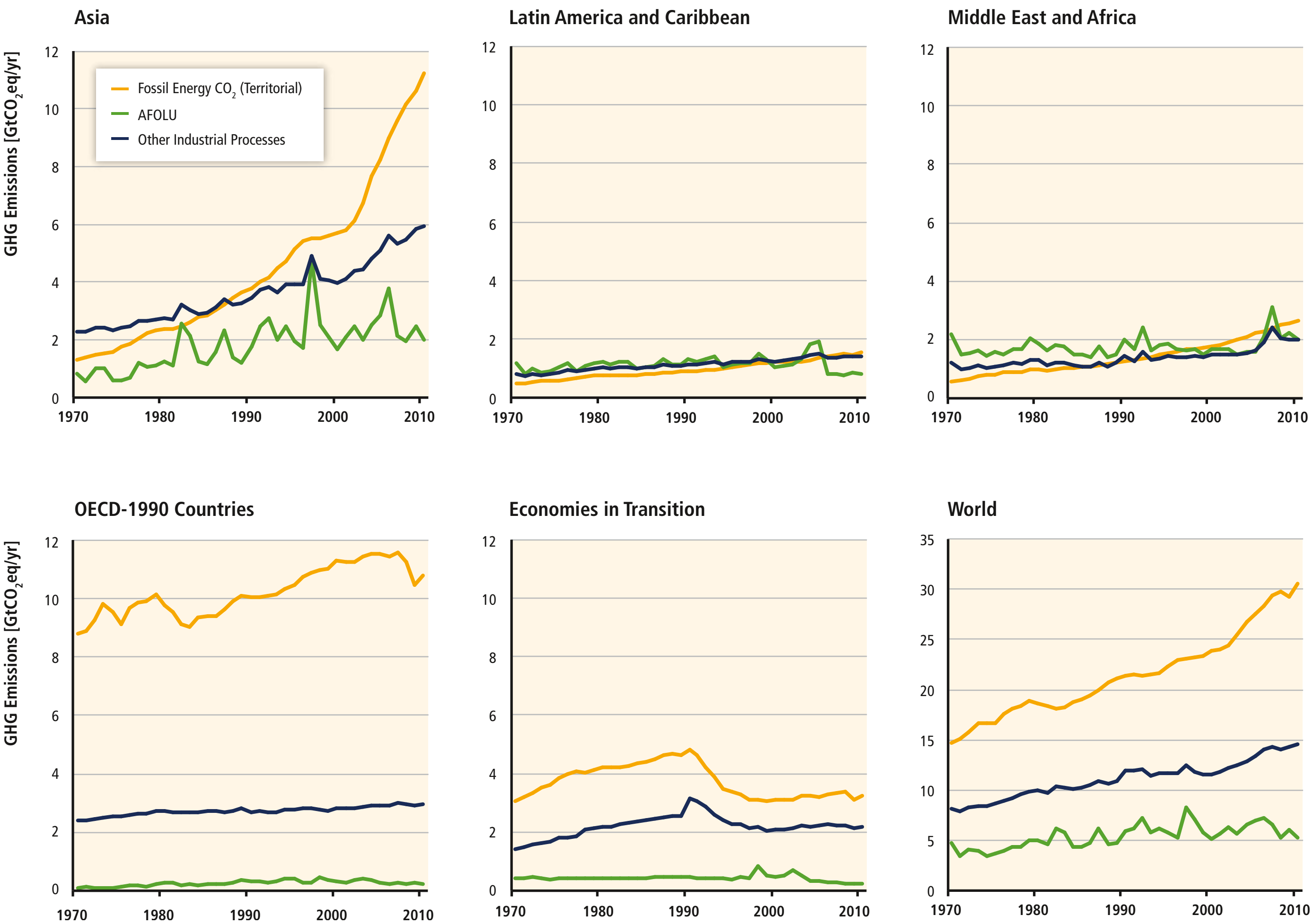


Figure 5.6 | Territorial GHG emissions per region over 1970–2010. Note that only the bottom-right panel for the World has a different scale for its vertical axis. Fossil energy CO_2 indicates emissions from fossil fuel combustion. Emissions are aggregated using 100-year GWP values. Data from JRC/PBL (2013) and IEA (2012). Regions are defined in Annex II.2 | The direct emission data from JRC/PBL (2013) (see Annex II.9) represents land-based CO_2 emissions from forest and peat fires and decay that approximate to CO_2 flux from anthropogenic emission sources in the FOLU sub-sector. For a more detailed representation of Agriculture and FOLU (AFOLU) GHG flux, see Section 11.2 and Figures 11.2 and 11.6.

omy (Suh, 2006; Nansai et al., 2009b), and energy consumption (Wier, 1998; Malla, 2009; Bolla and Pendolovska, 2011). Each of these topics will be discussed in more depth, starting in Section 5.3.2.

Obviously many drivers of GHG emissions are interlinked with each other, and furthermore, many of these drivers can be further decomposed into various subcomponents. For example, transportation emissions are an important driver of increasing GHG emissions globally. But there is a wide regional variation in its significance. Furthermore, the increase in vehicle miles driven per capita or changes in fuel economy of average vehicle fleet can also be referred to as a driver, while these drivers are underlying to the higher-level driver, namely changes to transportation emissions. Therefore, drivers to GHG emissions can only be understood in the context of scale, level of detail, and the framework under which the factors contributing to GHG emissions are analyzed.

5.3.1.1 Key drivers

Figure 5.6 shows that, globally AFOLU emissions have increased by 12 % between 1970 and 2010. The AFOLU emissions have been more pronounced in non-OECD-1990 regions and dominate total GHG emissions from MAF and LAM regions. Major increases in global GHG emission have been, however, associated with CO_2 emissions from fossil energy (+108 % between 1970 and 2010), which has been growing more rapidly since AR4 (IPCC, 2007b).

Figure 5.7 shows this increase in fossil energy CO_2 decomposed into changes in population (+87 %), per capita GDP adjusted with Purchasing Power Parity (PPP) (+103 %), energy intensity in GDP (–35 %) and CO_2 intensity of energy (–15 %) between 1970 and 2010. Over the last decade, however, the long trend of decreasing carbon intensity in energy has been broken, and it increased by 1.7 %. In short, the

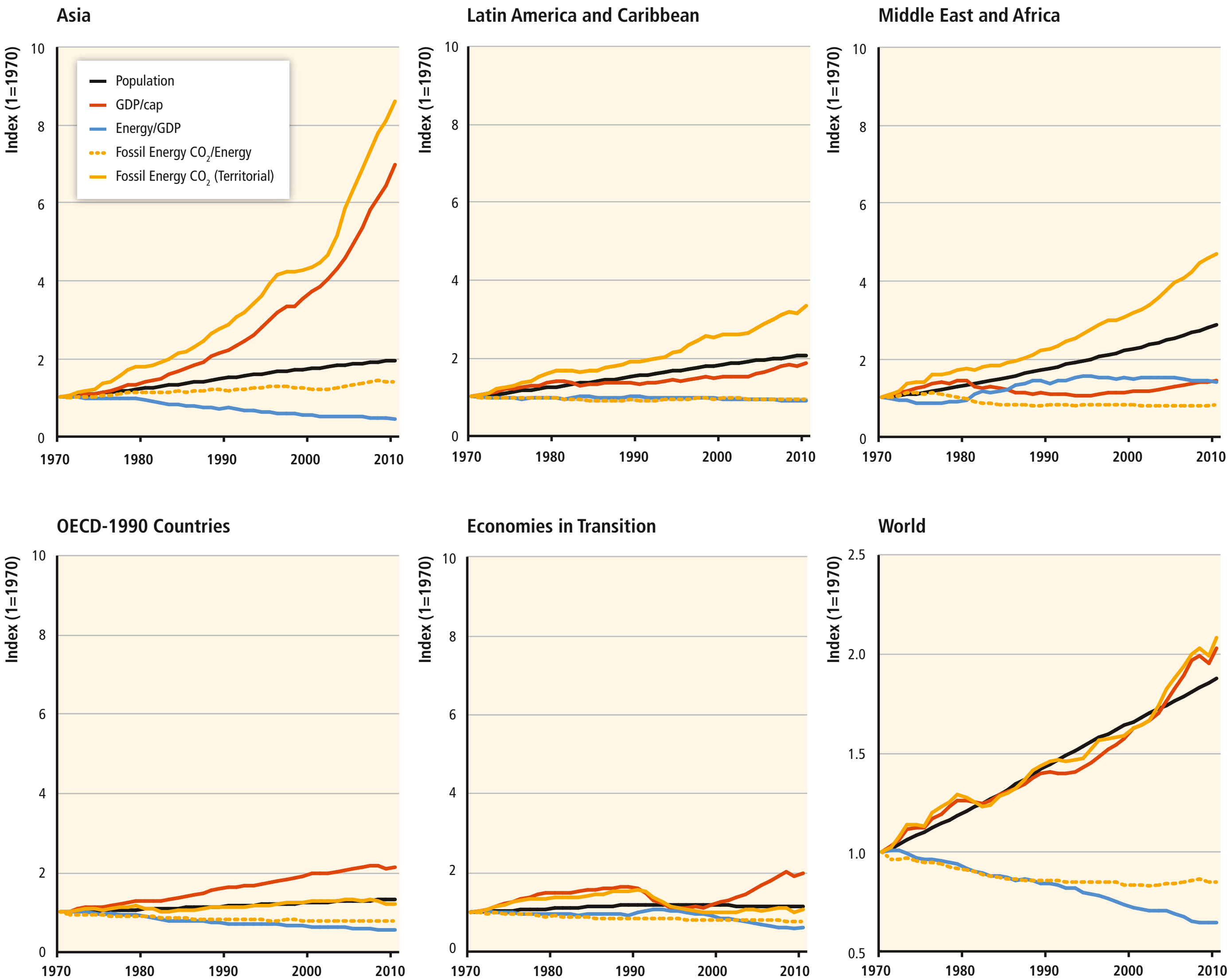


Figure 5.7 | Four factor decomposition of territorial CO_2 emission from fossil fuel combustion at regional level over 1970–2010. Note that only the bottom-right panel for the World has a different scale for its vertical axis. Data from IEA (2012) and JRC/PBL (2013); based on PPP-adjusted GDP. Regions are defined in Annex II.2.

improvements in energy intensity of GDP that the world has achieved over the last four decades could not keep up with the continuous growth of global population resulting in a closely synchronous behaviour between GDP per capita and CO_2 emission during the period.

At a regional scale, all regions but Asia show 5 % to 25 % reduction in CO_2 intensity of energy consumption, while Asia increased CO_2 intensity of energy consumption by 44 % between 1970 and 2010. Energy intensity of GDP declined significantly in the EIT, ASIA, and OECD-1990 (39 %–55 %) and moderately in LAM (9 %), while in MAF it increased by 41 %. Energy intensity of GDP may increase as an economy enters into an industrialization process, while it generally decreases as the industrialization process matures and as the share of service sector in the economy grows (Nansai et al., 2007; Henriques and Kander, 2010). In all regions, population growth has been a persistent trend. The EIT region showed the lowest population growth rate over the last four decades (16 %), whereas MAF marked 188 % increase in population during the same period. ASIA gained the most to its population from 1.9 billion to 3.7 billion during the period. Purchasing Power Parity (PPP-) adjusted GDP also grew in all regions ranging from 43 % (MAF), about two-fold (OECD-1990, EIT, and LAM) to a remarkable six-fold increase (ASIA) over the last four decades. In general, the use of PPP-adjusted GDP instead of Market Exchange Rate (MER)-based GDP gives more weight to developing economies and their GDP growth (Raupach et al., 2007).

In summary, the improvements in energy intensity in GDP over the last four decades could not keep up with the stable and persistent upward trends in GDP per capita and population. In particular, a strong growth in GDP per capita in ASIA combined with its population growth has been the most significant factors to the increase in GHG emissions during the period.

Global CO_2 emissions from fossil energy are decomposed into three factors using territorial and consumption accounts. Figure 5.8 high-

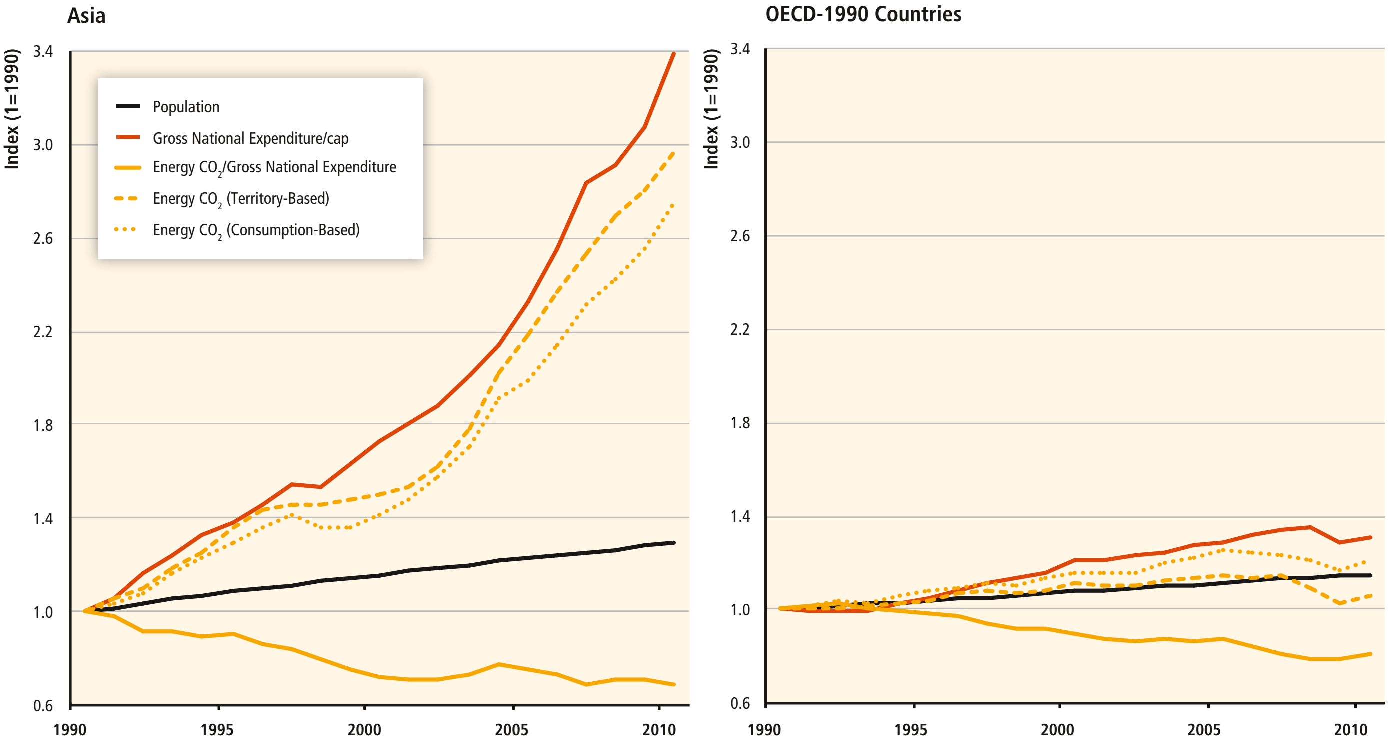


Figure 5.8 | Three factor decomposition of consumption-based and territorial CO_2 emission from fossil fuel combustion for Asia (left) and OECD (right) over 1990 – 2010. Data from IEA (2012) and JRC/PBL (2013). Regions are defined in Annex II.2.

lights the case of ASIA and OECD-1990, where the gap between the two approaches is largest, over the 1990–2010 period. Based on a territorial accounting, OECD-1990 increased its CO_2 emissions from fossil energy only by 6 % from 1990 to 2010. The increase in CO_2 emission from fossil energy embodied in consumption by OECD-1990, however, is more significant (22 %) during the period. On the other hand, CO_2 emission embodied in consumption by ASIA increased by 175 % during the period, while its territorial emissions increased by 197 % during the period. Increasing international trade played an important role in this result, which will be elaborated in Section 5.4.

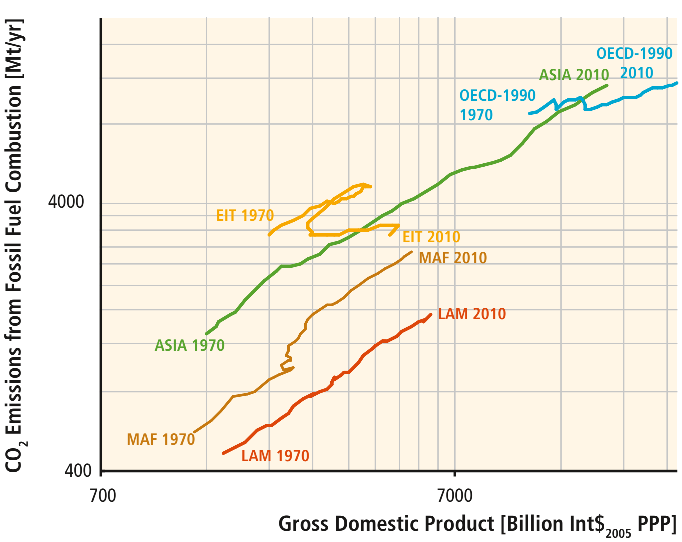


Figure 5.9 | Regional trajectories of territorial CO_2 emissions from fossil fuel combustion versus GDP over 1970 – 2010. Data from IEA (2012) and JRC/PBL (2013). Regions are defined in Annex II.2.

The strong correlation between GDP and CO_2 emissions can be identified from the historical trajectories of CO_2 emissions and GDP (Figure 5.9). Although there are notable exceptions (EIT), regional CO_2 emission trajectories are closely aligned with the growth in GDP. On average, 1 % of world GDP increase has been associated with 0.39 % increase in fossil energy CO_2 emission during the 1970–2010 period. Over the last two decades, however, 1 % of world GDP increase has been accompanied with 0.49 % increase in fossil energy CO_2 emission (1990–2010) due largely to the rapid growth of the energy-intensive non-OECD Asian economy.

Overall, the growth in production and consumption outpaced the reduction in CO_2 emissions intensity of production and that embodied in consumption. Together with the growth in population, global CO_2 emissions from fossil energy maintained a stable upward trend, which characterizes the overall increase in global GHG emissions over the last two decades.

Box 5.1 | IPAT and Kaya decomposition methods

The IPAT (Ehrlich and Holdren, 1971) and Kaya (Kaya, 1990) identities provide two common frameworks in the literature for analyzing emission drivers by decomposing overall changes in GHG emissions into underlying factors. The Kaya identity is a special case of the more general IPAT identity (Ehrlich and Holdren, 1971). The IPAT identity decomposes an impact (I, e.g., total GHG emissions) into population (P), affluence (A, e.g., income per capita) and technology (T, e.g., GHG emission intensity of production or consumption). The Kaya identity deals with a subset of GHG emissions, namely CO_2 emissions from fossil fuel combustion, which is the dominant part of the anthropogenic GHG emissions and their changes at a global level (Figure 5.6). While global GHG emissions measured in GWP 100 have increased in all three categories, namely fossil energy CO_2, AFOLU, and other over the last four decades, fossil energy CO_2 dominates the absolute growth of GHG emissions in all regions and the world during the period. Two approaches to GHG accounting are distinguished in the literature, namely territorial and consumption accounts (see Box 5.2 for the definition). The Kaya identity for territorial CO_2 emissions can be written as:

(1) Territorial CO_2 emissions =

$$\text{population} \times \frac{\text{GDP}}{\text{population}} \times \frac{\text{Energy}}{\$\text{GDP}} \times \frac{CO_2 \text{ emission}}{\text{Energy}}$$

In other words, CO_2 emissions are expressed as a product of four underlying factors: (1) population, (2) per capita GDP (GDP/population), (3) energy intensity of GDP (Energy/GDP), and (4) CO_2 intensity of energy (CO_2 emissions/energy) (Raupach et al., 2007; Steckel et al., 2011). Also even simpler decomposition forms can be found in the literature (Raupach et al., 2007). They are obtained when any two or three adjoining factors in the four-factor Kaya identity in equation (1) are merged. For example, merging energy intensity of GDP and CO_2 intensity of energy into CO_2 intensity of GDP, a three-factor decomposition can be written as:

(2) Territorial CO_2 emissions =

$$\text{population} \times \frac{\text{GDP}}{\text{population}} \times \frac{CO_2 \text{ emission}}{\text{GDP}}$$

Similarly, consumption-based CO_2 emissions can be decomposed such that

(3) Consumption – based CO_2 emissions =

$$\text{population} \times \frac{\text{GNE}}{\text{population}} \times \frac{\text{consumption} - \text{based } CO_2 \text{ emission}}{\text{GNE}}$$

In this case, consumption-based CO_2 emissions are decomposed into (1) population, (2) per capita consumption (GNE/population; GNE = Gross National Expenditure), and (3) embodied CO_2 intensity of consumption (consumption-based CO_2 emission/GNE). The Kaya identity can also be expressed as a ratio between two time periods to show relative change in CO_2 emissions and its contributing factors (Raupach et al., 2007).

5.3.2 Population and demographic structure

5.3.2.1 Population trends

In the second half of the 19th century, global population increased at an average annual rate of 0.55 %, but it accelerated after 1900. Population size and age composition are driven by fertility and mortality rates, which in turn depend on a range of factors, including income, education, social norms, and health provisions that keep changing over time, partly in response to government policies. Section 4.3.1 discusses these processes in depth. Figure 5.10 presents the main outcomes. Between 1970 and 2010, global population has increased by 87 %, from 3.7 billion to 6.9 billion (Wang et al., 2012a). The underlying process is the demographic transition in which societies move from a relatively stable population level at high fertility and mortality rates, through a period of declined mortality rates and fast population growth, and only at a later stage followed by a decline in fertility rates with a more stable population size.

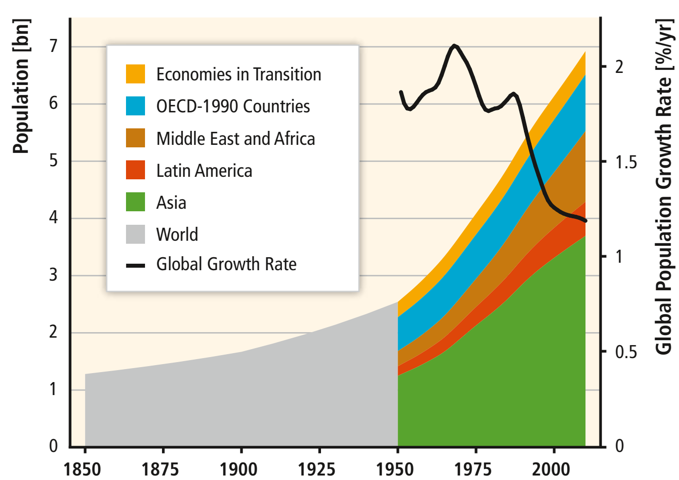


Figure 5.10 | Trends in regional and global population growth 1850–2010 | Global data up to 1950 (grey from (UN, 1999). Regional data from 1950 onwards from UN WPP (2012). Regions are defined in Annex II.2.

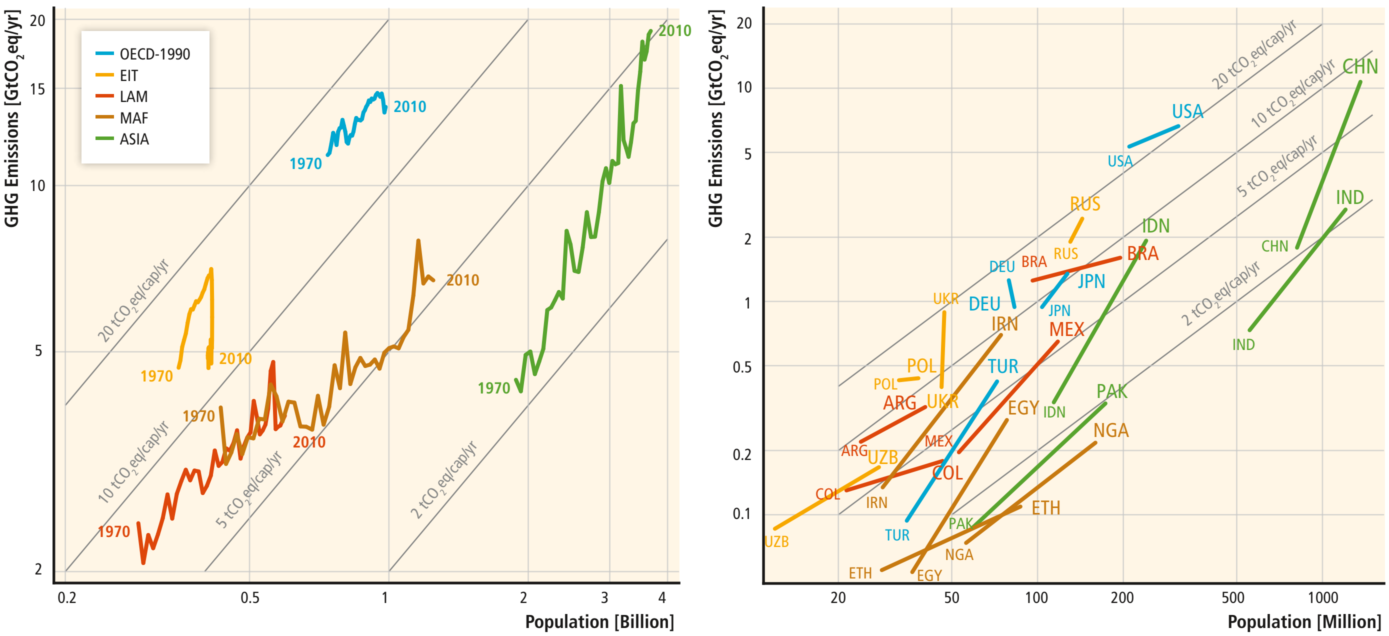


Figure 5.11 | Regional trends in population and GHG emissions (left panel) and for each region the four most populous countries in 2010 (right panel). Regions are defined in Annex II.2 | Grey diagonals connect points with constant emission intensity. Major GHG-emitting regions or countries are in the upper half. A shift to the right presents population growth. A steep line presents a growth in per capita emissions, while a flat line presents decreasing per capita emissions between 1971 and 2010 | Right panel: The small labels refer to 1970, the large labels to 2010 | Data from JRC/PBL (2013) and IEA (2012). (Note the log-log plot.)

Each person added to the global population increases GHG emissions, but the additional contribution varies widely depending on the socio-economic and geographic conditions of the additional person. There is a 91-fold difference in per capita CO_2 emissions from fossil fuels between the highest and lowest emitters across the nine global regions analyzed by Raupach et al. (2007). Global CO_2 emissions from fossil fuel combustion have been growing at about the growth rate of global population in most of the 1970–2010 period, but emissions growth accelerated toward the end of the period (Figure 5.7).

Aggregating population and GHG emissions data according to the five IPCC Representative Concentration Pathways (RC) regions (see Annex II.2), Figure 5.11 shows that between 1971 and 2010 population growth was fastest in the MAF; GHG emissions have increased most in ASIA while changes in population and emissions were modest in OECD-1990 and EIT. The evolution of total population and per capita GHG emissions in the same period is shown in Figure 5.11. With some fluctuations, per capita emissions have declined slightly from rather high levels in the OECD-1990 countries and the EIT, decreased somewhat from relatively lower levels in LAM and especially in the MAF, while more than doubled in ASIA. These trends raise concerns about the future: per capita emissions decline slowly in high-emission regions (OECD-1990 and EIT) while fast increasing per capita emissions are combined with relatively fast population and per capita income growth in ASIA (JRC/PBL, 2013).

There is a substantial number of empirical econometric studies that assess the role of various demographic attributes; an early example is (Dietz and Rosa, 1997). Those reviewed by O'Neill et al. (2012) confirm earlier observations that GHG emissions increase with the population size, although the elasticity values (percent increase in emissions per 1 % increase in population size) vary widely: from 0.32 (Martínez-Zarzoso and Maruotti, 2011) to 2.78 (Martínez-Zarzoso et al., 2007) (for the eight new European Union countries of Central Europe). Differences in statistical estimation techniques and data sets (countries included, time horizon covered, the number and kind of variables included in the regression model and their possible linkages to excluded variables) explain this wide range. Most recent studies find more than proportional increase of emissions triggered by the increase in population. Yet the literature presents contradicting results concerning whether population growth in rich or poor countries contributes more to increasing GHG emissions: Poumanyvong and Kaneko (2010) estimate elasticities ranging from 1.12 (high-income) to 1.23 (middle-income) to 1.75 (low-income) countries while Jorgenson and Clark (2010) find a value of 1.65 for developed and 1.27 for developing groups of countries.

5.3.2.2 Trends in demographic structure

Urbanization

Income, lifestyles, energy use (amount and mix), and the resulting GHG emissions differ considerably between rural and urban populations. The global rate of urbanization has increased from 13 % (1900) to 36 % (1970) to 52 % (2011), but the linkages between urbanization and GHG-emissions trends are complex and involve many factors including the level of development, rate of economic growth, availability of energy resources and technologies, and urban form and infrastructure.

Comparable direct measures of the effect of urbanization on emissions remain difficult due to challenges of defining consistent system boundaries, including administrative or territorial, functional or economic, and morphological or land use boundaries. Moreover, because urban areas are typically much smaller than the infrastructure (e.g., transport, energy) in which they are embedded, strict territorial emissions accounting such as that used for nations, omits important emissions sources such as from energy production (Chavez and Ramaswami, 2013). An alternative is to measure the effect of urbanization indirectly, through statistical analysis of national emission data and its relation to national urbanization trends. An analysis of the effects of urbanization on energy use and CO_2 emissions over the period 1975–2005 for 99 countries, divided into three groups based on GDP per capita, and explicitly considering the shares of industry and services and the energy intensity in the CO_2 emissions, concludes that the effects depend on the stage of development. The impact of urbanization on energy use is negative (elasticity of −0.132) in the low-income group, while positive (0.507) in the medium-income group, and strongly positive (0.907) in the high-income group. Emissions (for given energy use) are positively affected in all three income groups (between 0.358 and 0.512) (Poumanyvong and Kaneko, 2010). Consistent with this conclusion, a set of multivariate decomposition studies reviewed by O'Neill et al. (2012) estimate elasticity values between 0.02 and 0.76, indicating almost negligible to significant but still less than proportional increases in GHG emissions as a result of urbanization. In China, between 1992 and 2007, urbanization and the related lifestyle changes contributed to increasing energy-related CO_2 emissions (Minx et al., 2011).

Many studies observe that GHG emissions from urban regions vary significantly between cities, but that measurements are also widely dispersed due to differences in accounting methods, the coverage of GHGs and their sources, and the definition of urban areas (Dhakal, 2009). A comparison of GHG emissions in 10 global cities by considering geophysical characteristics (climate, resources, gateway status (port of entry and distribution centre for larger regions due to its geographic location), and technical features (urban design, electricity generation, waste processing) finds various outstanding determinants. For example, the level of household income is important because it affects the threshold temperature for heating and cooling of the residential area. The use of high versus low-carbon sources for electricity production, such as nuclear power, is an important determinant of urban GHG emissions in several global cities in the examined sample. Other determinants include connectivity, accessibility of destination and origin, and ability to use alternative transportation modes including mass transit, bicycling, or walking. GHG emissions associated with aviation and marine fuels reflect the gateway status of cities that, in turn, is linked to the overall urban economic activity (Kennedy et al., 2009).

An extended analysis of the urbanization-emissions linkage in 88 countries between 1975 and 2003 finds a diverse picture. In 44 countries, urbanization is found to be not a statistically significant contributor to emissions. In the other 44 countries, all other things equal, in the early phase of urbanization (at low-urbanization levels) emissions increased, while further urbanization at high-urbanization levels was associated with decreasing emissions (Martínez-Zarzoso and Maruotti, 2011). This also confirms that in fast-growing and urbanizing developing countries, urban households tend to be far ahead of rural households in the use of modern energy forms and use much larger shares of commercial energy. Urbanization thereby involves radical increases in household electricity demand and in CO_2 emissions as long as electricity supply comes from fossil fuelled, especially coal based power plants. Transition from coal to low-carbon electricity could mitigate the fast increasing CO_2 emissions associated with the combination of fast urbanization and the related energy transition in these countries.

The literature is divided about the contribution of urbanization to GHG emissions. Most top-down studies find increasing emissions as urbanization advances, while some studies identify an inverted U-shaped relationship between the two. Bottom-up studies often identify economic structure, trade typology, and urban form as central determinants that are more important than the fraction of people in urban areas (see Chapter 12). These findings are important to consider when extrapolating past emission trends, based on past urbanization, to the future, together with other related aspects.

Age structure and household size

Studies of the effect of age structure (especially ageing) on GHG emissions fall into two main categories with seemingly contradicting results: overall macroeconomic studies, and household-level consumption and energy use patterns of different age groups. A national-scale energy-economic growth model calculates for the United States that ageing tends to reduce long-term CO_2 emissions significantly relative to a baseline path with equal population levels (Dalton et al., 2008). Lower labour force participation and labour productivity would slow economic growth in an ageing society, leading to lower energy consumption and GHG emissions (O'Neill et al., 2010). In contrast, studies taking a closer look at the lifestyles and energy consumption of different age groups find that older generations tend to use more energy and emit above average GHGs per person. A study of the impacts of population, incomes, and technology on CO_2 emissions in the period 1975–2000 in over 200 countries and territories finds that the share of the population in the 15–64 age group has a different impact on emissions between different income groups: the impact is negative for high-income countries and positive for lower-income levels (Fan et al., 2006). This is consistent with the finding that (in the United States) energy intensity associated with the lifestyles of the 20–34 and the above 65 retirement-age cohorts tends to be higher than that of the 35–64 age group, largely explained by the fact that this middle-age cohort tends to live in larger households characterized by lower-energy intensity on a per person basis and that residential energy consumption and electricity consumption of the 65+ age group tends to be higher (Liddle and Lung, 2010). Similar results emerge for 14 'foundational' European Union countries between 1960 and 2000: an increasing share of the 65+ age group in the total population leads to increasing energy consumption although the aggregated data disguise micro-level processes:

ageing may well influence the structure of production, consumption, transport, social services, and their location (York, 2007). Several studies assessed above indicate that part of the increasing emissions with age is due to the differences in household size. A five-country multivariate analysis of household energy requirement confirms this (Lenzen et al., 2006). Immigration is not explicitly considered in these studies, probably because it does not make much difference.

It remains an open question by how much the household-level effects of increasing CO_2 emissions as a result of ageing population will counterbalance the declining emissions as a result of slower economic growth caused by lower labour force participation and productivity. The balance is varied and depends on many circumstances. The most important is changes in labour participation: increasing retirement age in response to higher life expectancy will keep former retirement-age cohorts (60+) economically active, which means that the implications of ageing for incomes, lifestyles, energy use, and emissions are 'postponed' and the ratio of active/retired population changes less. Other important aspects include the macroeconomic structure, key export and import commodity groups, the direction and magnitude of financial transfers on the macro side, and on the health status, financial profile, and lifestyle choices and possibilities of the elderly at the household level. This makes it difficult to draw firm conclusions about the ageing-emissions linkages.

Despite the widely varying magnitudes and patterns of household energy use due to differences in geographical and technological characteristics, lifestyles, and population density, most studies tend to indicate that past trends of increasing age, smaller household size, and increasing urbanization were positive drivers for increasing energy use, and associated GHG emissions.

5.3.3 Economic growth and development

5.3.3.1 Production trends

This section reviews the role of income per capita as a driver of emissions while reserving judgement on the appropriateness of GDP per capita as an indicator of development or welfare (see Kubiszewski et al., 2013). Global trends in per capita GDP and GHG emissions vary dramatically by region as shown in Figure 5.12. Economic growth was strongest in ASIA averaging 5.0 % per annum over the 1970–2010 period. Economic growth averaged 1.9 % p.a. in the OECD-1990, but was below the global average of 1.8 % in the remaining regions. The MAF and the reforming economies saw setbacks in growth related to the changing price of oil and the collapse of the centrally planned economies, respectively. However, all regions showed a decline in emissions intensity over time. Emissions per capita grew in ASIA and were fairly constant in LAM, OECD-1990, and EIT, as well as globally, and declined in MAF. The levels of GDP and emissions per capita also vary tremendously globally as shown in Figure 5.12.

Per capita emissions are positively correlated with per capita income. But per capita emissions have declined in all regions but ASIA over time, so that there has been convergence in the level of per capita

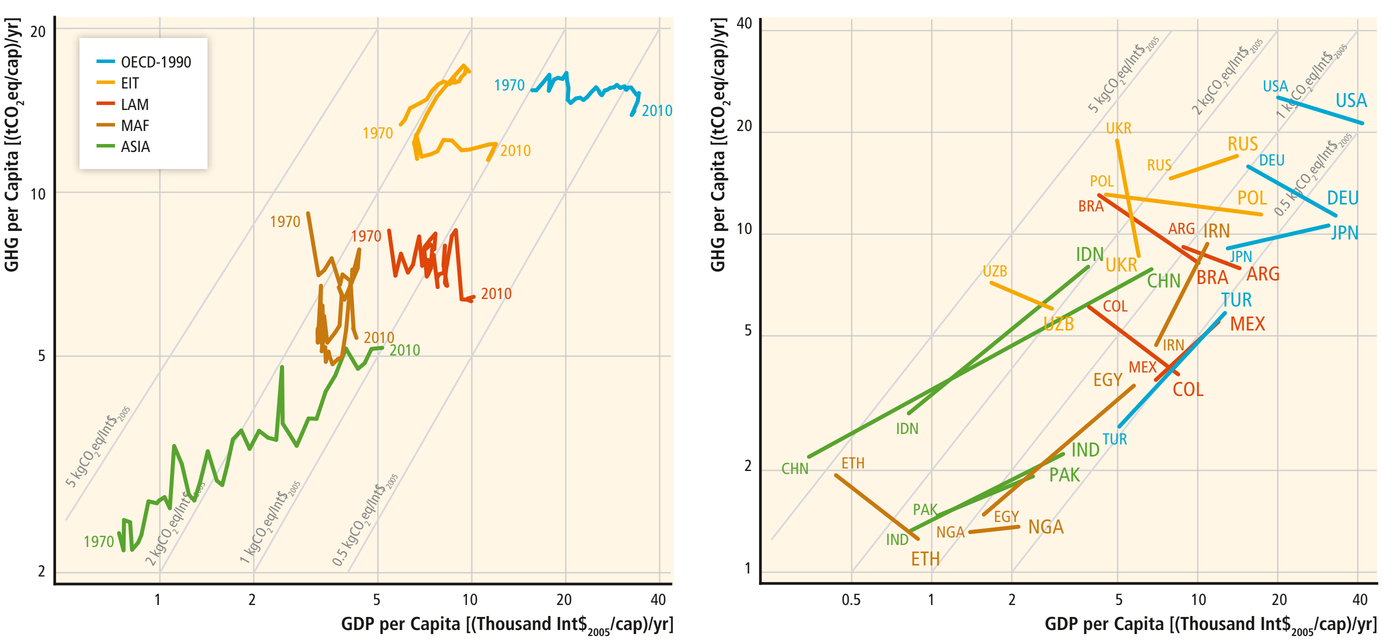


Figure 5.12 | Regional trends in per capita production and GHG emissions (left panel), and for each region the four most populous countries in 2010 (right panel). Regions are defined in Annex II.2. Grey diagonals connect points with constant emission intensity (emissions/GDP). A shift to the right presents income growth. A flat or downwards line presents a decrease in energy intensity, 1971 and 2010. Right panel: The small labels refer to 1970, the large labels to 2010. The figure shows a clear shift to the right for some countries: increasing income at similar per capita emission levels. The figures also show the high income growth for Asia associated with substantial emissions increase. Data from JRC/PBL (2013) and IEA (2012).

emissions over time. Despite this convergence, there is still a wide variation in per capita emissions levels among countries at a common level of income per capita due to structural and institutional differences (Pellegrini and Gerlagh, 2006; Matisoff, 2008; Stern, 2012).

The nature of the relationship between growth and the environment and identification of the causes of economic growth are both uncertain and controversial (Stern, 2011). The sources of growth are important because the degree to which economic growth is driven by technological change versus accumulation of capital and increased use of resources will strongly affect its impact on emissions. In particular, growth in developing countries might be expected to be more emissions-intensive than growth through innovation in technologically leading developed economies (Jakob et al., 2012). However, despite this, energy use per capita is strongly linearly correlated with income per capita across countries (Krausmann et al., 2008; see also Figure 5.15). The short-run effects of growth are slightly different; it seems that energy intensity rises or declines more slowly in the early stages of business cycles, such as in the recovery from the global financial crisis in 2009–2010, and then declines more rapidly in the later stages of business cycles (Jotzo et al., 2012).

Mainstream economic theory (Aghion and Howitt, 2009), and empirical evidence (e.g., Caselli, 2005) point to technological change and increases in human capital per worker as the key underlying drivers of per capita economic output growth in the long run. Technological change encompasses both quality improvements in products and efficiency improvements in production. Human capital is increased through improving workers' skills through education and training. While mainstream growth and development economics does not allocate much role for increasing energy and resource use as drivers of economic growth (Toman and Jemelkova, 2003), many researchers in energy and ecological economics do (Stern, 2011).

Productivity is lower in developing countries than developed countries (Caselli, 2005; Parente and Prescott, 2000). Developing countries can potentially grow faster than developed countries by adopting technologies developed elsewhere and 'catch up' to the productivity leaders (Parente and Prescott, 2000). Income per capita has risen in most countries of the world in the last several decades but there is much variation over time and regions, especially among low- and middle-income countries (Durlauf et al., 2005). The highest growth rates are found for countries that are today at middle-income levels such as China and India (and before them Singapore, South Korea, etc.), which are in the process of converging to high-income levels. But many developing countries have not participated in convergence to the developed world and some have experienced negative growth in income per capita. Therefore, there is both convergence among some countries and divergence among others and a bi-modal distribution of income globally (Durlauf et al., 2005). A large literature attempts to identify why some countries succeed in achieving economic growth and development and others not (Durlauf et al., 2005; Caselli, 2005; Eberhardt and Teal, 2011). But there seems to be little

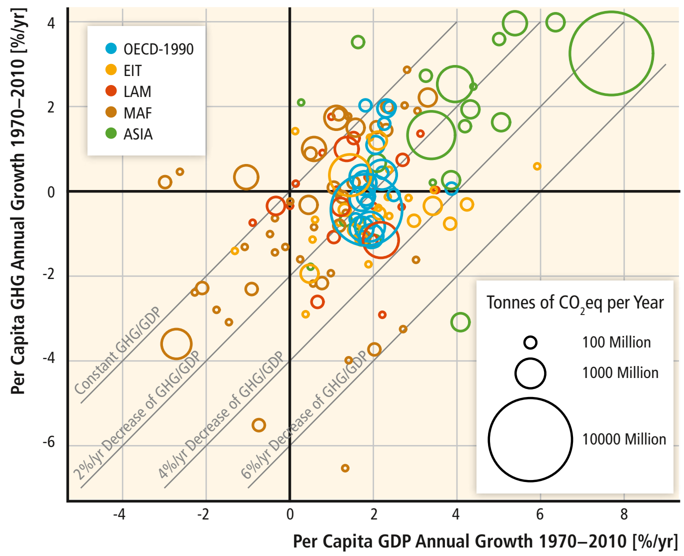


Figure 5.13 | Growth rates of per capita income and GHG emissions. The figure shows the correlation between the average annual growth rate of per capita income and per capita emissions from 1970–2010, for all countries with more than 1 million people by 2010 | Points along the grey lines have either constant emissions intensity or emissions intensity declining at 2 %, 4 % or 6 % per annum. The size of the circles is proportional to countries' emissions. The figure shows that fast growing economies also tend to have increasing emissions, while slower growing economies tend to have declining per capita emissions. This is despite quite rapidly declining emissions intensity in some fast growing economies (upper right corner). Regions are defined in Annex II.2 | Data from JRC/PBL (2013) and IEA (2012).

consensus as yet (Eberhardt and Teal, 2011). A very large number of variables could have an effect on growth performance and disentangling their effects is statistically challenging because many of these variables are at least partially endogenous (Eberhardt and Teal, 2011). This incomplete understanding of the drivers of economic growth makes the development of future scenarios on income levels a difficult task.

Ecological economists such as Ayres and Warr (2009) often ascribe to energy the central role in economic growth (Stern, 2011). Some economic historians, such as Wrigley (2010), Allen (2009), and to some degree Pomeranz (2000), argue that limited availability of energy resources can constrain economic growth and that the relaxation of the constraints imposed by dependence of pre-industrial economies on biomass energy and muscle power sources alone, with the adoption of fossil energy was critical for the emergence of the Industrial Revolution in the 18th and 19th centuries. Stern and Kander (2012) develop a simple growth model including an energy input and econometrically estimate it using 150 years of Swedish data. They find that since the beginning of the 19th century constraints imposed on economic growth by energy availability have declined as energy became more abundant, technological change improved energy efficiency, and the quality of fuels improved. A large literature has attempted using time series analysis to test whether energy use causes economic growth or vice versa, but results are significantly varied and no firm conclusions can be drawn yet (Stern, 2011).

The effect of economic growth on emissions is another area of uncertainty and controversy. The environmental Kuznets curve hypothesis proposes that environmental impacts tend to first increase and then eventually decrease in the course of economic development (Grossman and Krueger, 1994). This theory has been very popular among economists but the econometric evidence has not been found to be very robust (Wagner, 2008; Gallagher, 2009; Vollebergh et al., 2009; Stern, 2010) and in any case, even early studies found that carbon emissions continue to rise with increasing income (e.g., Shafik, 1994). More recent research (Brock and Taylor, 2010) has attempted to disentangle the effects of economic growth and technological change. Rapid catch-up growth in middle-income countries tends to overwhelm the effects of emissions-reducing technological change resulting in strongly rising emissions. But in developed countries economic growth is slower and hence the effects of technological change are more apparent and emissions grow slower or decline. This narrative is illustrated by Figure 5.13. Almost all countries had declining emissions intensity over time but in more rapidly growing economies, this was insufficient to overcome the effect of the expansion of the economy. As a result, though there is much variation in the rate of decline of emissions intensity across countries, there is, in general, a strong positive correlation between the rates of growth of emissions and income per capita. The rapidly growing countries tend to be middle- and lower-income countries and hence there is a tendency for per capita emissions to grow in poorer countries and decline in wealthier ones (Brock and Taylor, 2010).

In conclusion, while economic growth increases the scale of the economy in the Kaya decomposition and, therefore, should increase emissions, the technological change that is the main underlying driver of growth tends to reduce emissions. This has resulted in a tendency for slower growing or declining emissions per capita in wealthier, slower growing, economies, and global convergence in emissions per capita.

5.3.3.2 Consumption trends

Production and consumption are closely connected, but when we study their effect on GHG emissions, we find subtle but important differences. Box 5.2 presents two methods: one for allocating GHG emissions to production (territories), and the other to consumption. Between 1990 and 2010, emissions from Annex B countries decreased by 8 % when taking a territorial perspective (production) to carbon accounting, while over the same period, emissions related to consumption in Annex B increased by 5 % (Wiedmann et al., 2010; Peters et al., 2011, 2012; Caldeira and Davis, 2011; Andrew et al, 2013). In a similar vein, as Figure 5.14 shows, while territorial emissions from non-OECD Asian countries together surpassed those of the OECD-1990 countries in 2009, for consumption-based emissions, the OECD countries as a group contributed more than all non-OECD Asian countries together for every year between 1990 and 2010. The difference between the two methods also shows up in the trends for the per capita emissions. The OECD-1990 territorial per capita emissions declined over 1990–2010, while consumption-based emissions increased. By 2010, per capita territorial emissions for OCED countries are three times those for non-OECD Asian countries, but per capita consumption-related emissions differ by a factor of five. The overall picture shows a

Box 5.2 | Definitions of territorial and consumption-based emissions

The United Nations Framework Convention on Climate Change (UNFCCC) requires countries to submit, following the IPCC guidelines, annual National GHG Emissions Inventories to assess the progress made by individual countries on GHG emissions and removals taking place within national (including administered) territories and offshore areas over which the country has jurisdiction (IPCC, 1997; House of Commons, 2012). These inventories are called 'territorial-based emission inventories'.

Consumption-based emissions allocate emissions to the consumers in each country, usually based on final consumption as in the System of National Accounting but also as trade-adjusted emissions (Peters and Hertwich, 2008; DEFRA, 2012). Conceptually, consumption-based inventories can be thought of as consumption equals production minus emissions from the production of exports (see reviews by (Wiedmann et al., 2007; Wiedmann, 2009; Barrett et al., 2013). The methodology employed is predominately 'Multi-Regional Input-Output Analysis' (MRIO).

Note on Uncertainty—There is increased uncertainty in consumption-based emission estimates. MRIO datasets combine data from different data sets, often large and incoherent. As a result, uncertainties arise in relation to calibration, balancing, and harmonisation; use of different time periods; different currencies; different country classifications; levels of disaggregation, inflation, and raw data errors (Lenzen et al., 2004, 2010; Peters, 2007; Weber and Matthews, 2008; Peters et al., 2012). Production-based emissions data are a key input to the MRIO models that can vary for some countries significantly between databases (Peters et al., 2012). A process of harmonization can greatly reduce the necessary manipulations, and hence, uncertainties reflected in inconsistent reporting practices in different countries and regions (Peters and Solli, 2010; House of Commons, 2012; Barrett et al., 2013). For a detailed description in the variation of MRIO models, please read Peters et al.(2012). Peters et al (2012) concludes that estimates from different studies are robust and that the variation between estimates relates to different input data and approaches to assign emissions to trade and not uncertainty.

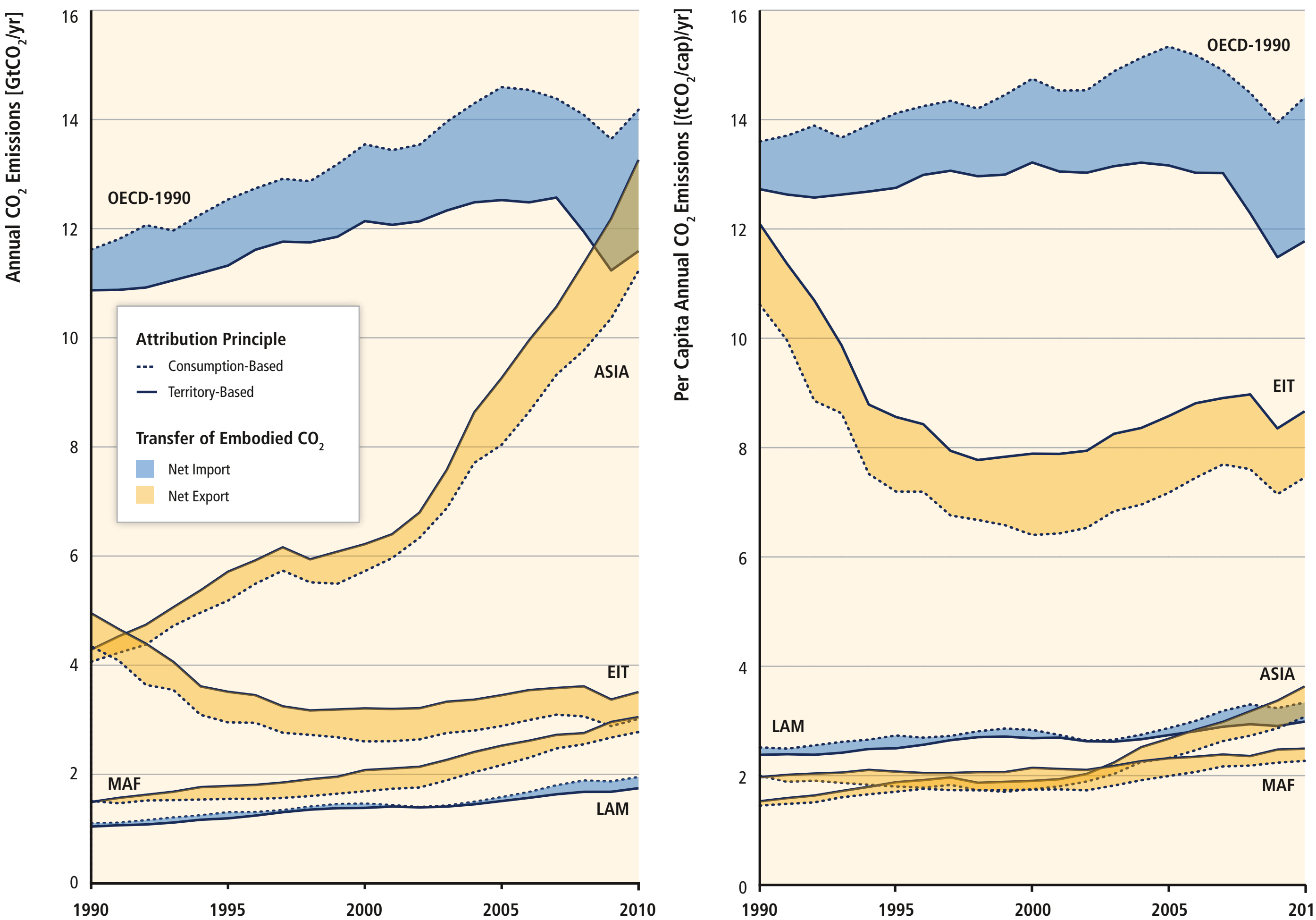


Figure 5.14 | Territory-based versus consumption-based CO_2 emissions in five world regions, from 1990 to 2010 | The left panel presents total emissions, while the right panel presents per capita emissions. The blue areas indicate that a region is a net importer of embodied CO_2 emissions. The yellow area indicates a region is a net exporter of embodied CO_2 | Data from Lenzen et al. (2010). Regions are defined in Annex II.2.

substantial gap between territorial and consumption-based emissions, due to emissions embedded in trade. For the OECD-1990 countries, the gap amounts to 2.6 $GtCO_2$ in 2010. The data shows that the reduction in territorial emissions that has been achieved in the OECD-1990 countries has been more than negated by an increase in emissions in other countries, but related with consumption in OECD-1990 countries. Furthermore, while countries with a Kyoto Protocol commitment did reduce emissions over the accounting period by 7 %, their share of imported over domestic emissions increased by 14 % (Peters et al., 2011; Aichele and Felbermayr, 2012).

Numerous studies have used a structural decomposition analysis to quantify the factors for changes in GHG emissions over time in both developed and developing countries (De Haan, 2001; Peters et al., 2007; Baiocchi and Minx, 2010; Wood, 2009; Weber, 2009). The analysis has been used to separate factors such as the intensity per output, shifts in production structure, as well as changes in the composition and the level of consumption. In all of these studies, increasing levels of consumption is the main contributor to increasing emissions. Specifically, all the studies show that reductions in emissions resulting from improvements in emissions intensity and changes in the structure of production and consumption have been offset by significant increases in emissions, resulting from the volume of consumption, resulting in an overall increase in emissions (De Haan, 2001; Peters et al., 2007; Baiocchi and Minx, 2010). For example, De Haan (2001) demonstrates for the Netherlands that final demand increased by 31 % over 11 years (1987–1998), Peters et al. (2007) demonstrate an increase of consumption by 129 % over 10 years for China, and Baiocchi and Minx (2010) show for the United Kingdom that final demand increased by 49 % between 1992 and 2004. In all these cases, the increase in final demand was greater than the emission reduction caused by structural change and efficiency improvements, leading to an overall increase in consumption-related emissions.

Calculating emissions based on a consumption-based approach sketches a more negative view on the decoupling of economic growth from greenhouse gas emissions. According to York (2007), territorial emissions showed a relative decoupling; emissions grew by 0.73 % for every 1 % increase in GDP per capita from 1960–2008. However, the elasticity of consumption-based emissions with respect to economic growth will have to be revised upwards for OECD-1990 countries, given that their consumption emissions grew at a faster rate than territorial ones (Peters et al., 2011). In this sense, there is less decoupling in industrialized nations.

5.3.3.3 Structural change

Changes in the structure of the economy—shares of each economic or industry sector in the output of the economy—might also affect emissions. Over the course of economic development, as income grows, the share of agriculture in the value of production and employment tends to decline and the share of services increases (Syrquin and Chenery, 1989). The share of manufacturing tends to follow an inverted U-shaped path (Hettige et al., 2000). The income levels at which these transitions occur differ across countries. For example, China's share of services in GDP and employment is small and its agriculture share large, given its income level (World Bank, 2011), while India has a relatively large service sector (Deb Pal et al., 2012). Between 1970 and 2010 the global share of agriculture in GDP has declined from 9 % to 3 % while the share of services increased from 53 % to 71 %. Industry declined from 38 % to 26 % of GDP (World Bank, 2011). Schäfer (2005) shows that there are similar changes in the sectoral composition of energy use. The share of total energy use used in services increases in the course of economic development while that of industry follows an inverted U-shaped curve. The share of residential energy use declines with rising per capita income.

The shift from the industrial sector to services reduces energy use and emissions less than commonly thought. Partly, this is due to strong gains in productivity in manufacturing. The productivity gain can be observed through the price of manufactured goods, which has historically fallen relative to the price of services. Because of the price decline, it appears that the share of manufacturing industry in the economy is falling when, in real output terms, it is constant or increasing (Kander, 2005). Part of the productivity gain in manufacturing is due to improvements in energy efficiency, which reduce energy intensity in the sector (Kander, 2005). Also, not all service sectors are low in energy intensity. Transport is clearly energy-intensive and retail and other service sectors depend on energy-intensive infrastructure.

In Austria and the United Kingdom, the transition of the industrial society into a service economy or post-industrial society did not lead to dematerialization (Krausmann et al., 2008), but instead it was systematically linked to an increase in per capita energy and material consumption as all parts of the economy shifted from traditional to modern methods of production. Further evidence (Henriques and Kander, 2010) for 10 developed countries (United States, Japan, and eight European countries), and three emerging economies (India, Brazil, and Mexico), indicates a minor role for structural change in reducing energy intensity, while the decline in energy intensity within industries is found to be the main driver of aggregate energy intensity. Yet the decomposition is sensitive to the level of disaggregation. A classic result in the growth-accounting literature (Jorgenson and Griliches, 1967) is that a finer disaggregation of inputs and outputs leads to lower estimates for technological change and a larger role for substitution between inputs and structural change. This is confirmed by Wing (2008), who found that structural change between industries explained most of the decline in energy intensity in the United States (1958–2000), especially before 1980 (Stern, 2011). An alternative perspective is provided by the literature on consumption-based emissions (see Section 5.3.3.2). Baiocchi and Minx (2010) show that the shift to a service economy in the United Kingdom was partly achieved by off-shoring emissions-intensive industrial activities and thus reducing industrial activity, and that the service sector uses imported emissions-intensive goods. Both of these offset the reduction in emissions from shifting toward the service sector in the United Kingdom. Likewise, Suh (2006) and Nansai et al. (2009b) show that if the entire supply chain is considered, the emissions intensity of services is much higher than if only the final production of services is considered.

The reform of centrally planned economies has been an important factor driving changes in GHG emissions. Emissions and energy intensity were high in China, the former Soviet Union, and many Eastern European countries prior to reform, and declined as their economies were reformed. China serves as a case in point. Its energy intensity was very high compared to similar but market-oriented countries before 1980, but China's energy intensity decreased sharply between 1980 and 2000, as it opened its economy through market-based reforms (Ma and Stern, 2008). Energy and emissions intensity rose and then fell again from 2000 to the present as at first easy options for energy efficiency improvements were exhausted and later new policies to improve energy and carbon intensity were put in place. On the other hand, China's carbon intensity of energy supply has increased steadily since at least 1970 (Stern and Jotzo, 2010). Sectoral shifts played only a small role in these large movements of the past three decades (Ma and Stern, 2008; Steckel et al., 2011), though they were important in the rise in emissions intensity from 2000 to 2005 (Minx et al., 2011).

In conclusion, the role of an increase in share of the service sector in output in reducing emissions is probably quite small, but finer-grained structural change could be important and economy-wide reforms contribute much to the adoption of more energy- and emissions-efficient production processes.

5.3.4 Energy demand and supply

5.3.4.1 Energy demand

Globally, per capita primary energy use, as estimated by the International Energy Agency (IEA) method (see Annex II.9), rose by 31 % from 1971–2010; however the five world regions exhibited two different pathways during this period, as seen in Figure 5.15 (left). In the OECD-1990 and EIT, energy use per capita rose by 13–14 %, while the other regions increased their per capita energy use at a much higher rate: LAM by 60 %, MAF by 90 %, and ASIA by 200 %. Nevertheless, the 2010 per capita energy use in these three regions still remains at less than half of the OECD-1990 and EIT countries 40 years ago.

The two pathways in per capita energy use are also reflected when looking at energy intensity over time (Figure 5.15 right). The measurement of energy intensity, i. e., ratio of energy use per unit of GDP and its limitations, are discussed in the following section. The differences in pathways between the OECD-1990 and EIT versus ASIA, LAM, and MAF illustrate the energy intensity gap between the industrialized and developing countries. In Figure 5.16, we show a similar chart for individual countries. Combining the left and right panels, we see that improvements in energy intensity have slowed the growth in energy use substantially, but have been insufficient to offset the growth in the scale of the economy (Stern, 2012).

The effects of the oil price shocks in 1973 and 1979 and perhaps 2008 (Hamilton, 2009) are particularly visible as dips in the OECD trend. These price shocks do not appear, however, to have reversed the upward trend in per capita primary energy use in the regions. In the long run, per capita energy consumption has increased with income and over time since the onset of the Industrial Revolution in Northern Europe (Gales et al., 2007) and the United States (Grübler, 2008; Tol et al., 2009) and since the Second World War in southern Europe (Gales et al., 2007).

Changes in total energy use can be decomposed to reflect the effects of growth in population and income per capita and changes in energy intensity, all of which are discussed in detail in other sections of this chapter as well as in Chapter 7.

The relationship between economic growth and energy use is complicated and variable over time. The provision of energy services is one of the necessary conditions for economic growth, yet in turn, economic growth increases the demand for energy services (Grübler et al., 2012). As income increases, so does energy use. This phenomenon, coupled with population growth, has resulted in global total primary energy use increasing by 130 % between 1971 and 2010, and almost 50 times since 1800 (Nakicenovic et al., 1998; Grübler, 2008).

5.3.4.2 Energy efficiency and Intensity

Energy efficiency can be defined as the ratio of the desired (usable) energy output for a specific task or service to the energy input for the given energy conversion process (Nakicenovic et al., 1996). For example, for an automobile engine, this is the mechanical energy at the crankshaft or the wheels divided by the energy input of gasoline. This definition of energy efficiency is called the first-law efficiency. Other approaches often define energy efficiency in relative terms, such as the ratio of minimum energy required by the current best practice technology to actual energy use, everything else being constant (Stern, 2012).

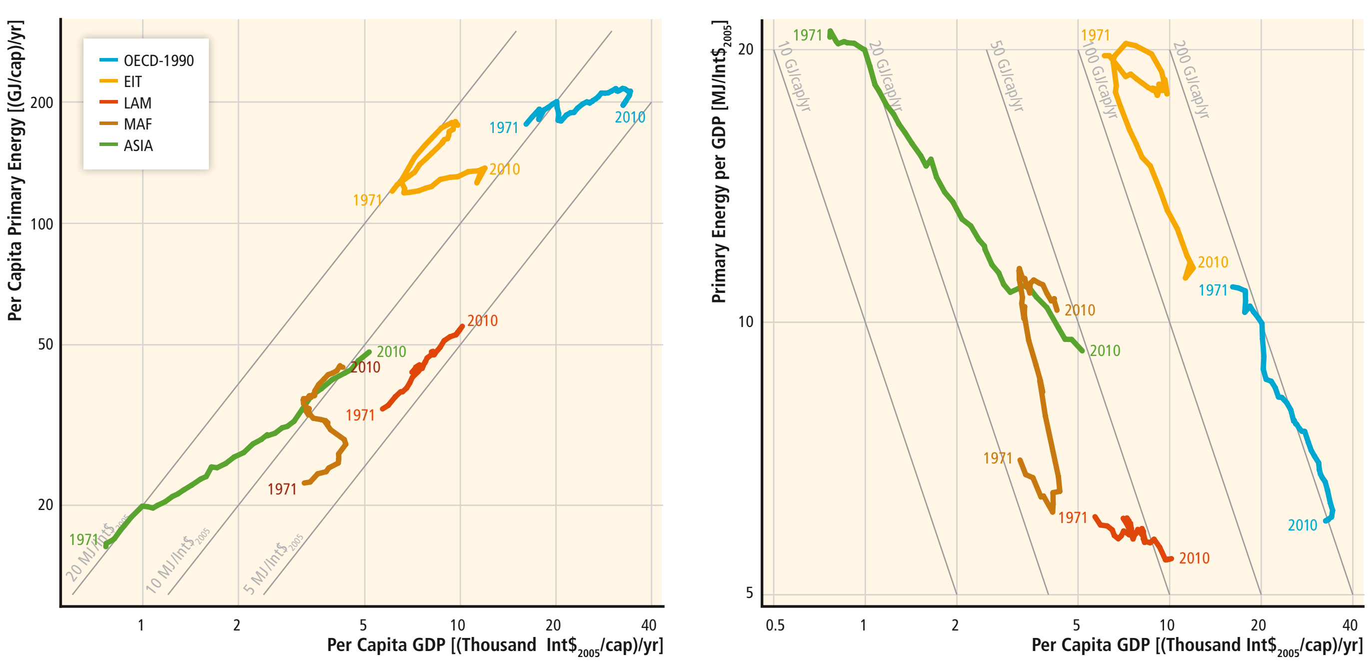


Figure 5.15 | Historical trend (1971–2010) by region in per capita primary energy (left panel), and primary energy intensity of GDP (right panel), against GDP per capita on the horizontal axis. Grey diagonals connect points with constant energy intensity (left panel) and constant per capita primary energy use (right panel). Note that both axes are logarithmic. Source: IEA (2012); UN WPP (2012); World Bank (2012). Regions are defined in Annex II.2.

In 2005, the global first-law efficiency of converting primary energy sources (such as coal or natural gas) to final energy forms (such as electricity or heat) was about 67 % (i. e., 330 EJ over 496 EJ). The efficiency of further converting final energy forms into useful energy is lower, with an estimated global average of 51 % (i. e., 169 EJ over 330 EJ). Thus, approximately one-third of global primary energy use is dissipated to the environment in the form of waste heat or what is colloquially termed energy 'losses' (Grübler et al., 2012).

The theoretical potential for efficiency improvements is thus very large (Grübler et al., 2012). However, efficiency improvements can lead to additional demand, a side-effect called the rebound effect, discussed later in Section 5.6.2, which needs to be taken into account (Pao and Tsai, 2010).

Economic studies, including those based on the Kaya identity (Nakicenovic and Swart, 2000), often use energy intensity—the ratio of energy use per dollar of GDP—as an indicator of how effectively energy is used to produce goods and services, also known as its inverse: the energy productivity. However, energy intensity depends on many factors other than technical efficiencies, as discussed in the remainder of this section, and is not an appropriate proxy of actual energy (conversion) efficiency (Ang, 2006; Filippini and Hunt, 2011; Stern, 2012; Grübler et al., 2012).

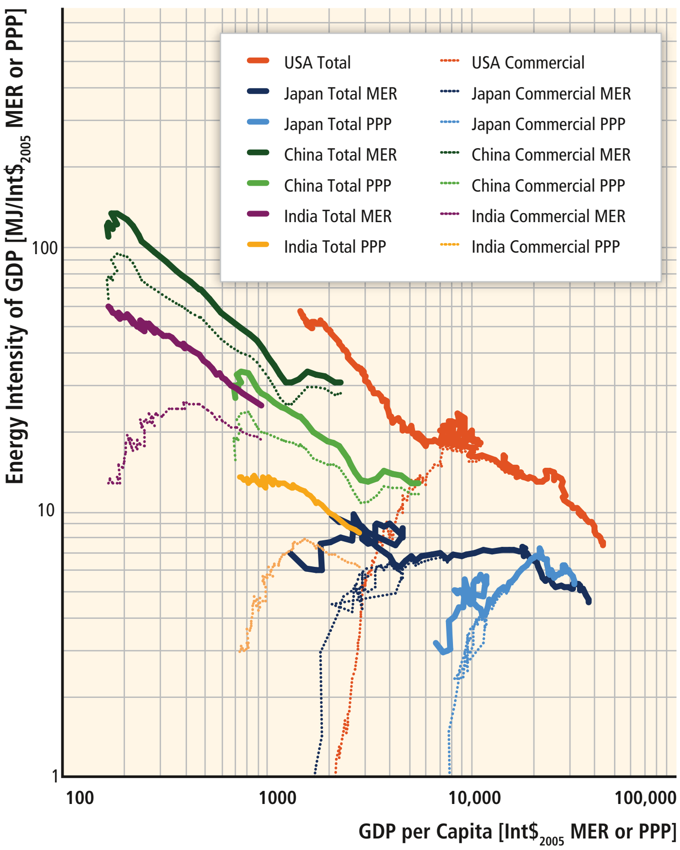


Figure 5.16 | Energy intensity improvements and per capita GDP—USA (1800–2008), Japan (1885–2008), India (1950–2008), and China (1970–2008). Source: Grübler et al., 2012. Note: Energy intensities (in MJ per USD) are always shown for total primary energy (bold lines), and commercial primary energy only (thin lines), and per unit of GDP expressed at market exchange rates (MER in USD_{2005}), and for China, India, and Japan also at purchasing power parities (PPP in $Int\$_{2005}$). For the United States, MER and PPP are identical.

Energy intensity metrics yield valuable insights into potentials for efficiency improvements related to various activities (Fisher and Nakicenovic, 2008; Grübler et al., 2012). Energy intensity measured at the economy-wide level is an attractive indicator because of its simplicity and ease of comparability across systems and time (e. g., national economies, regions, cities, etc.). However, the indicator is affected by a number of issues, including in relation to the way definitions are made and measurements are performed (Ang, 2006; Filippini and Hunt, 2011). Many factors besides technical efficiency drive energy intensity differences.

Energy intensities are strongly affected by energy and economic accounting conventions, which are not always disclosed prominently in the reporting reference. For energy, the largest influences on the metrics are whether primary or final energy are used in the calculations, and whether or not non-commercial energy[7] is included (Grübler et al., 2012; see Figure 5.16).

Figure 5.16 illustrates these differences in the evolution of historical primary energy intensity for four major world economies: China, India, Japan, and the United States. It shows the different ways energy intensity of GDP can be measured.

To see how the inclusion of non-commercial energy affects energy intensity, we take the United States as an example, as its PPP and MER GDP are the same by definition. The thin green curve shows United States commercial energy intensity. According to Grübler et al. (2012), commercial energy intensities increase during the early phases of industrialization, as traditional, less-efficient energy forms are replaced by commercial energy. Once this substitution is completed, commercial energy intensity peaks and starts to decline. This phenomenon is sometimes called the 'hill of energy intensity' (Grübler et al., 2012). These peaks are observed to be lower for countries reaching this transition stage now, promising lower energy intensity in developing countries that still have to reach the peak (Gales et al., 2007; Lescaroux, 2011; Reddy and Goldemberg, 1990; Nakicenovic et al., 1998). More important than this 'hill' in commercial energy intensities is, however, a pervasive trend toward overall lower total energy (including also non-commercial energy) intensities over time and across all countries (Grübler et al., 2012). It is interesting to note that despite the relatively wide upper and lower bounds of initial energy intensity among the investigated countries, they all exhibit very similar rates of energy

7 Non-commercial energy is energy that is not commercially traded such as the traditional biomass or agricultural residues, which are of particular importance in developing countries.

intensity improvements independent of whether they are on a more or less energy-intensive development trajectory.

The most important accounting factor is the exchange rate used for converting income measured in local national currencies to internationally comparable currency units based on either MER or PPP exchange rates (both illustrated in Figure 5.16) (Grübler et al., 2012). In the cases of India and China, MER energy intensities are very high, similar to the energy intensities of the industrialized countries more than 100 years ago. This gives the appearance of very high energy intensity of GDP in developing countries. However, China and India's PPP-measured GDPs are much higher, meaning that with the same dollar amount, a Chinese or Indian consumer can purchase more goods and services in developing countries than in industrialized countries. The PPP-measured energy intensities are thus much lower for developing countries, indicating substantially higher energy effectiveness in these countries than would be calculated using MER (Grübler et al., 2012). A further limitation of GDP accounting, especially for developing countries, is the exclusion of 'grey economies' in official statistics, which would increase GDP.

Countries with long-term statistical records show improvements in total energy intensities by a factor of five or more since 1800, corresponding to an global annual average decline of total energy intensities of about 0.75–1 % (Gilli et al., 1990; Fouquet, 2008). Improvement rates can be much faster over periods of a few decades, as illustrated in the case of China, which exhibited a steep decline (2–3 %/year for PPP- and MER-based energy intensities, respectively) between 1979 and 2000 before the trend flattened (Stern and Jotzo, 2010). Faster economic growth leads to a faster turnover of the capital stock of an economy, thus offering more opportunities to switch to more energy-efficient technologies. The reverse also applies for the economies in transition (Eastern Europe and the former Soviet Union in the 1990s) or recession; that is, with declining GDP, energy intensities increase.

Energy intensity has declined globally in all developed and major developing countries including India and China (Steckel et al., 2011). When traditional (non-commercial) biomass fuels are included in the measure of energy input, energy intensity has declined over time in most investigated countries (Gales et al., 2007). However, historical improvements in energy intensities have not been sufficient to fully offset GDP growth, resulting in increased energy consumption over time (Bruckner et al., 2010). The literature indicates some albeit inconsistent convergence in energy intensities among developed economies, but not for both developed and developing countries (Le Pen and Sévi, 2010; Mulder and de Groot, 2012).

Changes in energy intensity over time can be decomposed into the effects of structural change (the shift to more or less energy-intensive industries), changes in the mix of energy sources, technological change, and the quantities of other inputs such as capital and labour used (Stern, 2012; Wang, 2011). Globally, structural changes play a smaller role in determining trends in energy use and CO_2 emissions, though they can be important in individual countries (Cian et al., 2013). More generally for countries and regions, energy intensity is also affected by the substitution of capital and other inputs for energy (Stern, 2012). The drivers of energy intensity trends are difficult to isolate. For example, in the United States, most researchers find that technological change has been the dominant factor in reducing energy intensity (Metcalf, 2008). Similar results have been found for Sweden (Kander, 2005) and China (Ma and Stern, 2008; Steckel et al., 2011). However, Wing (2008) finds that structural change explained most of the decline in energy intensity in the United States (1958–2000), especially before 1980, and Kaufmann (2004) attributes the greatest part of the decline to substitution towards higher-quality energy sources, in particular electricity that produces more output per Joule. Similarly, Liao et al. (2007) conclude that structural change, instead of technological change, is the most dominant factor in reducing energy intensity in China.

Some differences in energy intensity among countries are easily explained. Countries with cold winters and formerly centrally planned economies tend to be more energy-intensive economies, though the latter have improved energy intensities significantly in recent decades through reform of energy markets (Stern, 2012). The role of economic structure, resource endowments, and policies explain much of the differences in energy intensities (Ramachandra et al., 2006; Matisoff, 2008; Wei et al., 2009; Stern, 2012; Davidsdottir and Fisher, 2011). There is no clear one-to-one link between overall energy intensity and energy efficiency in production (Filippini and Hunt, 2011), though there is evidence for the role of energy prices. Higher energy prices are associated with lower levels of energy consumption and are significantly determined by policy. Countries that have high electricity prices tend to have lower demand for electricity, and vice-versa (Platchkov and Pollitt, 2011), with a price elasticity of demand for total energy use between −0.2 and −0.45 for the OECD countries between 1978 and 2006 (Filippini and Hunt, 2011).

5.3.4.3 Carbon-intensity, the energy mix, and resource availability

Carbon intensity is calculated as the ratio of emissions of CO_2 per unit of primary or final energy, whereas decarbonization refers to the rate at which the carbon intensity of energy decreases. Throughout the 20th century, the choice of fossil-fuels for energy has progressed towards less carbon intensive fuels and to conversion of energy to more usable forms (e.g., electricity) (Grübler et al., 2012). Hydrogen-rich fuels release, during combustion, more energy for every carbon atom that is oxidized to CO_2 (Grübler et al., 1999). The result is a shift from fuels such as coal with a high-carbon content to energy carriers with a lower-carbon content such as natural gas[8], as well as the introduction of near-zero carbon energy sources, such as renewables, including sus-

[8] For further detailed information on carbon emissions for various combustible fuels, see IPCC (1997) and IPCC (2006).

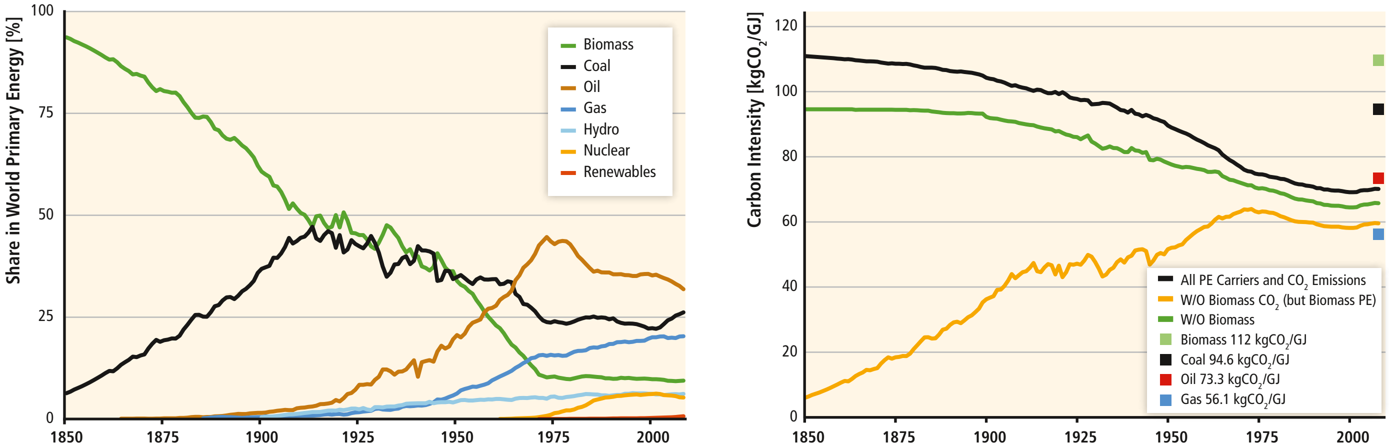


Figure 5.17 | Left Panel: Structural change in world primary energy (in percent) over 1850–2008 illustrating the substitution of traditional biomass (mostly non-commercial) by coal and later by oil and gas. The emergence of hydro, nuclear and new renewables is also shown. Source: Nakicenovic et al. (1998) and Grübler (2008). Right panel: Decarbonization of primary energy (PE) use worldwide over 1850–2008 (kg of CO_2 emitted per GJ). The black line shows carbon intensities of all primary energy sources, orange line of commercial energy sources without biomass CO_2 emissions, assuming they have all been taken up by the biosphere under a sustainable harvesting regime (biomass re-growth absorbing the CO_2 released from biomass burning) and the green line shows global decarbonization without biomass and its CO_2 emissions. Note: For comparison, the specific emission factors (OECD/IPCC default emission factors, lower-heating value (LHV) basis) for biomass (wood fuel), coal, crude oil, and natural gas are also shown (coloured squares). Source: updated from Grübler et al. (2012).

tainably managed biomass (biogenic carbon is reabsorbed through new growth), and nuclear, and consequently further decarbonization of energy systems (Grübler and Nakićenović, 1996; Grübler, 2008). Decarbonization can also affect the emissions of other GHGs and radiatively active substances such as aerosols. Figure 5.17 (left panel) shows the historical dynamics of primary energy. It indicates that the changes in primary energy are very slow, because it took more than half a century to replace coal as the dominant source of energy.

Figure 5.17 (right panel) illustrates the historical trend of global decarbonization of primary energy since 1850 in terms of the average carbon emissions per unit of primary energy (considering all primary energy sources, commercial energy sources with and without biomass). Historically, traditional biomass emissions related to LUCs, i.e., from deforestation to land for food and energy crops, have far exceeded carbon releases from energy-related biomass burning, which indicates that in the past, biomass, like fossil fuels, has also contributed significantly to increases in atmospheric concentrations of CO_2 (Grübler et al., 2012).

The global rate of decarbonization has been on average about 0.3 % annually, about six times too low to offset the increase in global energy use of approximately 2 % annually (Grübler et al., 2012). A significant slowing of decarbonization trends since the energy crises of the 1970s is noteworthy, particularly the rising carbon intensities as a result of increased use of coal starting in 2000 (IEA, 2009; Stern and Jotzo, 2010; Steckel et al., 2011). Recent increases in natural gas, in particular shale gas use, will tend to partially offset the carbonization trends.

Some future scenarios foresee continuing decarbonization over the next several decades as natural gas and non-fossil energy sources increase their share in total primary energy use. Other scenarios anticipate a reversal of decarbonization in the long term as more easily accessible sources of conventional oil and gas are replaced by more carbon-intensive alternatives such as coal and unconventional oil and gas (Fisher et al., 2007). Nonetheless, almost all scenarios anticipate an increase in future demand for energy services. The increase in energy demand means higher primary energy requirements and, depending on the rates of future energy-efficiency improvements, higher emissions. Therefore, energy-efficiency improvements alone will not be sufficient to significantly reduce GHG emissions, and it is thus essential to accelerate the worldwide rate of decarbonization. Current evidence indicates that further decarbonization will not be primarily driven by the exhaustion of fossil fuels, but rather by economics, technological and scientific advances, socio-political decisions, and other salient driving forces. Furthermore, new information and communication technologies (ICTs) can help reduce the energy needs and associated emissions to improve the efficiency measures as a result of better management of energy generation and end-use, e.g., emergence of smart grids and better control of end-use devices.

Fossil fuel reserves and resources make up the hydrocarbon endowments, which as a whole are not known with a high degree of certainty. Reserves are the part of global fossil occurrences that are known with high certainty and can be extracted using current technologies at prevailing prices. Thus, the quantification and classification of reserves relies on the dynamic balance between geological assurance, technological possibilities, and economic feasibility. There is little controversy that oil and gas occurrences are abundant, whereas the reserves are more limited, with some 50 years of production for oil and about 70 years for natural gas at the current rates of extraction (Rogner et al., 2012). Reserve additions have shifted to inherently more challenging and potentially costlier locations, with technological progress outbalancing potentially diminishing returns (Nakicenovic et al., 1998; Rogner et al., 2012).

In general, estimates of the resources of unconventional gas, oil, and coal are huge (GEA, 2012; Rogner et al., 2012) ranging for oil resources to be up to 20,000 EJ or almost 120 times larger than current global production; natural gas up to 120,000 EJ or 1300 times current production, whereas coal resources might be as large as 400,000 EJ or 3500 times larger than current production. However, global resources are unevenly distributed and are concentrated in some regions and not others (U.S. Energy Information Administration, 2010). These upper estimates of global hydrocarbon endowments indicate that their ultimate depletion cannot be the relied upon to limit global CO_2 emissions. For example, the carbon embedded in oil and gas reserves exceeds the current carbon content of the atmosphere. The emissions budget for stabilizing climate change at 2 °C above pre-industrial levels is about the same as the current carbon content of the atmosphere, meaning that under this constraint only a small fraction of reserves can be exploited (Meinshausen et al., 2009). Chapter 7 of this report discusses in detail the current and future availability of global energy resources (see also Table 7.2).

5.3.5 Other key sectors

This section briefly describes GHG emission trends for the other main economic sectors (transport, buildings, industry, AFOLU, and waste) and the correlation between emissions and income, showing marked differences between sectors and countries. The following sections provide short discussions of trends and drivers by sector, while the following chapters (7–11) provide detailed analyses. Note that in Chapter 5, we consider only direct emissions for the buildings sector, whereas Chapter 9 also includes indirect emissions.

GHG emissions grew in all sectors, except in AFOLU where positive and negative emission changes are reported across different databases and uncertainties in the data are high (see Section 11.2). As is clear from Figure 5.18, high-income countries contribute mostly to emissions associated with transport (Chapter 8) and buildings (Chapter 9). Low and lower middle-income countries contribute the largest share of emissions associated with AFOLU (Chapter 11). Between 2000 and 2010, emissions by upper middle-income countries from energy (+3.5 $GtCO_2e$/yr) and industry (+2.4 $GtCO_2e$/yr) more than doubled, and by 2010, emissions from industry in upper middle-income countries have passed those from high-income countries.

The large increase in energy and industry emissions in upper middle-income countries is consistent with the observed income growth and the correlation between emissions and income for these sectors (Figure 5.19). There is a robust positive relation between income and emissions, particularly for annual income levels between 1000 and 10,000 $Int\$_{2005}$/cap, while for transport, the correlation between income and emissions continues into higher-income levels. We find no positive correlation between income and emissions for AFOLU.

In 2010, the typical high-income country (median of the high-income group, population-weighted) had per capita emissions of 13 tCO_2eq/cap yr, while per capita emissions in the typical low-income country were only about one-tenth of that value, at 1.4 tCO_2eq/cap yr. But, there is a large variation among countries that have similar income levels. The per capita emissions in high-income countries range from 8.2 to 21 tCO_2eq/cap yr, for the (population weighted) 10 and 90 percentile, respectively. Many low-income countries (median income of 1,200 $Int\$_{2005}$/cap) have low per capita emissions (median of 1.4 tCO_2eq/yr), but for the low-income country group, average per capita emissions (4.3 tCO_2eq/yr) are pulled up by a few countries with very high emissions associated with land-use.

5.3.5.1 Transport

Global transport GHG emissions[9] grew from 2.8 $GtCO_2eq$ in 1970 to 7 $GtCO_2eq$ in 2010 (JRC/PBL, 2013). The OECD-1990 countries contributed the largest share of the emissions (i.e., 60 % in 1970, 56 % in 1990, and 46 % in 2010) but the highest growth rates in transport emissions were in the upper middle-income countries and international bunkers. The overall picture shows that transport emissions have steadily increased but show a marked decrease around 2008/2009.

Increasing demand for passenger and freight transport, urban development and sprawl, lack of rail and bus transit and cycle infrastructure in many regions, transport behaviour constrained by lack of modal choice in some regions, a high fuel-consuming stock of vehicles, relatively low oil prices, and the limited availability of low-carbon fuels have been the principal drivers of transport sector CO_2 emission growth over the past few decades (Jolley, 2004; Davies et al., 2007; IPCC, 2007; Timilsina and Shrestha, 2009; Ubaidillah, 2011; Wang et al., 2011 Chapter 8).

The marked growth rate of international transport emissions after 2002 coincides with growth in Chinese exporting industries sugges 3ting an influence of trade policies and world trade agreements on transport emissions (Olivier et al., 2011).

The high oil prices of 2008 and the global recession in 2009 both resulted in a decrease in fossil fuel consumption for the OECD countries, with CO_2 emissions declining by 2.0 % in 2008, and an estimated 6.3 % in 2009. GHG emissions in non-OECD countries were not affected (US EIA, 2011).

There is a strong correlation between per capita transport emissions and per capita incomes and alignment of the two variables is sharper in the high-income countries (Figure 5.19) as the demand for personal transportation increases as standards of living rise and economic activity increases (US EIA, 2011).

[9] Consisting of direct CO_2, CH_4, N_2O, and F-gases (Freight Vision, 2009).

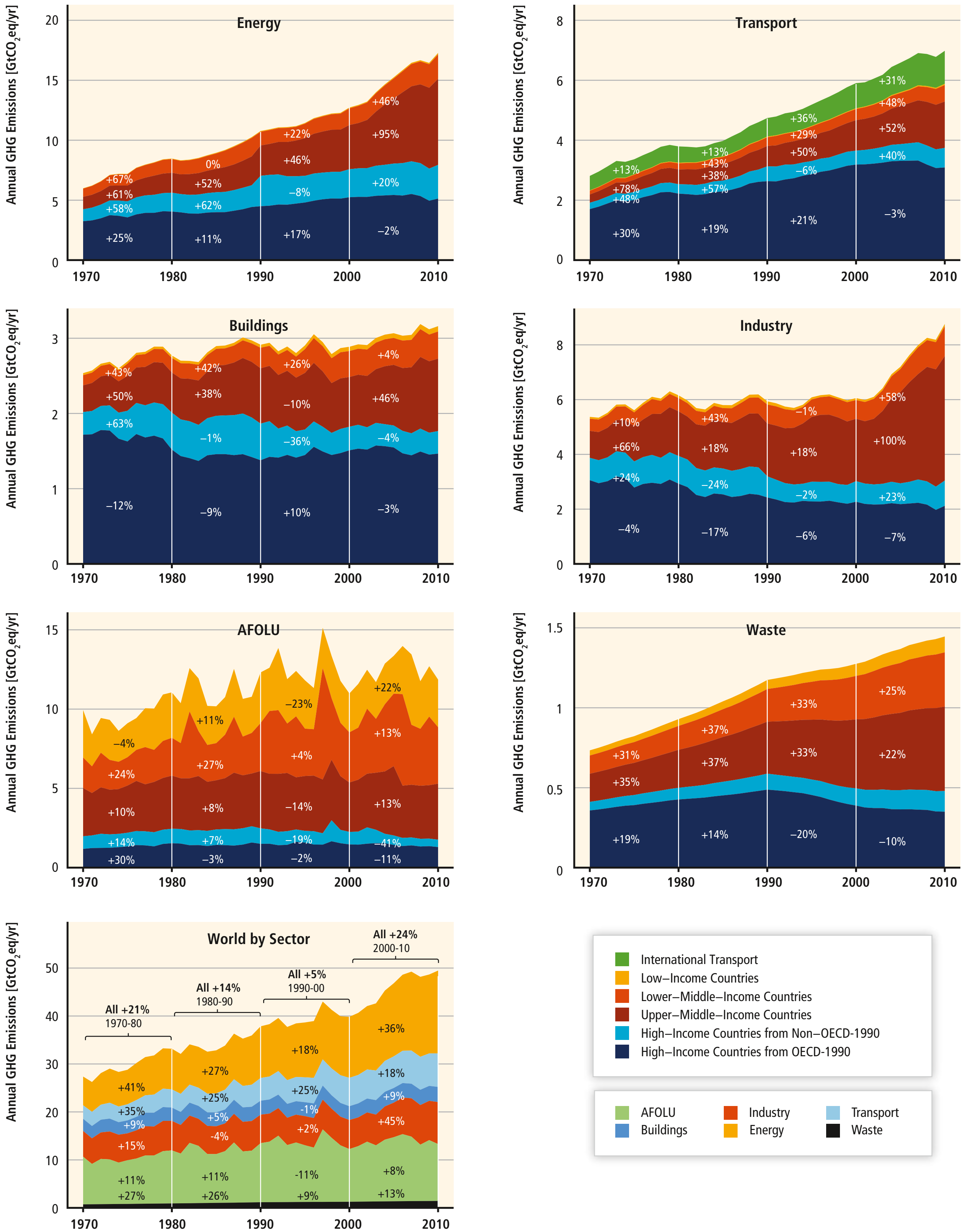
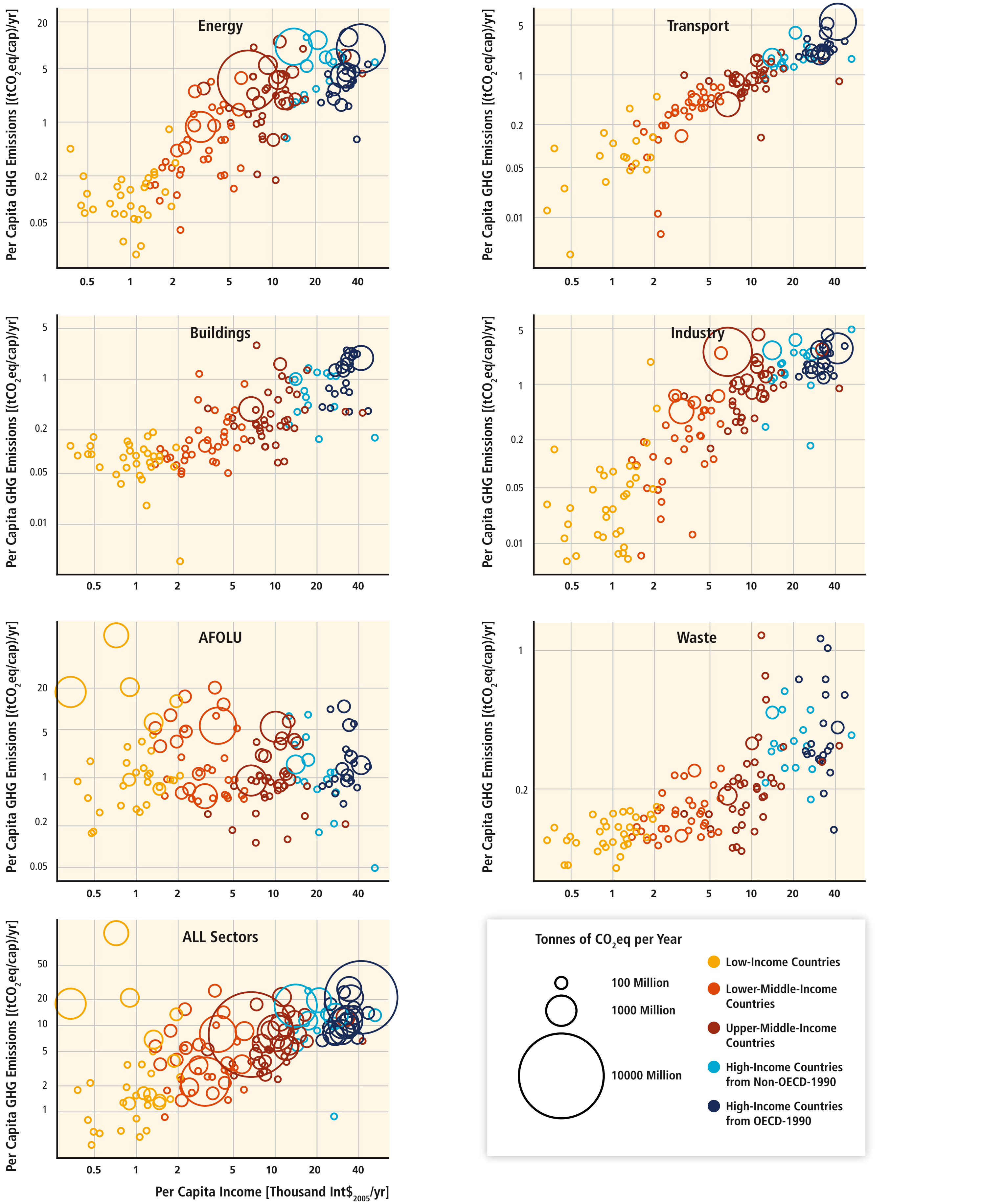


Figure 5.18 | Regional and sector distribution of GHG emission trends. Regions are defined in Annex II.2 | The figure shows annual GHG emissions for the six key sectors discussed in Sections 5.3.4 and 5.3.5 | The left-lower panel presents global sector emissions to assess the relative contribution. Decadal growth rates are projected on the charts for emissions exceeding 0.2 $GtCO_2eq/yr$. The direct emission data from JRC/PBL (2013) and IEA (2012) (see Annex II.9) represents land-based CO_2 emissions from forest and peat fires and decay that approximate to CO_2 flux from anthopogenic emission sources in the Forestry and Other Land Use (FOLU) sub-sector. For a more detailed representation of Agriculture and FOLU (AFOLU) GHG flux see Section 11.2 and Figures 11.2 and 11.6.


Energy
Transport
Buildings
Industry
AFOLU
Waste
ALL Sectors
Per Capita GHG Emissions [(tCO2eq/cap)/yr]
Per Capita Income [Thousand Int$2005/yr]
Tonnes of CO2eq per Year
100 Million
1000 Million
10000 Million
Low-Income Countries
Lower-Middle-Income Countries
Upper-Middle-Income Countries
High-Income Countries from Non-OECD-1990
High-Income Countries from OECD-1990

⇒

Figure 5.19 | The relation between income and GHG emissions for the six key sectors discussed in Sections 5.3.4 and 5.3.5 | The left-lower panel presents the relation for emissions aggregated over all sectors. Each circle is one country, for the year 2010 | The area of a circle is proportional to the aggregate emissions for that country and sector, using the same scale consistently over all panels. The bubble size is bounded from below for visual ease. Note the logarithmic scales on both x and y axes. For most sectors apart from AFOLU, there is a clear positive relation between income and emissions. Data from JRC/PBL (2013) and IEA (2012). The direct emission data from JRC/PBL (2013) (see Annex II.9) represents land-based CO_2 emissions from forest and peat fires and decay that approximate to CO_2 flux from anthopogenic emission sources in the Forestry and Other Land Use (FOLU) sub-sector. For a more detailed representation of Agriculture and FOLU (AFOLU) GHG flux see Section 11.2 and Figures 11.2 and 11.6 | Regions are defined in Annex II.2.

5.3.5.2 Buildings

Building sector emissions grew from 2.5 $GtCO_2eq$ in 1970 to 3.2 $GtCO_2eq$ in 2010 with emissions growth rates in OECD-1990 countries being largely negative. Positive-emission growth rates were registered in the upper and lower middle-income countries, although the largest contribution to buildings emissions still came from OECD-1990 countries (Figure 5.18).

Per capita buildings emissions and per capita income are positively correlated. Considering a life-cycle assessment starting with manufacturing of building materials to demolition, over 80 % of GHG emissions take place during the building operation phase (UNEP, 2009) largely from consumption of electricity for heating, ventilation, and air conditioning (HVAC), water heating, lighting, and entertainment (US DOE, 2008). On average, most residential energy in developed countries is consumed for space heating, particularly in cold climates. 58 % of the demand for energy in buildings was contributed by space heating in 1990 and 53 % in 2005, while water heating contributed 17 % in 1990 and 16 % in 2005, appliances 16 % and 21 %, respectively, and cooking and lighting about 5 % (IEA, 2008; UNEP, 2009). In low-income countries, a large proportion of operational energy is derived from polluting fuels, mainly wood and other biomass, such as dung and crop residues, and a high number of people (2.4 billion) still use biomass for cooking and heating (International Energy Agency, 2002, 2006).

5.3.5.3 Industry

Direct emissions from industry (excluding waste / waste water and AFOLU contributions[10]) grew from 5.4 $GtCO_2eq/yr$ in 1970 to 8.8 $GtCO_2eq/yr$ in 2010. The contribution of OECD countries dominated these emissions at the start of the period with over 57 % of the total but declined to 24 % of the total in 2010. The middle-income countries have become the major emitters, particularly after 2000 (Figure 5.18) when the annual growth rate in emissions increased very significantly in the middle income countries. There is a positive correlation between per capita emissions from industry and per capita income up to an income level of 10,000 $Int\$_{2005}$/cap. Beyond that income level, the correlation decreases due to improvements in energy efficiency in the industrialized OECD countries (European Environment Agency, 2009).

Energy use in industry, which is the major source of emissions from the sector, has grown in both absolute and relative terms in the OECD-1990 region and in relative terms in EIT countries driven by changes in income, the level of industrial output, fuel switching, and structural changes (International Energy Agency, 2003). There has also been a complex restructuring and relocation of the production and consumption of goods and supply of services that has shaped the location of industrial emissions, resulting in the shift of emissions to some non-OECD Asian economies (De Backer and Yamano, 2012; Backer and Yamano, 2007).

The production of energy-intensive industrial goods including cement, steel, aluminium has grown dramatically. From 1970 to 2012, global annual production of cement increased 500 %; aluminium 400 %; steel 150 %, ammonia 250 %; and paper 200 % (USGS, 2013); with energy-intensive industries increasingly being located in developing nations (IPCC, 2007a). Rapid growth in export industries has also driven emissions growth, and since 2001, China dominates in production of goods for own consumption and export (Weber et al., 2008; see Chapter 10).

Non-energy industrial emissions such as perfluorocarbon (PFC) emissions have declined in many OECD countries, while trends in SF_6 emissions vary and HFC emissions have increased very rapidly, driven more by use in refrigeration equipment (International Energy Agency, 2003).

5.3.5.4 Agriculture, Forestry, Other Land Use

Emission of GHGs in the AFOLU sector increased by 20 % from 9.9 $GtCO_2eq$ in 1970 to 12 $GtCO_2eq$ in 2010 (Figure 5.18) contributing about 20–25 % of global emissions in 2010 (JRC/PBL, 2013). Both the agriculture sub-sector and the FOLU sub-sector showed an increase in emissions during the period 1970–2010, but there is substantial uncertainty and variation between databases (see Section 5.2.3); Chapter 11 provides an overview of other estimates. In the agriculture sub-sector, CH_4 from enteric fermentation and rice cultivation, and nitrous oxide (N_2O) mainly from soil, application of synthetic fertilizer and manure, and manure management made the largest contribution (≥ 80 %) to total emissions in 2010. Between 1970 and 2010, emissions of CH_4 increased by 20 %, whereas emissions of N_2O increased by 45–75 %. Though total global emissions increased, per capita emissions went down from 2.5 tonnes in 1970 to 1.7 tonnes in 2010 because of growth in population. Per capita

[10] Industry emissions including emissions from waste and waste water are reported in Section 10.2 in Chapter 10.

emissions decreased in LAM, MAF, and EIT countries, whereas in ASIA and OECD-1990 countries, it remained almost unchanged. There was no clear relation between emissions in the AFOLU sector and per capita income (Figure 5.19).

Between 2000 and 2010, emission in the AFOLU sector marginally increased from 11.0 $GtCO_2eq$ to 11.9 $GtCO_2eq$ (Figure 5.18), but per capita emissions marginally decreased from 1.8 tCO_2eq/cap yr to 1.7 tCO_2eq/cap yr (JRC/PBL, 2013).

Drivers of emissions included increased livestock numbers linked to increased demand for animal products, area under agriculture, deforestation, use of fertilizer, area under irrigation, per capita food availability, consumption of animal products, and increased human and animal populations. Global agricultural land increased by 7 %, from 4560 Mha to 4900 Mha between 1970 and 2010 (FAOSTAT, 2013). Global population increased by about 90 % from 3.6 to 6.9 billion during the period. As a result, per capita cropland availability declined by about 50 %, from 0.4 ha to 0.2 ha. On the other hand, crop productivity increased considerably during the period. For example, cereal production has doubled from 1.2 Gt to 2.5 Gt and the average yield of cereals increased from 1600 kg ha^{-1} to 3000 kg ha^{-1}. To enable this increase, use of nitrogenous fertilizer increased by 230 % from 32 Mt in 1970 to 106 Mt in 2010 (FAOSTAT, 2013), which was a major driver for increased N_2O emission (Spark et al., 2012). During the past 40 years, there has been increase in irrigated cropped area (Foley et al., 2005). Population of cattle, sheep, and goats increased 1.4-fold and that of pigs and poultry 1.6 and 3.7-fold, respectively (FAOSTAT, 2014). This has increased GHG emissions directly and also through manure production (Davidson, 2009). Global per capita food availability and consumption of animal products increased, particularly in Asia (FAOSTAT, 2013).

Emissions in the AFOLU sector increased during the last four decades with marginal increase in the last decade (2000–2010). The continued growth in world population causing greater demand for food with reduced per capita land availability will have significant impact on emission. Further details of emissions, more on forestry and land use, and opportunities for mitigation in the AFOLU sector are discussed in Chapter 11.

Box 5.3 | Trends and drivers of GHG emissions in Least Developed Countries

Almost 90 % of 1970–2010 GHG emissions in the Least Developed Countries (LDCs) are generated by agriculture, forestry, and other land use activities (AFOLU) (Figure 5.20), and emissions have increased by 0.6 % per year in these countries during the last four decades. For the LDCs, the primary activities within AFOLU include subsistence farming and herding, and use of wood as fuel for cooking and heating (Golub et al., 2008; Dauvergne and Neville, 2010; Erb et al., 2012).

The effects of population growth on energy use and emissions are, in relative terms, greater in the LDCs and developing countries than in the developed countries (Poumanyvong and Kaneko, 2010). The dominance of AFOLU over buildings, industry, and transport as sources of emissions for LDC (Figure 5.20) suggests population growth as a major contributor to the growth in LDC emissions. Yet the low historic emissions growth of 0.6 % annually is substantially below population growth of 2.5 % annually. Changes in land use with regard to biofuels (Ewing and Msangi, 2009) and agricultural practices (Mann et al., 2009; Bryan et al., 2013) may also have affected the increase in emissions.

Changes in future trends of GHG emissions in LDCs will depend on the pace of urbanization and industrialization in the LDCs. Although currently most LDCs continue to have a large share of rural population, the rate of urbanization is progressing rapidly. This pattern is expected to lead to increasing access to and use of energy and emissions (Parikh and Shukla, 1995; Holtedahl and Joutz, 2004; Alam et al., 2008; Liu, 2009) particularly since early stages of urbanization and industrialization are associated with higher emissions than later stages (Martínez-Zarzoso and Maruotti, 2011).

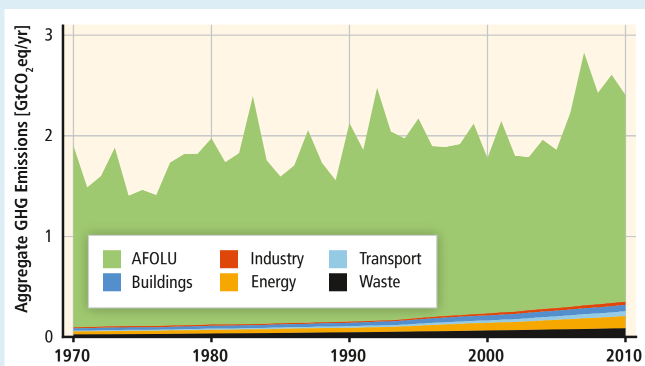


Figure 5.20 | Territorial GHG emissions per sector in LDCs over 1970–2010 aggregated using 100-year GWP values. The figure shows that for all sectors apart from AFOLU, emissions have increased sharply in relative terms. Yet AFOLU presents the largest share of emissions. Data from JRC/PBL (2013) and IEA (2012). The direct emission data from JRC/PBL (2013) (see Annex II.9) represents land-based CO_2 emissions from forest and peat fires and decay that approximate to CO_2 flux from anthopogenic emission sources in the Forestry and Other Land Use (FOLU) sub-sector. For a more detailed representation of Agriculture and FOLU (AFOLU) GHG flux see Section 11.2 and Figures 11.2 and 11.6.

5.3.5.5 Waste

Total global emissions from waste almost doubled from 1970–2010 (Figure 5.18), while in the period 2000–2010, the increment was 13 % (1278 $MtCO_2eq$ vs. 1446 $MtCO_2eq$) (JRC/PBL, 2013). In 2010 GHG emissions from waste represented 3.0 % of total GHG emissions from all sources (1446 $MtCO_2eq$), compared to 2.6 % in 1970 (734 $MtCO_2eq$) (JRC/PBL, 2013). The main sources of waste GHG emissions were solid waste disposal on land (46 % of total waste GHG emissions in 1970 and 43 % in 2010) and wastewater handling (51 % of total waste GHG emissions in 1970 and 54 % in 2010), waste incineration (mainly CO_2) and other sources are of minor importance (JRC/PBL, 2013).

Since 1998 waste GHG emissions from ASIA are greater than from OECD-1990 countries (mainly wastewater emissions). While in 1970 emissions from OECD-1990 countries represented 50 % of emissions (364 $MtCO_2eq$) and ASIA 27 % (199 $MtCO_2eq$), in 2010 ASIA represented 41 % of waste GHG emissions (596 $MtCO_2eq$) and OECD-1990 27 % (391 $MtCO_2eq$) (Figure 5.18) (JRC/PBL, 2013). The main GHG from waste is CH_4—mainly emitted from municipal solid waste disposal on land and from wastewater—representing 91 % of the total in 1970 (90 % in 2010), followed by N_2O (7 % in 1970, 8 % in 2010) (Monni et al., 2006; JRC/PBL, 2013).

Waste generation is closely related to population, urbanization, and affluence (see also Section 10.14). Waste generation rates are correlated with different indicators of affluence, including GDP per capita, energy consumption per capita, and private final consumption per capita (Monni et al., 2006; Bogner et al., 2008). Similarly Sjöström and Östblom (2009) remark that waste quantities have grown steadily along with GDP over recent decades. Moreover they report that the total quantity of municipal waste per capita increased by 29 % in North America, 35 % in OECD, and 54 % in the EU15 from 1980 to 2005 (Sjöström and Östblom, 2009).

There are many uncertainties concerning estimation of past, current, and future emissions, as well as the mitigation potential in the waste sector, the most important relating to the poor quality of the activity data needed for estimation of emissions (Monni et al., 2006; Bogner et al., 2008).

5.4 Production and trade patterns

5.4.1 Embedded carbon in trade

Between 1971 and 2010, world trade has grown by 6 % a year on average, meaning it doubled nearly every 12 years (World Trade Organisation, 2011), outpacing the growth of world GDP, which was 3.1 % per year on average. The ratio of world exports of goods and commercial services to GDP in real terms has increased substantially; steadily since 1985, and by nearly one-third between 2000 and 2008, before dropping in 2009 as world trade fell as a result of the Global Financial Crisis (World Trade Organisation, 2011). While information on the size of physical trade is more limited, Dittrich and Bringezu (2010) estimate that between 1970 and 2005, the physical tonnage of international trade grew from 5.4 to 10 Gt. Statistics on CO_2 emissions associated with international shipping support these findings (Heitmann and Khalilian, 2011); international shipping has grown at a rate of 3.1 % per annum for the past three decades (Eyring et al., 2010), and there is evidence of a recent acceleration in seaborne trade suggesting that trade, measured in ton-miles has increased by 5.2 % per annum (on average) between 2002 and 2007. This is further supported by van Renssen (2012), who observes a doubling of shipping and aviation emissions between 1990 and 2010.

Trade has increased the developing countries' participation in the global economy. According to the World Trade Organization, "From 1990 to 2008, the volume of exports from developing countries grew consistently faster than exports from developed countries, as did the share of developing countries' exports in the value of total world exports". Between 2000 and 2008, the volume of developing countries' exports almost doubled, while world exports increased by 50 %. Non-OECD Asia is by far the most important exporting region in the developing country group, with a 10 % share of world exports in 1990 (USD 335 million), which increased to 21 % (USD 2603 million) in 2009 (World Trade Organisation, 2011).

The consumption accounts presented in Section 5.3.3.2 showed that between 1990 and 2000, global CO_2 emissions increased by about 10 %, and by a further 29 % between 2000 and 2008 (Le Quere et al., 2009; Peters et al., 2011). Over the full period, all of the growth in CO_2 emissions occurred in non-Annex B countries while CO_2 emissions in Annex B countries stabilized. Partly, this was due to the collapse of the former Soviet Union in the early 1990s, which reduced emissions in these countries between 1990 and 2000. But the pattern also relates to the rapid increase in international trade between Annex B and non-Annex B countries. Twenty percent of the growth in CO_2 emissions in non-Annex B countries can, through trade, be attributed to the increased demand for products by Annex B countries (Peters et al., 2011).

In 1990, the global CO_2 emissions associated with exported products was 4.3 $GtCO_2$ (Peters et al., 2011). This figure includes the CO_2 emissions through the whole supply chain associated with the production of the final product, using the 'Environmentally Extended Multi-Region Input-Output Analysis' (Davis and Caldeira, 2010; Minx et al., 2009). In 2008, this figure had increased to 7.8 $GtCO_2$, (average annual increase of 4.3 %) (Peters et al., 2011). Between 1990 and 2000, the growth in the embedded CO_2 emissions of products being traded grew by 10 %. Between 2000 and 2008, CO_2 emissions embedded in trade grew by a further 26 %, demonstrating a more recent and rapid increase (Peters et al., 2011). In 2005, China accounted for 25 % of the total global CO_2

Box 5.4 | Definition of carbon leakage

Carbon leakage refers to phenomena whereby the reduction in emissions (relative to a benchmark) are offset by an increase outside the jurisdiction (Peters and Hertwich, 2008; Barrett et al., 2013). Leakage can occur at a number of levels, be it a project, state, province, nation, or world region. This can occur through:

- **Changes in the relative prices** whereby national climate regulation reduces demand for fossil fuels, thereby causing a fall in world prices resulting in an increase in demand outside the jurisdiction

- **Relocation of industry** where a firm relocates their operation to another nation due to less favourable financial benefits in the original jurisdiction brought about by the reduction measures

- **Nested regulation** where, for example, the European Union imposes an aggregate cap on emissions meaning that the efforts of individual countries exceed the cap freeing up allowances in other country under the scheme

- **Weak consumption leakage** describes the increase of emissions in one country as a consequence of actions or policies that are unrelated to climate policy (such as a changed quantity or composition of imports) in another country.

emissions embedded in exports, with China's exported emissions at 1.7 Gt (Weber et al., 2008) compared to the global total of 6.8 Gt (Peters et al., 2011). In terms of total CO_2 emissions due to the production of goods and services that were finally consumed in another country, a number of papers suggest that this represents between 20 % and 26 % of total global emissions in 2004 (Davis and Caldeira, 2010; Peters et al., 2011).

Trade explains the divergence between territorial and consumption-based emissions in OECD countries to the extent that it has resulted in an increase of emissions in the exporting countries. The associated increase in emissions in exporting countries (mostly non Annex B) is often defined in the literature as 'weak leakage' (see Box 5.4) (Davis and Caldeira, 2010; Rothman, 2000; Peters and Hertwich, 2008; Weber and Peters, 2009; Strømman et al., 2009; Peters, 2010; Yunfeng and Laike, 2010). Lenzen et al. (2010) confirm these findings along with numerous national-level studies (Wiedmann et al., 2010; Hong et al., 2007; Liu et al., 2011; Ackerman et al., 2007; Weber and Matthews, 2007; Mäenpää and Siikavirta, 2007; Muñoz and Steininger, 2010; Minx et al., 2011).

Trade has allowed countries with a higher than global average emission intensity to import lower emission intensity goods and vice versa. For example, exports from China have a carbon intensity four times higher than exports from the United States (Davis and Caldeira, 2010). Net exports of carbon could occur due to (i) a current account surplus, (ii) a relatively high energy intensity of production, (iii) a relatively high carbon intensity of energy production, and (iv) specialization in the export of carbon-intensive products (Jakob et al., 2013). Jakob and Marchinski (2013) argue that further analysis is required to better understand the gap in consumption and territorial emissions, and to assess the validity of possible but different causes.

Calculating emissions embodied in trade tells us the amount of emissions generated to produce goods and services that are consumed elsewhere, but it doesn't allow us to establish a causal interpretation. In particular, it doesn't allow identifying which fraction of observed changes in regional emissions can be attributed to regulatory changes undertaken elsewhere, such as adoption of climate measures in one region (often called 'strong carbon leakage' in the literature). Due to the sparse data available, only a few empirical studies exist. (Aichele and Felbermayr, 2012, 2013) provide evidence for a strong carbon leakage effect resulting from the Kyoto protocol. Most estimates of how GHG emissions could react to regional regulatory changes have so far relied on numerical modelling. These studies find a wide variety of rates of leakage (i. e., the fraction of unilateral emission reductions that are offset by increases in other regions), with one study demonstrating that under some specific assumptions, leakages rates could even exceed 100 % (Babiker, 2005). However, it has also been pointed out that energy represents a small fraction of the total cost for most industries and therefore leakage should not be expected to render unilateral climate policies grossly ineffective (Hourcade et al., 2008; Jakob, 2011). This is confirmed by recent model comparison of 12 computable general equilibrium models. Boehringer et al. (2012) finds leakage rates between 5 % and 19 %, with a mean value of 12 %. However, taking into account (non-energy related) industrial process emissions, which are not included in the latter model comparison, may result in higher leakage rates, as some of the most energy—as well as trade-intensive sectors are also important sources of industrial process emissions (Bednar-Friedl et al., 2012) find that accounting for industrial process emissions raises the leakage rate by one-third.

5.4.2 Trade and productivity

Trade does not only affect emissions through its effect on consumption patterns, the relocation of production, and emissions for international transport, it also affects emissions through its effect on innovation and the exchange of technologies between trading partners. Section 5.6

assesses the literature on innovation while this section assesses the theoretical and empirical literature on channels through which trade (broadly defined as trade in goods and foreign direct investment) affects productivity (Havrylyshyn, 1990).

At the aggregate level, trade can improve productivity through increased allocative efficiency. Furthermore, trade increases the international flow of intermediate goods (Hummels et al., 2001; Koopman et al., 2008), allowing for the production of higher-quality final products with the same amount of emissions and other inputs (Rutherford and Tarr, 2002). Though, trade may impede productivity growth in developing countries if it causes them to specialize in low-tech labour and energy intensive sectors with little scope for productivity improvements. Trade can also increase income inequality in developing countries. For example, because the least skill-intensive industries in developed countries often become the most skill-intensive sectors in developing countries (Zhu and Trefler, 2005; Meschi and Vivarelli, 2009), developing countries can experience a negative impact on productivity growth (Persson and Tabellini, 1994).

At the sector level, trade liberalization increases competition in import-competing sectors, and causes the least-productive firms in these sectors to collapse or exit (Pavcnik, 2002). Therefore, through this mechanism, trade liberalization can cause job losses, especially for those working in the previously protected sectors. At the same time, trade can also increase productivity, energy-efficiency, and research and development (R&D) incentives in import-competing sectors: trade intensifies import-competition and increases the remaining firms' domestic market shares, both of which are associated with higher R&D efforts—possibly because firms with large market shares use innovation to deter entry (Blundell et al., 1999).

Aside allocation and competition effects, trade can increase productivity growth through knowledge spillovers. Multinationals do more R&D than purely domestic firms, thus Foreign Direct Investment (FDI) can increase the knowledge stock of the recipient country. Moreover, the entry of foreign multinationals facilitates the diffusion of energy-saving technologies if domestic firms reverse-engineer their products or hire away their employees (Keller and Yeaple, 2009). In addition to these horizontal spillovers, foreign entrants have an incentive to share their knowledge with domestic suppliers and customers to improve the quality of domestically sourced inputs and to enable domestic customers to make better use of their products (Javorcik, 2004).

Turning to empirical analyses, there are many studies that estimate the effect of trade on sector overall productivity or the international diffusion of specific technologies, but little that quantify the effect of trade, through productivity, on emissions. Empirical work, mostly focusing on labour and total factor productivity, suggests that trade openness indeed enhances productivity. Coe and Helpman (1995) and Edwards (2001) find that foreign R&D has a larger positive effect for countries with a higher import volume, and that for small countries, foreign R&D matters more for domestic productivity than domestic R&D. Keller (2000) finds that imports from high-productivity countries lead to more productivity growth than imports from low-productivity countries. According to Kim (2000), trade liberalization increased total factor productivity growth by 2 percentage points in Korea between 1985–1988. For United States firms, FDI spillovers accounted for 14 % of productivity growth between 1987–1996 (Keller and Yeaple, 2009).

With regards to specifically environmental applications, Verdolini and Galeotti (2011a) and Bosetti and Verdolini (2012) constructed and tested a model to show that the factors that impede international trade in physical goods, such as geographic distance, also hinder the diffusion of environmentally benign technologies. Reppelin-Hill (1998) finds that the Electric Arc Furnace, a technology for cleaner steel production, diffused faster in countries that are more open to trade. Trade reduces global energy efficiency if it relocates production to countries that have a comparative advantage in unskilled labour but low-energy efficiency (Li and Hewitt, 2008). Lastly, Mulder and De Groot (2007) document a convergence of energy-productivity across OECD countries over time. The results may be attributable to knowledge diffusion through trade, but the authors do not estimate a link between convergence and trade.

5.5 Consumption and behavioural change

Behaviour is an underlying driver affecting the factors in the decomposition of anthropogenic GHG emissions. Although it is difficult to delineate and attribute the effects of behaviour unambiguously, there is empirical evidence of variation in behaviour and consumption patterns across regions, social groups, and over time, and its connection to, e. g., energy and emission intensity of consumption.

This section reviews the evidence of how behaviour affects energy use and emissions through technological choices, lifestyles, and consumption preferences. It focuses on behaviour of consumers and producers, delineates the factors influencing behaviour change, and reviews policies and measures that have historically been effective in changing behaviour for the benefit of climate change mitigation.

5.5.1 Impact of behaviour on consumption and emissions

Consumer choices with regard to food, mobility, and housing, and more generally consumption patterns affect the environmental impact and GHG emissions associated with the services (Faber et al., 2012). Consumption patterns are shaped not only by economic forces, but also by technological, political, cultural, psychological, and environmental factors. For example, domestic energy use and travel choices are intrinsically related to social identity, status, and norms (Layton et al., 1993; Black et al., 2001; Steg et al., 2001; Exley and Christie, 2002). Senses of security, clean environment, family ties, and friendships are also viewed as important factors in determining consumption patterns (Chitnis and Hunt, 2012). The cultural context in which an individual lives and the inherent values of a society also shape the intrinsic motivation underlying consumer choices (Fuhrer et al., 1995; Chawla, 1998, 1999). As an example, the high proportion of people following a vegetarian diet in India can be attributed to its cultures and religions, resulting in lower GHG emissions per caloric intake (Ghosh, 2006). Similar explanations are given for India's relatively low levels of waste generation coupled with higher levels of waste recycling and re-use (Ghosh, 2006). Cross-cultural differences are also revealed at higher-income levels. In some high-income countries people appreciate high-density neighbourhoods and public transport more as compared to other countries (Roy and Pal, 2009).

Studies indicate that approximately one-third of food produced for human consumption (about 1.3 billion tonnes per year) is wasted globally, adding to GHG emissions for food production (Gustavsson et al., 2011). It is estimated that substantially more food is wasted in the developed countries than in developing countries. In Europe and North America, per capita food waste by consumers is estimated at 95–115 kg/year, while in sub-Saharan Africa and South/Southeast Asia is about 6–11 kg/year (Gustavsson et al., 2011). There is significant inter-regional variation with regard to the stage of the food chain at which wastage occurs. About 40 % of food wastage in medium- and high-income countries is generated at the consumer and retail stages, while in low-income countries food waste at the consumer level is much smaller and food waste in the early and middle stages of the food supply chain reaches about 40 %. Food losses and waste in low-income countries are attributed to financial, managerial, and technical limitations, while consumer behaviour and lack of coordination between different actors in the supply chain influence food wastage in the high-income countries (Gustavsson et al., 2011).

Empirical evidence indicates that per capita energy consumption varies widely across regions (see Sections 5.3 and 5.4), resulting in significantly different CO_2 emissions in per capita terms and per unit economic activity, but that GDP per capita does not explain all variation (see Figures 5.16 and 5.19). While part of this variability can be attributed, inter alia, to population density, infrastructure and resource endowments, social and cultural predispositions, such as lifestyle, also influence the choice and consumption levels of energy and materials (Marechal, 2009; Tukker et al., 2010; Sovacool and Brown, 2010). Historic data show a clear increase at the global level of key consumption activities of households that contribute to emissions, such as personal travel by car, intake of meat and fossil fuel consumption (Mont and Plepys, 2008). Energy intensity, which depends on behaviour at the individual and economy-wide level, is therefore one of the key determinants of emissions in the decomposition analysis. Behaviour is not only an implicit and relevant driver of emissions, but also equally important a potential agent for change in emissions.

Apart from individuals and households, companies and organizations also contribute to emissions, through both direct and indirect use of energy. Businesses, policy makers, as well as non-governmental consumer organizations also play a role in inducing behaviour change and therefore indirectly changing emissions. Studies show that environmental values are important determinants of willingness to accept climate change policy measures, and that values and norms are required for climate policy support within public and private organizations (Biel and Lundqvist, 2012).

Technological solutions directed at improving resource productivity may not be sufficient for curbing the environmental impact of consumption (Hunt and Sendhil, 2010). Complementary to eco-efficiency in production, sustainable development strategies may need to support sufficiency in consumption, shifting from a culture of consumerism without limits to a society with less materialistic aspirations (Mont and Plepys, 2008). This implies an addition to the focus on more environmentally sound products and services; finding happiness with lower levels of material consumption, especially in higher-income countries (Hunt and Sendhil, 2010).

5.5.2 Factors driving change in behaviour

The literature differentiates between efficiency behaviours, (1) the purchase of more or less energy-efficient equipment (e.g., insulation), and (2) curtailment behaviours that involve repetitive efforts to reduce energy use, such as lowering thermostat settings (Gardner and Stern, 1996). It is suggested that the energy saving potential through efficiency behaviour is greater than that through curtailment behaviour. However, energy-efficient appliances can lead to an increase in demand for the service due to the lower cost of these services, discussed in Section 5.6.2.

Behavioural economics studies anomalies in consumer's energy choices but it is also used to design approaches aimed at influencing and modifying those behaviours (see Sections 2.4 and 3.10.1). There is evidence that consumers consistently fail to choose appliances that offer energy savings, which, according to engineering estimates, more than compensate for their higher capital cost. In analyses of appliance choices, Hausman (1979) and subsequent studies found implicit consumer discount rates ranging from 25 % to over 100 % (Train, 1985; Sanstad et al., 2006). A variety of explanations have been offered, including consumer uncertainty regarding savings, lack of liquidity and financing constraints, other hidden costs, and the possibility that the engineering estimates may overstate energy savings in practice. Recent ideas draw on bounded rationality, the notion that consumers 'satisfice' rather than 'optimize' (Simon, 1957), the importance of non-price product attributes and consumers' perceptions thereof (Lancaster, 1965; Van den Bergh, 2008), and asymmetric information and the principal-agent problem (Akerlof, 1970; Stiglitz, 1988). From psychology and behavioural economics come notions such as loss aversion (consumers place more weight on avoiding a loss than on securing a gain of the same magnitude (Kahneman et al., 1982); see Greene (2011) for an application to energy efficiency), attention[11] and the role of salience[12] (Fiske and Morling, 1996), priming (Richardson-Klavehn and Bjork, 1988), affect (Slovic et al., 2002), norms[13] (Axelrod, 2006), a present-bias in inter-temporal decision making (O'Donoghue and Rabin, 2008; DellaVigna, 2009), and mental accounts (separate decision making for subsets of commodities; Thaler, 1999). The literature is not unanimous, though, regarding the magnitude of the 'energy efficiency gap' (Allcott and Greenstone, 2012).

Ayres et al. (2009) estimate that non-price, peer-comparison interventions can induce a consumption response equivalent to a 17–29 % price increase.[14] Newell et al. (1999) provides evidence that the United States room air conditioners energy efficiency gain since 1973 is only about one quarter induced by higher energy prices, while another quarter is due to raised government standards and labelling.

Behavioural interventions can be aimed at voluntary behavioural change by targeting an individual's perceptions, preferences, and abilities, or at changing the context in which decisions are made. Such non-price context interventions have been used across countries with varying degrees of success to bring about behaviour change in consumption choices and patterns of energy use. These include antecedent strategies (involving commitment, goal setting, information or modelling) and consequence strategies (feedback or rewards) (Abrahamse et al., 2005; Fischer, 2008). As an example, the Property Assessed Clean Energy (PACE) program tackles the high-discount rate that residential energy users ascribe to investments associated with energy-efficiency retrofits of buildings through providing local governments financing for retrofits of buildings repayable through a supplement to property taxes (Ameli and Kammen, 2012). Various United States and United Kingdom government agencies and the private sector, including some electric and water utilities, have developed strategies collected under the rubrics Nudge (Thaler and Sunstein, 2009) and Mindspace (Dolan et al., 2012). These programs involve elements such as increasing the salience of financial incentives, invoking norms, providing information on social comparisons, and modifying the choice architecture (the structure of the choice) including the default alternative.[15] Laboratory studies and small-scale pilots have demonstrated a potential role for behavioural interventions, but there is uncertainty on the scalability of these interventions and the level of impacts they can achieve (Hunt and Sendhil, 2010).

The state of awareness and concern about climate change and the willingness to act is an important underlying driver for voluntary reduction in energy consumption by individuals. Some studies indicate that the provision of information, or awareness creation by itself, is unlikely to bring about significant change in consumption behaviour and reduction in emissions (Van Houwelingen and Van Raaij, 1989; Kollmuss and Agyeman, 2002; Jackson, 2005). Other studies indicate that awareness creation and provision of information facilitates the deployment of energy-efficient technologies. The establishing of benchmarks for the energy consumption of homes and commercial buildings may contribute to reduce information asymmetries in the marketplace and to lower the discount rates used by consumers to evaluate future efficiency gains (Cox et al., 2013). Coller and Williams (1999) suggest that information about energy consumption will result in a 5 % decline in discount rates for energy decisions made by the median population, an estimate that is adopted by Cox et al. (2013).

Rewards are seen to have effectively encouraged energy conservation, though with possibly short-lived effects (Dwyer and Leeming, 1993; Geller, 2002). Feedback has also proven to be useful, particularly when given frequently (Becker et al., 1981), while a combination of strategies is generally found to be more effective than applying any one strategy (Abrahamse et al., 2005).

Ability to change, or opportunities, is also essential, and can be constrained by institutional and physical structures. Old habits are also seen as a strong barrier to changing energy behaviours (Pligt, 1985; Kollmuss and Agyeman, 2002; Mont and Plepys, 2008; Whitmarsh, 2009).

5.6 Technological change

5.6.1 Contribution of technological change to mitigation

The AR4 acknowledged the importance of technological change as a driver for climate change mitigation (IPCC, 2007a). It also gave an extensive review of technological change and concluded, among other things, that there is a relationship between environmental regulation and innovative activity on environmental technologies, but that policy is not the only determinant for technological change. It also discussed the debate around technology push and market pull for technological change, the role of different actors and market failures around technological innovation. Since 2007, more studies have documented improvements of energy efficiency and the impact of different drivers, including technological change, on energy intensity (e.g., Fan and Xia; Sheinbaum et al., 2011; Wu et al., 2012).

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[11] For example, Allcott (2011) indicates that 40 % of US consumers do not consider a vehicle's gasoline consumption when purchasing a car.

[12] Chetty et al. (2009) show that consumers' reaction to taxes depends on the visibility and salience of the tax.

[13] Responsiveness to norm-based messages has been demonstrated in a number of domains (e.g., Frey and Meier, 2004; Cialdini et al., 2006; Salganik et al., 2006; Goldstein et al., 2008; Cai et al., 2009).

[14] Similarly, with household water use, Ferraro and Price (2011) find that the social-comparison effect is equivalent to what would be expected if average prices were to increase by 12 % to 15 %.

[15] UK Cabinet Office (2012).

5.6.1.1 Technological change: a drive towards higher or lower emissions?

Previous assessment reports have focused on the contribution of technological change in reducing GHG emissions. The rising emissions in emerging economies and accompanied rapid technological change, however, point at a question of whether technological change might also lead to rising emissions—in developed and developing countries. Due to a combination of rebound effects (see Section 5.6.2) and an observed tendency towards cost-saving innovations, the rebound effect could be enhanced so much that energy-saving technological change could indirectly lead to an increase in emissions (Fisher-Vanden and Ho, 2010). Probably more importantly, technological change may favour non-mitigation issues over reduction of GHG emissions. For example, compact cars in the 1930s have a similar fuel consumption rate to compact cars in the 1990s, but have far advanced in terms of speed, comfort, safety, and air pollution (Azar and Dowlatabadi, 1999).

The energy sector is of great importance to technological change and climate change mitigation. Changes in the energy intensity that are not related to changes in the relative price of energy are often called changes in the autonomous energy-efficiency index (Kaufmann, 2004; Stern, 2011). How do macro-economic factors affect differences in energy efficiency between countries and changes over time? Using country-based case study approach, the general trend at the macro-level over the 20th century in the United States, the United Kingdom, Japan, and Austria has been to greater energy efficiency (Warr et al., 2010).

Recent research investigates the factors that affect the adoption of energy-efficiency policies or energy-efficiency technology (Matisoff, 2008; Fredriksson et al., 2004; Gillingham et al., 2009; Linares and Labandeira, 2010; Wei et al., 2009; Popp, 2011; Stern, 2011). Differences in endowments, preferences, or the state of technology create differences in the adoption of energy-efficiency technologies across countries and among individuals over time. The rate of adoption may also be influenced by market failures such as environmental externalities, information access, and liquidity constraints in capital markets, and behavioural factors. Behavioural factors are discussed in Section 5.5.2. The variation of implementation of energy-efficiency measures varies greatly, both between countries and between sectors and industries, especially if developing countries are taken into account (Sanstad et al., 2006).

5.6.1.2 Historical patterns of technological change

There is ample evidence from historical studies, for instance in the United States, Germany, and Japan, that technological change can affect energy use (Carley, 2011b; Welsch and Ochsen, 2005; Unruh, 2000). In Japan, it has also shown to be a driver for reduction of CO_2 emissions (Okushima and Tamura, 2010). Technological change is also a dominant factor in China's fast-declining energy intensity until 2003 (Ma and Stern, 2008); but between 2003 and 2010, energy intensity declined only slightly (IEA, 2012).

Technological change in the energy sector is best studied. Several studies find that technological change in energy was particularly pronounced in periods with a great political sense of urgency and/or energy price hikes, such as during oil crises (Okushima and Tamura, 2010; Karanfil and Yeddir-Tamsamani, 2010). Wilbanks (2011) analyzes the discovery of innovations and argues that only with a national sense of threat and the entailing political will it is worthwhile and possible to set up an "exceptional R&D" effort in the field of climate change mitigation. Aghion et al. (2012) conclude an increase in clean technology patenting in the auto industry as a consequence of policy-induced increases in energy prices. In a study on 38 countries, Verdolini and Galeotti (2011b) find that technological opportunity and policy, proxied by energy prices, affect the flow of knowledge and technological spillovers.

There is more evidence supporting the conclusion that policy matters as a part of systemic developments. Dechezleprêtre (2008) find that the Kyoto Protocol has a positive impact on patenting and cross-border technology transfer, although they did not evaluate the impact of those on emissions. In a study on photovoltaic (PV) technology in China, a policy-driven effort to catch up in critical technological areas related to manufacturing proved successful, although it also mattered that capabilities could be built through the returning of a Chinese diaspora (de la Tour et al., 2011). Calel and Dechezleprêtre (2012) show that the European Union Emissions Trading System led to an increase in climate technology-related patents in the European Union.

5.6.2 The rebound effect

Section 3.9.5 distinguishes between 'direct' and 'indirect' rebound effects. Direct rebounds appear when, for example, an energy-efficient car has lower-operating costs encouraging the owner to drive further (Sorrell, 2007). In addition, this could apply to a company where new, more energy efficient technology reduces costs and leads to an increase in production. Indirect rebounds (Lovins, 1988; Sorrell, 2007) appear when increased real income is made available by saving energy costs that are then used to invest or purchase other goods and services that emit GHG emissions (Berkhout et al., 2000; Thomas and Azevedo, 2013). For example, savings in fuel due to a more-efficient car provides more disposable income that could be spent on an additional holiday. These could include substitution or income effects or changes in consumption patterns (Thomas and Azevedo, 2013). Economy-wide changes include market price effects, economic growth effects, and adjustments in capital stocks that result in further increases in long-run demand response for energy (Howarth, 1997).

Rebound effects are context-specific, making it difficult to generalize on their relative size and importance. Being context-specific means that there is evidence of both negative rebound effects where further energy saving is induced beyond the initial savings and 'backfire' where the rebound effects exceed the initial saving (Gillingham et al., 2013; Chakravarty et al., 2013; Saunders, 2013). There is much debate on the size of the rebound effect with considerably more evidence on direct rebounds than on indirect rebounds. There are numerous studies relying predominately on econometric techniques to evaluate rebounds. A comprehensive review of 500 studies suggests that direct rebounds are likely to be over 10 % and could be considerably higher (i. e., 10 % less savings than the projected saving from engineering principles). Other reviews have shown larger ranges with Thomas and Azevedo (2013) suggesting between 0 and 60 %. For household-efficiency measures, the majority of studies show rebounds in developed countries in the region of 20–45 % (the sum of direct and indirect rebound effects), meaning that efficiency measures achieve 65–80 % of their original purposes (Greening et al., 2000; Bentzen, 2004; Sorrell, 2007; Sorrell et al., 2009; Haas and Biermayr, 2000; Berkhout et al., 2000; Schipper and Grubb, 2000; Freire González, 2010). For private transport, there are some studies that support higher rebounds, with Frondel et al. (2012) findings rebounds of between 57 and 62 %.

There is evidence to support the claim that rebound effects can be higher in developing countries (Wang et al., 2012b; Fouquet, 2012; Chakravarty et al., 2013). Roy (2000) argues that rebound effects in the residential sector in India and other developing countries can be expected to be larger than in developed economies because high-quality energy use is still small in households in India and demand is very elastic (van den Bergh, 2010; Stern, 2011; Thomas and Azevedo, 2013). However, there is considerable uncertainty of the precise scale of rebound effects in developing countries with more research required (Thomas and Azevedo, 2013; Chakravarty et al., 2013). In terms of developed countries, Fouquet (2012) provides evidence on diminishing rebound effects in developed countries due to less inelastic demand for energy.

While generalization is difficult, a circumstance where rebounds are high is when energy costs form a large proportion of total costs (Sorrell, 2007). Rebounds effects are often diminished where energy-efficiency improvements are coupled with an increase in energy prices. For industry, targeted carbon-intensity improvements can reduce costs and therefore prices and subsequently increase output (Barker et al., 2007). Therefore, the relative scale of the saving is a good indicator of the potential size of the rebound effect. In conclusion, rebound effects cannot be ignored, but at the same time do not make energy-efficiency measures completely redundant. By considering the size of the rebound effect, a more-realistic calculation of energy-efficiency measures can be achieved providing a clearer understanding of their contribution to climate policy. Particular attention is required where efficiency saving are made with no change in the unit cost of energy.

5.6.3 Infrastructure choices and lock in

Infrastructure in a broad sense covers physical, technological, and institutional categories but is often narrowed down to long-lasting and capital-intensive physical assets to which public access is allowed, such as transport infrastructure (Ballesteros et al., 2010; Cloete and Venter, 2012). The assessment in this part focuses on the narrower physical part. Among physical infrastructure are buildings, roads and bridges, ports, airports, railways, power, telecom, water supply and waste water treatment, irrigation systems, and the like. Energy consumption and CO_2 emissions vary greatly between different types of infrastructure. Infrastructure choices reflect the practice at the time of investment but they have long-lasting consequences. The infrastructure and technology choices made by industrialized countries in the post-World War II period, at low energy prices, still have an effect on current worldwide GHG emissions. Davis et al. (2010) estimate the commitment to future emissions and warming by existing CO_2-emitting devices, totalling to 500 (280–700) $GtCO_2$ between 2010 and 2060, and an associated warming of 1.3 °C (1.1 °C to 1.4 °C).

Transport is a case in point. Air, rail, and road transport systems all rely on a supporting infrastructure, and compete for distances in the range of 1500 km. Of these options, railways typically have the lowest emissions, but they require substantial infrastructure investments. Similarly, for urban transport, public transport requires substantial infrastructure investments to provide mobility with relatively low-emission intensities. At the same time, existing roads are designed for use for decades and consequently automobiles remain a major means for mobility. In United States cities, 20–30 % of the land-area is used for roads, the corresponding share for major cities in Asia is 10–12 % (Banister and Thurstain-Goodwin, 2011; Banister, 2011a; b). But the emerging megacities around the world are associated with population expansion and large-scale increase in infrastructure supply. Investment in urban physical investment in these emerging megacities will have a significant long-lasting impact on GHG emissions. Investment in waste disposal facilities (incinerators) is an example of a path dependency and lock-in of an industry barrier that will prevent material efficiency strategies for a long period of time. A recent study proves how this lock-in effect in places such as Denmark, Sweden, Germany, or the Netherlands is threatening recycling and encouraging the shipment of waste that otherwise could be treated locally with less environmental cost (Sora and Ventosa, 2013).

Carley (2011a) provides historical evidence from the United States electricity sector indicating that crucial drivers—market, firm, government, and consumer—can work together to improve efficiency, but that they can also lead to "persistent market and policy failures that can inhibit the diffusion of carbon-saving technologies despite their apparent environmental and economic advantages" (Unruh, 2000, 2002).

Avoiding the lock-in in emission-intensive physical infrastructure is highly important to reduce emissions not only in the short run but also far into the future. At the planning stage, when choice of materials and construction are made, a forward-looking life-cycle assessment can help to reduce undesired lock-in effects with respect to the construction and operation of large physical infrastructure.

5

5.7 Co-benefits and adverse side-effects of mitigation actions

The implementation of mitigation policies and measures can have positive or negative effects on broader economic, social, and/or environmental objectives—and vice versa. As both co-benefits and adverse side-effects occur, the net effect is sometimes difficult to establish (Holland, 2010).[16] The extent to which co-benefits and adverse side-effects will materialize in practice as well as their net effect on social welfare differ greatly across regions, and is strongly dependent on local circumstances, implementation practices, as well as the scale and pace of the deployment of the different mitigation measures (see Section 6.6). Section 4.8 relates co-benefits to sustainable development, Section 5.2 covers the historic emission trends of many substances related to air quality co-benefits and adverse side-effects, Section 6.6 covers the forward-looking perspective, and the sectoral dimensions are discussed in Sections 7.9, 8.7, 9.7, 10.8, and 11.7. While Section 12.8 focuses on co-effects in cities, Chapter 15 considers the policy implications. This section looks at co-benefits and adverse effects from a macro-perspective to understand their role in decision making for climate change mitigation and sustainable development. We focus on cross-sectoral air pollution literature and the role of pollutant emission trends and briefly discuss the difficulty for assessing the role of co-benefits and adverse effects as an underlying driver when it plays a role for GHG-mitigation decisions. Figure 5.21 offers a picture of the connection between climate change and other social and environmental objectives through policies affecting the emissions of various substances. The following chapters will assess many of these interactions between air pollutants associated with the combustion of fossil fuels and their direct and indirect impacts.

The quantitative key findings of the AR4 were three-fold: First, the reduction of fossil fuel combustion will lead to the reduction of a number of air pollutants that interact with a number of policy objectives (see Figure 7.8). Second, the policy costs of achieving air pollution objectives through direct control measures decrease as a result of mitigation policies. Third, monetized health benefits counterbalance a substantial fraction of mitigation costs, even exceeding them in certain cases, particularly in developing countries (Barker et al., 2008). The next section will assess new literature that relates to the third finding while the post-AR4 literature on the first two findings is presented in the sector chapters and summarized in Section 6.6.

[16] Co-benefits and adverse side-effects describe co-effects without yet evaluating the net effect on overall social welfare. Please refer to Sections 3.6.3 and 4.8.2 as well as to the glossary in Annex I.

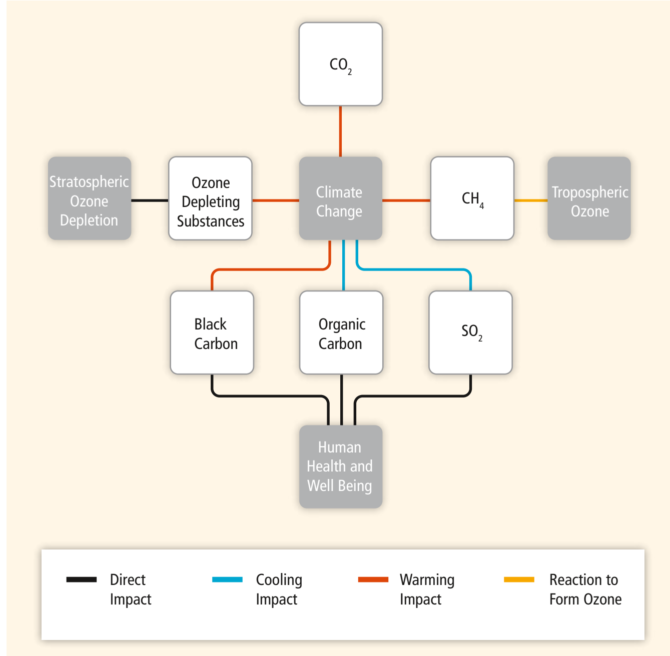

Figure 5.21 | Impacts of and links between selected substances emitted to the atmosphere. Adopted from (UNEP, 2012).

5.7.1 Co-benefits

A substantial share of estimated co-benefits is related to improving health through limiting air pollution while reducing GHG emissions. Estimates in the literature for the monetized air quality co-benefits from climate change mitigation range from 2 to 930 USD_{2010}/tCO_2, and co-benefits in developing countries around twice those in industrialized countries (see Nemet et al., 2010a) for a review and (West et al., 2013) for the high estimate. The gap between developing and industrialized countries results from lower levels of air pollution control and higher pollution levels in the former countries, and thus the greater potential for improving health, particularly in the transport and household energy demand sectors (Markandya et al., 2009; Nemet et al., 2010b; West et al., 2013; Shukla and Dhar, 2011). In industrialized countries, substantial reductions in air pollutant emissions have already occurred in the absence of climate policy and further tightening of air regulations is underway (Rao et al., 2013). If climate policy provides only small incremental reductions, then the co-benefit is small (see Section 3.6.3), while large emission reductions are expected to yield substantial air quality co-benefits and associated cost savings (see Section 6.6.2).

Much of the literature assessed in AR4 did not explicitly analyze policies targeted at reducing air pollution—thereby neglecting the associated opportunity costs of mitigation polices (Bollen et al., 2009; Edenhofer et al., 2013). But for countries and regions that do not have or do not enforce current air quality regulations, it is important to consider expected future air pollution policies. Rapidly industrializing developing countries may follow the pattern of developed countries and adopt regulations to improve local air quality (and provide immediate local

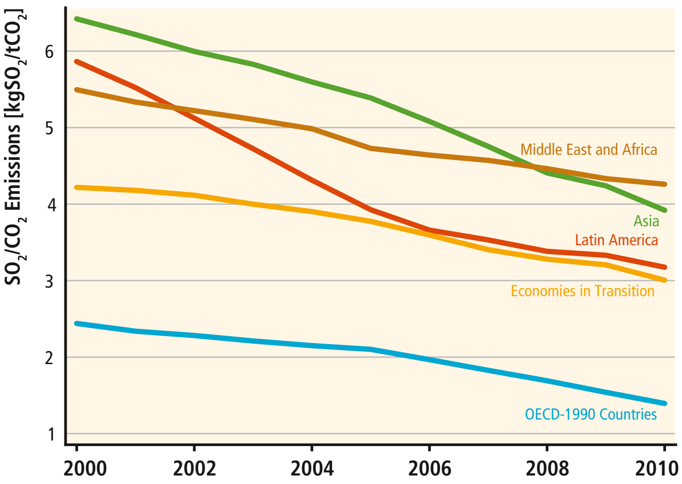

Figure 5.22 | Trends for SO_2 per CO_2 emissions per region over 2000–2010 | For CO_2: territorial, excluding AFOLU and Waste. Data Source: JRC/PBL, 2013. For SO_2, data source: Klimont et al., 2013. Regions are defined in Annex II.2.

health and environmental benefits) before focusing on climate policy (Nemet et al., 2010b; Klimont et al., 2013). If this is indeed the case, the co-benefits of climate policy will be much smaller. Figure 5.22 shows the declining trend in SO_2-emission intensity per CO_2 emissions (see Section 5.2 for trends in global SO_2 emissions). It shows that assumptions about the extrapolation of the historic trends into the future will be a major determinant of future co-benefits estimates (Burtraw and Evans, 2003; Bell et al., 2008), see Section 6.6.2.7 for an example from the scenario literature).

Due to a lack of a counterfactual historic baseline for other policies, it is not possible to determine a clean ex-post measure for the co-benefits of climate policies such as the Kyoto Protocol. But it is clear that drivers for fossil fuel combustion affect both CO_2 emissions and SO_2 emissions (see van Vuuren et al., 2006).

5.7.2 Adverse side-effects

There are also adverse side-effects associated with mitigation. A comprehensive discussion is given in the following chapters (6–12), while this section presents some examples in the context of air pollution. While many low-carbon energy supply technologies perform better than pulverized coal technologies for most air pollutants, some solar energy technologies, for example, have comparable or even higher life-cycle emissions of SO_2 (see Figure 7.8 in Section 7.9.2). Desulphurization of existing coal power plants, however, requires additional consumption of coal in the thermal power sector implying higher CO_2 emissions for a given electricity output (Pan, 2013). While CO_2 capture processes reduce SO_2 emissions at the same time, some carbon dioxide capture and storage (CCS) technologies would imply an increase in NO_x and/or ammonia (NH_3) emissions (Koornneef et al., 2012).

For the displacement of fossil-based transport fuels with biofuels, many studies indicate lower carbon monoxide and hydrocarbon emissions, but NO_x emissions are often higher. Next-generation biofuels are expected to improve performance, such as the low particulate matter emissions from lignocellulosic ethanol (see Hill et al., 2009; Sathaye et al., 2011; and Sections 8.7 and 11. A.6). In the buildings sector, the most important health risks derive from insufficient ventilation practices in air-tight buildings (Section 9.7).

5.7.3 Complex issues in using co-benefits and adverse side-effects to inform policy

Mitigation options that improve productivity of energy, water, or land use yield, in general, positive benefits. The impact of other mitigation actions depend on a wider socio-economic context within which the action is implemented (Sathaye et al., 2007). A complete incorporation of co-benefits and adverse side-effects into climate policy is compli-

Box 5.5 | The Chinese experience with co-benefits from a cross-sectoral perspective[1]

Pan et al. (Pan et al., 2011) estimate the amount of green jobs in three sectors (energy, transportation, and forestry) and the result suggests a number at least 4.5 million in 2020 in China. The wind power industry in China, including power generation and turbine manufacturing, has created 40,000 direct jobs annually between 2006 and 2010 (Pan et al., 2011). Beijing's ambitious metro-system plan, which includes 660 km by 2015 and another 340 km during 2016–2020,could bring more than 437,000 jobs each year (Pan et al., 2011). China's forestation activities could create as many as 1.1 million direct and indirect jobs annually during 2011–2020 to achieve its 2020 goals (Pan et al., 2011).

In 2007, China called for a more environmentally friendly and resource-saving models of production and consumption (Pan, 2012). Twelve out of 17 mandatory targets in the 12th five-year (2011–2015) plan are related to the protection of natural resources and the environment; the rest are related to the improvement of social welfare (Pan, 2012). The actions taken under the five-year plan include progressive pricing for electricity consumption; implementation of energy consumption quota, disaggregated emission targets; emissions-trading schemes; initiatives for eco-cities and low-carbon cities; and upgraded building codes with improved enforcement (Pan, 2012).

1 See Sections 7.9, 8.7, 9.7, 10.9, and 11.8 for sectoral effects.

cated, but it is part of a shift of the development paradigm towards sustainability (Pan, 2012).

Co-benefits are pervasive and inseparable (Grubb et al., 2013). It is not possible to 'separate' each benefit with different decisions: both technically and politically, most decisions involve multiple dimensions. In addition, most suggested policy changes involve large changes in the policy environment as opposed to the concept of marginal changes (see also Section 3.6.3). Finally, many effects are measured in very different metrics or are not quantified at all. As an example, whereas local air quality co-benefits are measured in health terms, energy security is typically measured with indicators of the sufficiency of domestic resources (e.g., dependence on fossil fuel imports) and resilience of energy supply (see Sections 6.6 and 7.9 for details). All these characteristics make a comprehensive analysis of co-benefits and adverse side-effects of a particular policy or measure challenging. This is why a synthesis of results from different research communities is crucial for robust decision making (see Section 6.6).

Despite the difficulties, side-effects from climate policy are important for policy design (see Section 15.2.4). Costs of mitigation policies are over- or under-estimated when co-benefits and adverse side-effects are not included (see Sections 3.6.3 and 6.3.6). Co-benefits estimates are particularly important for policymakers because most of the climate benefits are realized decades into the future while most co-benefits, such as improvement in air quality, are realized immediately (Barker et al., 2008; Nemet et al., 2010b; Shindell et al., 2012; Jack and Kinney, 2010; Henriksen et al., 2011).

5.8 The system perspective: linking sectors, technologies and consumption patterns

Between 1970 and 2010 global greenhouse gas emissions have increased by approximately 80 %. The use of fossil fuels for energy purposes has been the major contributor to GHG emissions. Emissions growth can be decomposed in population growth and per capita emissions growth. Population growth is a major immediate driver for global GHG-emissions trends. Global population grew from 3.7 to 6.9 billion. The largest growth rates are found in MAF.

GHG emissions can be attributed to regions according to the territorial location of emissions, or alternatively emissions can be attributed to the consumption of goods and services, and located to regions where consumption takes place. There is an emerging gap between territorial and consumption-based emissions, signalling a trend where a considerable share of CO_2 emissions from fossil fuel combustion in developing countries is released in the production of goods and services exported to developed countries. At a regional level, OECD-1990 is the largest net importer of CO_2 embedded in trade, while ASIA is the largest net exporter. This emerging gap opens questions about the apparent decoupling between economic growth and GHG emissions in several Annex I countries; when consumption-related emissions are taking into account both GDP and GHG emissions have grown. Yet, a robust result is that, between 2000 and 2010, the developing country group has overtaken the developed country group in terms of annual CO_2 emissions from fossil fuel combustion and industrial processes, from both territorial and consumption perspectives.

When considering per capita emissions, rather than aggregate GHG emissions, other trends become visible. Global average per capita GHG emissions have shown a rather stable trend over the last 40 years. This global average, however, masks differences between regions and sectors. A strong correlation appears between per capita income and per capita GHG emissions both from a cross-country comparison on income and emission levels, and when considering income and emissions growth. The relation is most clearly for the sectors' energy, industry, and transport (Section 5.3.5), and holds despite the reduction in the average emission intensity of production, from 1.5 to 0.73 $kgCO_2eq/Int\$_{2005}$ over the same 40-year period.

ASIA had low per capita emission levels in 1970, but these increased steadily, by more than 150 %. The EIT region showed a rapid increase in per capita emissions between 1970 and 1990, and a sharp drop immediately after 1990. In 2010, per capita emissions are comparable in ASIA, LAM, and MAF (5.2, 6.4, and 5.4 tCO_2eq/yr, respectively) but per capita GHG emissions in OECD-1990 and EIT are still higher by a factor of 2 to 3 (14.1 and 11.9 tCO_2eq/yr, respectively). Also, between 1970 and 2010, per capita land-use related emissions decreased, but fossil fuel-related emissions increased. Regions vary greatly with respect to the income trends. The OECD-1990 and LAM countries showed a stable growth in per capita income, which was in the same order of magnitude as the GHG-intensity improvements, so that per capita emissions remained almost constant and total emissions increased by the rate of population growth. The EIT showed a decrease in income around 1990, which together with decreasing emissions per output and a very low population growth led to a robust decrease in overall emissions. The MAF sector also shows a decrease in GDP per capita but a high population growth led to a robust increase in overall emissions. Emerging economies in Asia showed very high economic growth rates; rapidly expanding industries resulted in sharply increasing emissions. In 2010, ASIA emitted more than half of worldwide industry-related emissions. ASIA showed both the highest economy-wide efficiency improvements measured as output per emissions, and the largest growth in per capita emissions.

The underlying drivers for economic growth are diverse and vary among regions and countries. Technological change and human capital are key underlying drivers, but some authors also underscore the availability of energy resources to play a central role in economic growth. Economic growth is strongly correlated to growth in energy use, and the direction of causality is not clearly established. At the global level, per capita primary energy consumption rose by 29 % from 1970 to 2010, but due to population growth total energy use has increased much more – 140 % over the same period.

Energy-related GHG emissions can be further decomposed in two additional immediate drivers: energy intensity and carbon intensity. Energy intensity has declined globally in all developed and major developing countries including India and China. This decline can be explained through technological changes, the effects of structural changes, and the substitution of other inputs such as capital and labour used. These historical improvements in energy intensities, however, have not been enough to compensate the effect of GDP growth, thus, increasing energy consumption over time as a result.

In addition, energy resources have historically become less carbon-intensive, though increased use of coal, relative to other resources, since 2000 has changed the trends exacerbating the burden of energy-related GHG emissions. Estimates of the resources of coal and conventional plus unconventional gas and oil are very large; indicating that resource scarcity has not been and will not be an underlying driver for decarbonization.

The immediate drivers that directly affect GHG emissions, namely population, GDP per capita, energy intensity and carbon intensity, are affected, in turn, by underlying drivers as described in Figure 5.1. These underlying drivers include resource availability, development status and goals, level of industrialization and infrastructure, international trade, urbanization, technological changes, and behavioural choices. Among these, infrastructure, technological changes and behavioural choices appear to be critical but, even though their influences on other drivers is well established, the magnitude of this impact remains difficult to quantify.

Co-benefits have large potential to contribute to emission reductions, but its historic contribution is not established. Infrastructural choices have long-lasting effects directing the development path to higher or lower energy and carbon intensities. Infrastructure also guides the choices in technological innovation. Technological change affects both income and emission intensity of income; it can lead to both increasing and decreasing GHG emissions. Historically, innovation increased income but also resource use, as past technological change has favoured labour productivity increase over resource efficiency. There is clear empirical evidence that prices and regulation affect the direction of innovations. Innovations that increase energy efficiency of appliances often also lead to increased use of these appliances, diminishing the potential gains from increased efficiency, a process called 'rebound effect'.

Behaviour and life-styles are important underlying drivers affecting the emission intensity of expenditures through consumption choices and patterns for transportation modes, housing, and food. Behaviour and lifestyles are very diverse, rooted in individuals' psychological traits, cultural, and social context, and values that influence priorities and actions concerning climate change mitigation. Environmental values are found to be important for the support of climate change policies and measures. Chapter 4 discusses formal and civil institutions and governance in the context of incentivizing behavioural change. There are many empirical studies based on experiments showing behavioural interventions to be effective as an instrument in emission reductions, but not much is known about the feasibility of scaling up experiments to the macro economy level.

As described across the different sections of the chapter, factors and drivers are interconnected and influence each other and, many times, the effects of an individual driver on past GHG emissions are difficult to quantify. Yet historic trends reveal some clear correlations. Historically, population growth and per capita income growth have been associated with increasing energy use and emissions. Technological change is capable to substantially reduce emissions, but historically, labour productivity has increased more compared to resource productivity leading to increased emissions. Regulations and prices are established as directing technological change towards lower emission intensities. Behavioural change is also established as a potentially powerful underlying driver, but not tested at the macro level. Policies and measures can be designed and implemented to affect drivers but at the same time these drivers influence the type of policies and measures finally adopted. Historic policies and measures have proved insufficient to curb the upward GHG emissions trends in most countries. Future policies need to provide more support for emission reductions compared to policies over the period 1970 – 2010, if the aim is to change the future GHG emissions trends.

5.9 Gaps in knowledge and data

- **There is a need for a more timely and transparent update of emission estimates.** The collection and processing of statistics of territorial emissions for almost all countries since 1970, as used in Section 5.2, is far from straightforward. There are multiple data sources, which rarely have well-characterized uncertainties. Uncertainty is particularly large for sources without a simple relationship to activity factors, such as emissions from LUC, fugitive emissions, and gas flaring. Formally estimating uncertainty for LUC emissions is difficult because a number of relevant processes are not well-enough characterized to be included in estimates. Additionally, the dependence of the attribution of emissions to sectors and regions on the relative weight given to various GHGs is often not specified.

- **The calculation of consumption-based emissions (in addition to territorial emissions) is dependent on strong assumptions.** The calculations require an additional layer of processing on top of the territorial emissions, increasing uncertainties without a clear characterization of the uncertainties. The outcomes presented in Sections 5.3.1 and 5.3.3.2 are only available for years since 1990.

- **Empirical studies that connect GHG emissions to specific policies and measures or underlying drivers often cannot be interpreted in terms of causality, have attribution problems, and provide competing assessments.** Statistical association is not the same as a chain of causality, and there are competing explanations for correlations. Studies can attribute changes in emissions to changes of activities when all other things are kept equal, but historically, all other things rarely are equal. Section 5.3 identifies population, income, the economic structure, the choice of energy sources related to energy resource availability and energy price policies as proximate and underlying drivers for greenhouse gas emissions. But for most demography variables other than the population level, the literature provides competing assessments; different studies find different significant associations, and at different levels. Underlying drivers work in concert and cannot be assessed independently. From a cause-effect perspective, there is, for instance, no conclusive answer whether ageing, urbanization, and increasing population density as such lead to increasing or decreasing emissions; this depends on other underlying drivers as well. The results from the literature are often limited to a specific context and method. Our understanding could benefit from a rigorous methodological comparison of different findings (Sections 5.3.2, 5.6, 5.7).

- **It is debated whether greenhouse gas emissions have an 'autonomous' tendency to stabilize at higher income levels** (Section 5.3.3.1). It is agreed that economic growth increases emissions at low- and middle-income levels. With respect to energy, there are competing views whether energy availability is a driver for economic growth, or inversely that economic growth jointly with energy prices drives energy use, or that the causality depends on the stage of development (Sections 5.3.3.1 and 5.3.4).

- **The net effect of trade, behaviour, and technological change as a determinant of a global increase or decrease of emissions is not established** (Sections 5.4.2, 5.6.1, 5.7). There is evidence that the social, cultural, and behavioural context is an important underlying driver, and there are case studies that identify emission reductions for specific policies and technologies. For technology, empirical studies that ask whether innovations have been emission-saving or emission-increasing are limited in scope (Section 5.6.1). There is a rich theory literature on the potential of innovations to make production energy—or emission efficient—but evidence on the macro-effects and the rebound effect is still context-dependent (Section 5.6.2). How much carbon is exactly locked in existing physical infrastructure is uncertain and gaps of knowledge exist in how long physical infrastructure like housing, plants, and transport infrastructure typically remains in place in which geographical context (Section 5.6.3). Finally, most if not all of the literature on co-benefits and risk tradeoffs focuses on future potential gains. There is a total absence of empirical assessment about the role that co-benefits and adverse sideeffects have played, historically, in policy formation and GHG emissions (Section 5.7).

5.10 Frequently Asked Questions

FAQ 5.1 Based on trends in the recent past, are GHG emissions expected to continue to increase in the future, and if so, at what rate and why?

Past trends suggest that GHG emissions are likely to continue to increase. The exact rate of increase cannot be known but between 1970 and 2010, emissions increased 79 %, from 27 Gt of GHG to over 49 Gt (Figure 5.2). Business-as-usual would result in that rate continuing. The UN DESA World Population Division expects human population to increase at approximately the rate of recent decades (Section 5.3.2.1) of this report. The global economy is expected to continue to grow (Sections 5.3.3 and 5.4.1), as well as energy consumption per person (Sections 5.3.4.1 and 5.5.1). The latter two factors already vary greatly among countries (Figure 5.16), and national policies can affect future trajectories of GHG emissions directly as well as indirectly through policies affecting economic growth and (energy) consumption (Section 5.5). The existing variation and sensitivity to future policy choices make it impossible to predict the rate of increase in GHG emissions accurately, but past societal choices indicate that with projected economic and population growth, emissions will continue to grow (Section 5.8).

FAQ 5.2 Why is it so hard to attribute causation to the factors and underlying drivers influencing GHG emissions?

Factors influencing GHG emissions interact with each other directly and indirectly, and each factor has several aspects. Most things people produce, consume, or do for recreation result in GHG emissions (Sections 5.3 and 5.5). For example, the food chain involves land use, infrastructure, transportation, and energy production systems (Section 5.3). At each stage, emissions can be influenced by available agricultural and fishing technologies (Section 5.6), by intermediaries along the supply chain (Section 5.4), by consumers and by technology choices (Section 5.5). Technology and choice are not independent: available technologies affect prices, prices affect consumer preferences, and consumer preferences can influence the development and distribution of technologies (Sections 5.5). Policies, culture, traditions, and economic factors intervene at every stage. The interaction of these factors makes it difficult to isolate their individual contributions to carbon emissions growth or mitigation (Section 5.8). This interaction is both a cause for optimism, because it means there are many pathways to lower emissions, and a challenge because there will be many potential points of failure in even well-designed plans for mitigation.

FAQ 5.3 What options, policies, and measures change the trajectory of GHG emissions?

The basic options are to have individuals consume less, consume things that require less energy, use energy sources that have lower-carbon content, or have fewer people. Although inhabitants of the most developed countries have the option to consume less, most of the human population is located in less-developed countries and economies in transition where population growth is also higher (Section 5.3.2). In these countries, achieving a 'middle-class lifestyle' will involve consuming more rather than less (Section 5.3.3.2). Accepting that population will continue to grow, choices will involve changes in technology and human behaviour, so that the production and use of products and services is associated with lower rates of GHG emissions (technology Section 5.6), and consumers choose products, services, and activities with lower-unit GHG emissions (behaviour Section 5.5).

FAQ 5.4 What considerations constrain the range of choices available to society and their willingness or ability to make choices that would contribute to lower GHG emissions?

Choices are constrained by what is available, what is affordable, and what is preferred (Section 5.3.3). For a given product or service, less carbon-intensive means of provision need to be available, priced accessibly, and appeal to consumers (Section 5.3.4.2). Availability is constrained by infrastructure and technology, with a need for options that are energy-efficient and less-dependent on fossil fuels (Section 5.3.5). The choice of what to consume given the availability of accessible and affordable options is constrained by preferences due to culture, awareness, and understanding of the consequences in terms of emissions reduction (Sections 5.5.1, 5.5.2). All of these constraints can be eased by the development of alternative energy generation technologies and distribution systems (Section 5.6), and societies that are well-informed about the consequences of their choices and motivated to choose products, services, and activities that will reduce GHG emissions (Sections 5.5.3, 5.7).

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