INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
Working Group III – Mitigation of Climate Change

Chapter 5

Drivers, Trends and Mitigation

Chapter:	5	
Title:	Drivers, Trends and Mitigation	
Authors:	CLAs:	Gabriel Blanco, Reyer Gerlagh, Sangwon Suh
	LAs:	John Barrett, Heleen de Coninck, Cristobal Felix Diaz Morejon, Ritu Mathur, Nebosja Nakicenovic, Alfred Ofosu Ahenkorah, Jiahua Pan, Himanshu Pathak, Jake Rice, Richard Richels, Steven Smith, David Stern, Ferenc L. Toth, Peter Zhou
	CAs:	Robert Andres, Giovanni Baiocchi, Michael Hanemann, Michael Jakob, Peter Kolp, Emilio la Rovere, Thomas Michielsen, Keisuke Nansai, Mathis Rogner, Steven Rose, Estela Santalla, Tommy Wiedmann, Thomas Wilson, Diana Ürge-Vorsatz,
	REs:	Marcos Gomes, Aviel Verbruggen
	CSAs	Joseph Bergesen, Rahul Madhusudanan

Drivers, Trends and Mitigation

Contents

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 production vs. consumption-based emissions. In all cases, global and regional trends are analysed. 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 28 to 49 GtCO2eq/yr (+80%) between 1970 and 2010, reaching the highest value in human history *(high confidence)*. GHG emissions grew on average 2.3% per year between 1970 and 2000, compared to 1.4% per year between 1970 and 2000. [5.2.1]

With 76% in 2010, CO2 remains the major anthropogenic GHG *(high confidence).* The share of fossil fuel-related CO2 emissions for energy purposes increased consistently over the last 40 years reaching 34 GtCO2/yr, or 69% of global GHG emissions in 2010.[1] Agriculture, deforestation and other land use changes have been the second contributors whose emissions, including other GHGs, have reached 12 GtCO2eq/yr *(low confidence)*, 24% of global GHG emissions in 2010. Since 1970, CO2 emissions increased by about 90%, and CH4 and N2O increased by about 47% and 43%, respectively. Fluorinated gases emitted in industrial processes continue to represent less than 2% of anthropogenic GHG emissions. [5.2.1]

Over the last four decades GHG emissions have risen in every region, though trends in the different regions have been dissimilar. In Asia GHG emissions grew by 330% reaching 19 GtCO2eq/yr in 2010, in MAF by 70%, in LAM by 57%, in OECD by 22%, and in EIT by 4%. Although small in absolute terms, GHG emissions from international transportation are growing rapidly. [5.2.1]

Cumulative fossil CO2 emissions (since 1750) more than tripled from 420 GtCO2 by 1970 to 1300 GtCO2 (±8%) by 2010 (*high confidence*). Cumulative CO2 emissions associated with agriculture, deforestation and other land use change (AFOLU) have increased from about 490 GtCO2 in 1970 to approximately 680 GtCO2 (±45%) in 2010.[2] Considering cumulative CO2 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 tCO2eq/cap) is almost ten times that of low-income countries (1.4 tCO2eq/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 and EIT are between 1.9 and 2.7 times higher than per capita GHG emissions in LAM, MAF and Asia.[3] 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 to 2010, GHG

[1] 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.

[2] Values in brackets (±XX) provide uncertainty ranges for a 90% confidence interval.

[3] The country compositions of OECD-1990, EIT (Reforming Economies), LAM (Latin America and Caribbean), MAF (Middle East and Africa), and Asia are defined in Annex II of the report.

emissions grew in all sectors: energy supply (+36%, to 17 GtCO2eq/yr), industry (+39%, to 10 GtCO2eq/yr), transport (+18%, to 7.0 GtCO2eq/yr), buildings (+9%, to 3.2 GtCO2eq/yr), AFOLU (+8% to 12 GtCO2eq/yr). 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 CO2 emissions slightly decreased between 2000 and 2010, but consumption-based CO2 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, production-related emissions and consumption-related emissions that include CO_2 embedded in trade flows. The gap shows that a considerable share of CO_2 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 CO2 emissions from fossil fuel combustion and industrial processes from both production and consumption perspectives. [5.3.3]

The trend of increasing fossil CO2 emissions is robust *(very high confidence)***.** Five different fossil fuel CO2 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 CO2 emissions from fossil fuels have relatively low uncertainty, assessed to be ±8%. Uncertainty in fossil CO2 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 4,800 to 9,800 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. MAF showed a decrease in GDP per capita, but a high population growth 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 4 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 to 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, 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 lead to more intensive use of resources, diminishing 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 are particularly important for policymakers because of their shorter-term realization *(limited evidence, low agreement).* Policies addressing fossil fuels may reduce not only CO2 emissions but also SO2 emissions and other pollutants that directly affect human health. Mitigation measures may also produce adverse side-effects, such as those generated by large-scale hydropower plants or by the production of certain biofuels. 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 to 2010, in most regions and countries policies have proved insufficient in influencing infrastructure, technological, or behavioural choices at a scale that curb the upward GHG emissions trends. [5.6, 5.8]

5.1 Introduction and overview

The concentration of greenhouse gases, including CO2 and CH4, in the atmosphere has been steadily rising since the beginning of the Industrial Revolution (Etheridge et al., 1996, 2002; NRC, 2010). Anthropogenic CO2 emissions from the combustion of fossil fuels have been the main contributors to the rising of GHG concentration levels in the atmosphere, followed by CO2 emissions from land use, land use change and forestry (LULUCF).

Chapter 5 analyzes the anthropogenic 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.

Chapter 5 first considers the immediate drivers, or factors in the decomposition, of total GHG emissions. For energy, the factors are population, GDP (production) and 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 3 groups through the dotted lines.

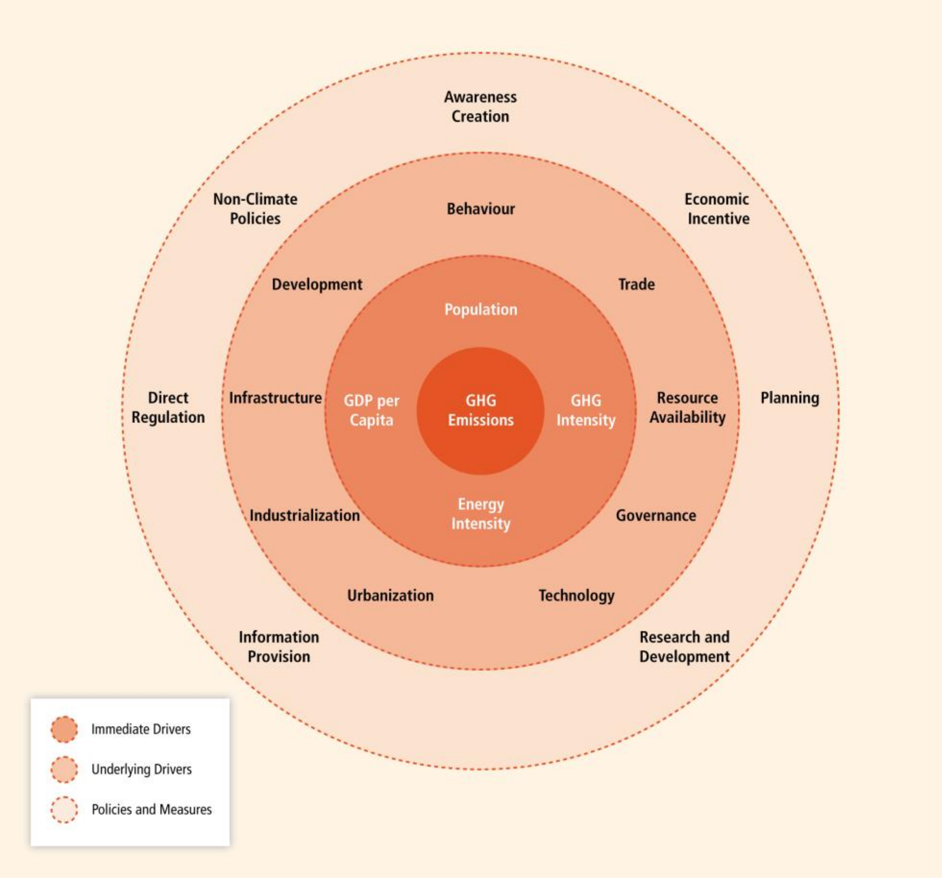


Figure 5.1. Interconnections among GHG emissions, immediate drivers, underlying drivers, and policies and measures. Immediate drivers comprise the factors in the decomposition of emissions. Underlying drivers refer to the processes, mechanisms and characteristics that influence emissions through the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

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 subsections 5.3.4 *Energy demand and supply* and 5.3.5 *Other key sectors* that 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 subsections 5.3.2 *Population and demographic structure*, 5.3.3 *Economic growth and development*, and 5.3.4 *Energy demand and supply*. Past trends of the immediate drivers are identified and analyzed in these subsections.

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

Section 5.7 *Co-benefits and trade-offs of mitigation actions* identifies the effects of GHG 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* syntheses 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 shortages 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.

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, GWP-weighted territorial global greenhouse gas (GHG) emissions increased from 28 to 49 GtCO2eq, an 80% increase (Figure 5.2). Total GHG emissions increased by 8 GtCO2eq over the 1970s, 6 GtCO2eq over the 1980s, and by 2 GtCO2 over the 1990s, estimated as linear trends. Emissions growth accelerated in the 2000s for an increase of 10 GtCO2eq. The annualized GHG growth rate over these decadal periods was 2.5%, 1.5%, 0.7%, and 2.3%. The main regional changes underlying these global trends were the reduction in GHG emissions in the EIT region starting in the 1990s and the rapid increase in GHG emissions in developing Asia in the 2000s. Emissions values in section 5.2 are from 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. EDGAR emissions estimates for specific compounds are compared to other results in the literature below.

Similar trends were seen for fossil CO2 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 CO2 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 CO2 emissions growth, however, are higher than in the past due to an overall expansion of the global economy due to population growth.

Carbon dioxide (CO2) is the largest component of anthropogenic GHG emissions (Figure 1.3). CO2 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, CO2, including net land-use change emissions, comprised over 75% of 100-year GWP weighted anthropogenic GHG emissions (Figure 1.3). Between 1970-2010, global anthropogenic fossil CO2 emissions more than doubled, while CH4 and N2O each increased by about 45%, although there is evidence that CH4 emissions may not have increased over recent decades (see Section 5.2.3). Fluorinated gases, which represented about 0.4% in 1970, increased to comprise 2% 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 IPCC WG I report (Boucher and Randall, 2013; Hartmann et al., 2013). Forcing from aerosols and ozone precursor compounds are considered in the next section.

Following general practice (e.g. UNFCCC), 100-year GWPs from the IPCC second assessment report (Schimel et al. 1996) are used as the index for converting GHG emissions to common units of CO2 equivalent emissions in this section. There is no unique method of comparing trends for different climate forcing agents. A change to 20 or 500 year GWP values would change the trends by ±6% (see discussion of metrics in Chapter 3). Similarly, use of updated AR4 or AR5 GWPs, which change values by a smaller amount, would not change the overall conclusions in this section. The largest absolute 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)).

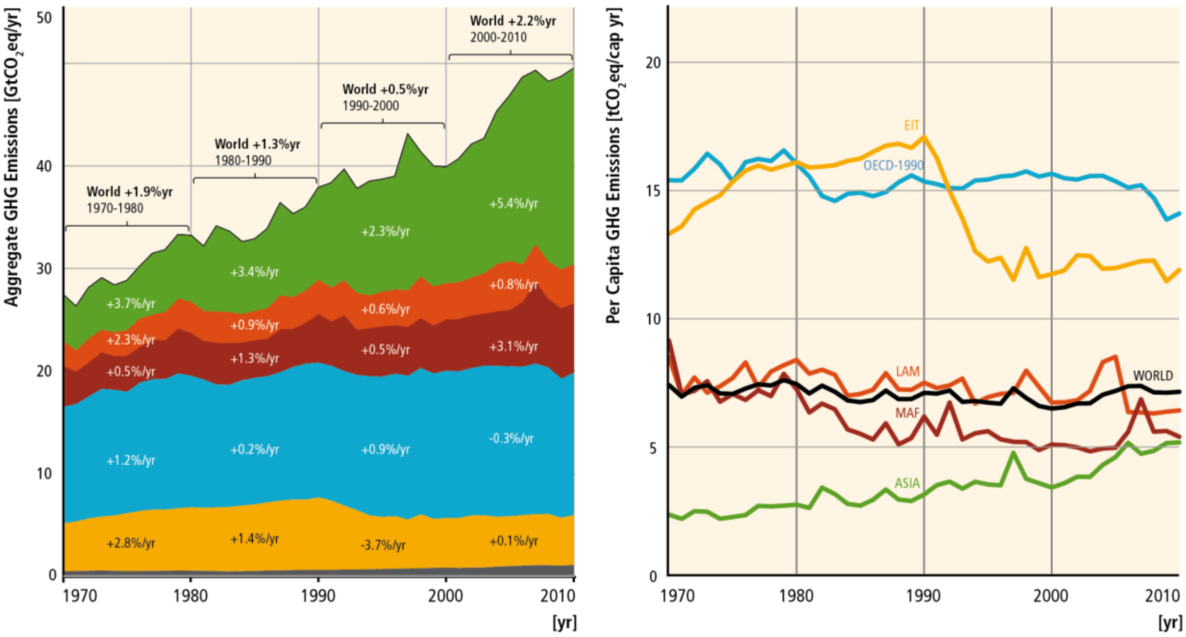


Figure 5.2. Left panel: GHG emissions per region (territorial, see Section 5.5.1) over 1970-2010, including fossil, agriculture and land-use/land-use change sectors, aggregated using 100-year GWP values. Right panel: The same data presented as per-capita GHG emissions. (JRC/PBL, 2012).

Global per-capita GHG emissions (Figure 5.2b) 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 the developing ASIA region. Per-capita emissions in regions other than EIT were fairly flat until the last several years when per-capita emissions have decreased slightly in OECD-1990 and LAM.

Fossil CO2 emissions have growth substantially over the past two centuries (Figure 5.3-left). Fossil carbon dioxide emissions over 2002-2011 were estimated at 30 ±8% GtCO2/yr (Andres et al., 2012), (90% confidence interval). Emissions in the 2000s as compared to 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 1990 OECD 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.

Fossil CO2 emissions made up the largest share (80%) of the emissions increase between 2000 and 2010. In 2011 fossil CO2 emissions were 3% higher than in 2010, taking the average of estimates from JRC/PBL (Olivier et al., 2013), EIA, and 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% GtCO2/yr (Ciais et al., 2013). One estimate of land-use change emissions by region is shown in Figure 5.3b, (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 order 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 Quere et. al ((Le Quéré et al., 2012)) and WG I (Ciais et al., 2013).

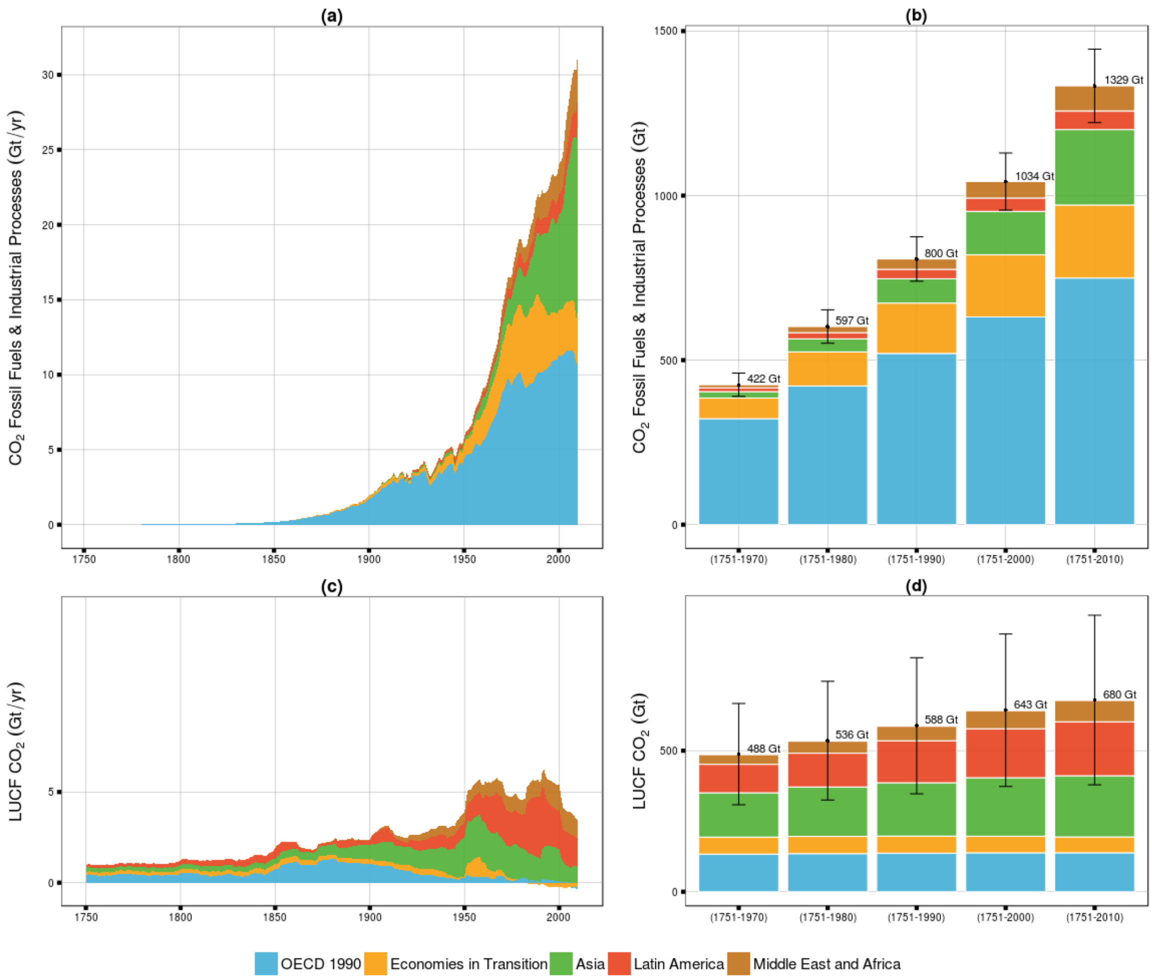


Figure 5.3. (a) Historic fossil CO2 emissions per region (territorial, (Boden et al., 2012)). **(c)** An illustrative estimate of historical land-use change emissions (Houghton et al., 2012). **(b)** and **(d)** show cumulative emissions over selected time periods by region. Whisker lines give an indication of the range of emission results.

Cumulative CO2 emissions, which are a rough measure of the impact of past emissions on atmospheric concentrations, are also shown in Figure 5.3. About half of cumulative fossil CO2 emissions to 2010 were from the OECD-1990 region, 20% from the EIT region, 15% from the Asia region, and the remainder from LAM, Middle East, Africa, and international shipping (not shown).The cumulative contribution of LUC emissions was similar to that of fossil fuels until the late 20th century. By the 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 CO2 emissions. Cumulative fossil CO2 emissions to 2011 are estimated to be 1340 ± 110 GtCO2/year, while cumulative land-use change emissions are 660 ± 290 GtCO2/year (WG I 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 (CH4) is the 2nd most important greenhouse gas, although its apparent impact in these figures is sensitive to the index used to convert to CO2 equivalents (see Chapter 3). 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 methane emissions from JRC/PBL (2013) of 7.3 GtCO2eq is 7% higher than the 6.8 GtCO2eq 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 nitrous oxide (N2O) that is emitted during agricultural and industrial activities as well as during combustion and human waste disposal. Current estimates are that about 40% of total N20 emissions are anthropogenic. The 2005 estimate of N2O emissions from JRC/PBL ((JRC/PBL, 2013)) of 3.0 GtCO2eq is 12% lower than the 3.4 GtCO2 estimate of US EPA ((US EPA, 2012)), which is well within an estimated 30% to 90% uncertainty (Section 5.2.3).

In addition to CO2, CH4 and N20, the fluorinated gases ("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., CFCs, 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).

GHGs are emitted from many societal activities, with global emissions from the energy sector consistently increasing the most each decade over the last 40 years (Figure 5.18). A notable change over the last decade is large 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 greenhouse gases, 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)(Myhre et al., 2014)(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, 2007; 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 SO2), although trends in climate and land-use also impact these forcing agents.

Sulphur dioxide (SO2) 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 SO2 emissions over this period is estimated to be relatively low (±10%), although regional uncertainty can be higher (Smith et al., 2011).

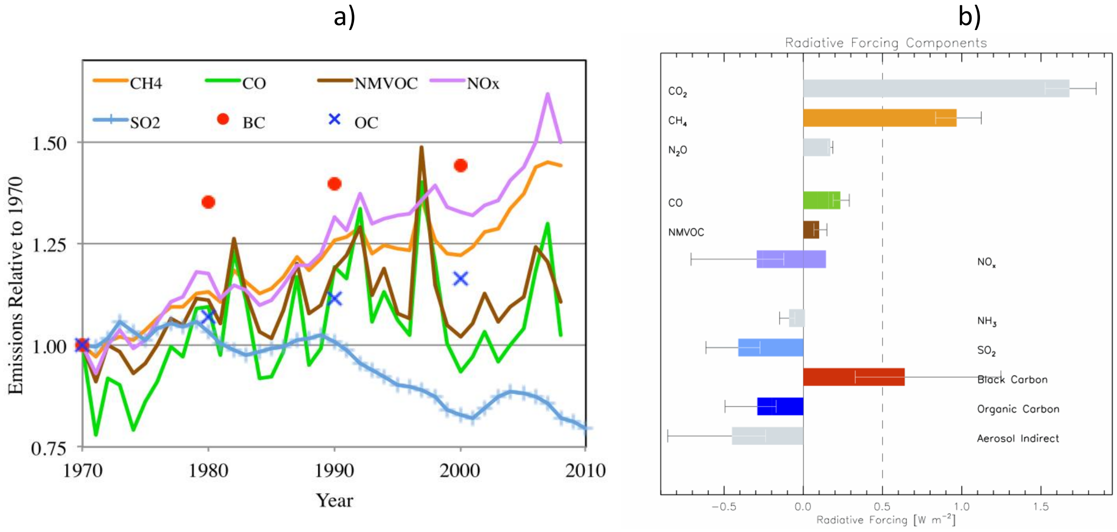


Figure 5.4. a) Global trends for air pollutant and methane emissions from anthropogenic and open burning, normalized to 1970 values. Short-timescale variability, in CO and NMVOC in particular, is due to grassland and forest burning. Data sources: EDGAR (JRC/PBL, 2012), except for SO2 (Smith et al., 2011);(Klimont et al., 2013a), and BC/OC (Lamarque et al., 2010). **b)** 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).

A recent update of carbonaceous (BC & OC) aerosol emissions trends (black and organic carbon) found an increase from 1970 through 2000, with a particularly notable increase in black carbon 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).

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 methane, 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 NOx 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, 2007). The lower values here are largely due to lower estimates of land-use change CO2 emissions (by 0-50%) and N2O emissions (by 20-40%) and fossil CO2 emissions (by 0-5%). These differences in these emissions are expected 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 10% (Andres et al., 2012). Uncertainties in fossil-fuel CO2 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 (2 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 CO2 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 CO2 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 CO2 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 5.4 compares five estimates of fossil CO2 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.

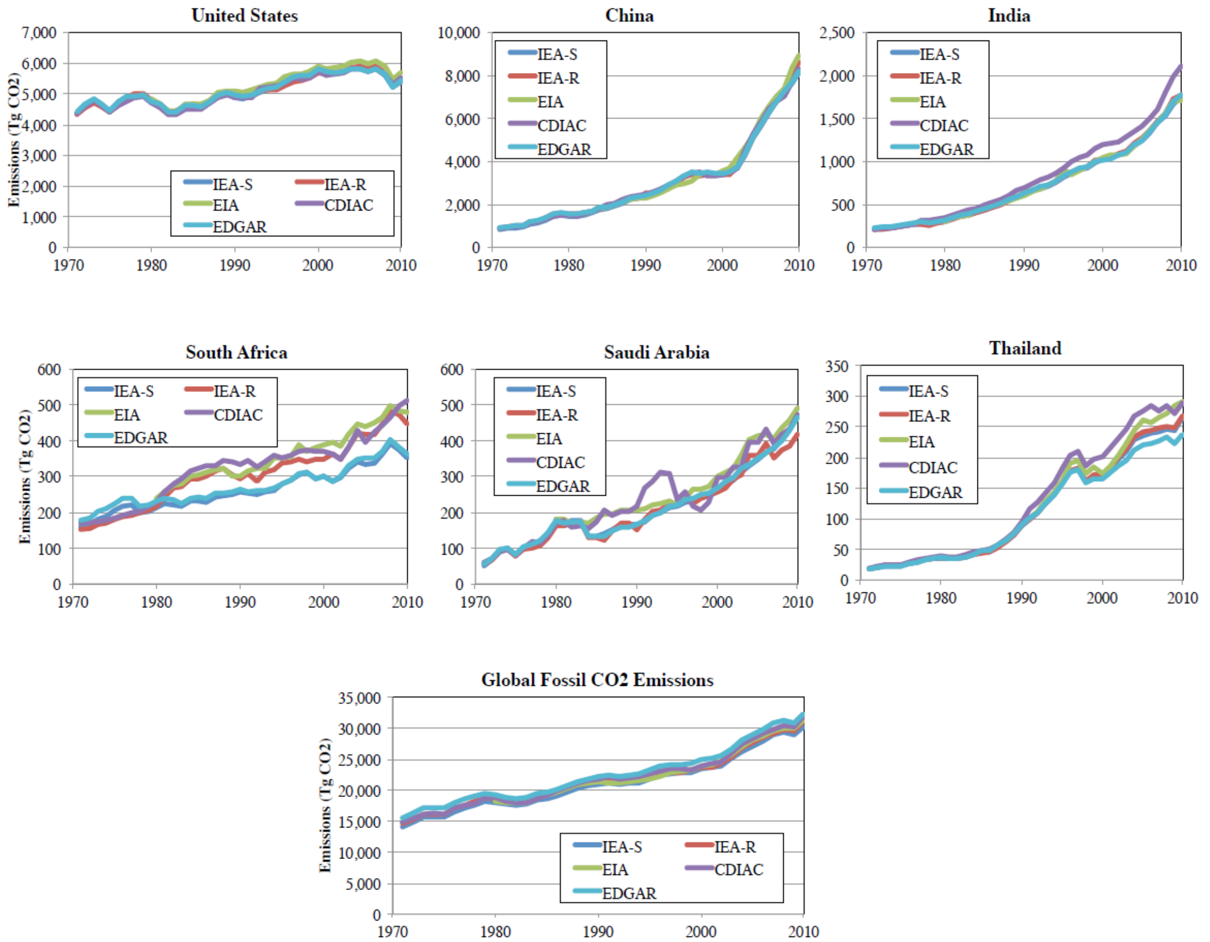


Figure 5.5. Upper panel: five estimates of fossil CO2 emissions for the three countries with the largest emissions (and complete time series). Middle panel: the three countries with the largest percentage variation between estimates. Lower panel: global emissions (TgCO2). Emissions data are harmonized data from Macknick (Macknick, 2011)(downloaded Sept 2013) and JRC/PBL (JRC/PBL, 2013), and include fossil fuel combustion, cement production, and gas flaring. Note that the vertical scales differ significantly between plots.

5.2.3.3 Other GHGs and non-fossil fuel CO2

Uncertainty is particularly large for sources without a simple relationship to activity factors, such as emissions from land-use change (Houghton et al., 2012); see also CH11 for a comprehensive discussion), fugitive emissions of CH4 and fluorinated gases (Hayhoe et al., 2002), biogenic emissions of CH4 and N2O, and gas flaring (Macknick, 2011). Formally estimating uncertainty for land-use change 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 carbon dioxide, with fewer global estimates (EDGAR, 2012; US EPA, 2012; Höglund-Isaksson et al., 2012). The relationship between emissions and activity levels for methane 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 ±6-11% for HCFC-22 (Saikawa et al., 2012), 20-80% for various perfluorocarbons (Ivy et al., 2012), and 8-11% for SF_6 (Rigby et al., 2010).

5.2.3.4 Total GHG uncertainty

Estimated uncertainty ranges for greenhouse gases 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 land-use change 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 UNEP Gap Report ((UNEP, 2012), appendix), which is lower largely due to a lower uncertainty for fossil CO_2.

5.2.3.5 SO_2 and aerosols

Uncertainties in SO_2 and carbonaceous aerosol (BC and OC) emissions have been estimated by Smith et al. ((Smith et al., 2011)) and Bond et al. ((Bond et al., 2004, 2007)). SO_2 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 black carbon 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 and 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 land-use change emissions are sufficiently high to make trends over recent decades uncertain in direction and magnitude (see also CH11).

While two global inventories both indicate that anthropogenic methane emissions have increased over the last three decades, a recent 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 a 86 Mt-CH4 (or 30%) increase over 1980-2010 and the EPA (2012) historical estimate has a 26 Mt-CH4 increase from 1990-2005 (with a further 18 Mt-CH4 projected increase to 2010). Kirschke et al ((Kirschke et al., 2013)) derive 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 sulphur dioxide emissions have decreased over the last two decades, decreasing again in recent years following an increase from about 2000 to 2005 (Klimont et al., 2013a). 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 to 2010 (Lu et al., 2011).

5.2.3.7 Uncertainties in consumption-based CO_2 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). Application of different models and assumptions results in different estimates between consumption-based CO_2 emissions, direct comparisons of which remains as a large gap in the literature.

Uncertainties in consumption-based emission accounts arise from various sources (Lenzen et al., 2010) including : (1) uncertainty in the territorial-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 input.

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 literature 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.

Neither is there a unique method to identify the drivers of climate change, nor can they always be objectively defined: human activities manifest themselves through a complex network of interactions, and isolating a clear cause-and-effect of a certain phenomenon purely through the lens of scientific observation is often difficult. Therefore, the term, “driver” may not represent exact “causality” but is used to indicate “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., 2011a; 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 economy (Suh, 2006; Nansai et al., 2009b), and energy consumption (Wier, 1998; Malla, 2009; Bolla and Pendolovska, 2011). Each of these topics will be elaborated on beginning in section 5.3.2.

Obviously many drivers of GHG emissions are interlinked to each other, and furthermore, many of these drivers can be further decomposed into various subcomponents. For example, transportation emissions is 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.

Box 5.1. IPAT and Kaya decomposition methods

The IPAT (Ehrlich and Holdren, 1971) and Kaya (Kaya, 1990) identities provide to common frameworks in the literature for analysing 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 emission) 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 GWP100 have increased in all three categories, namely fossil energy CO_2, Agriculture, Forestry and Other Land Use (AFOLU), and the rest 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.

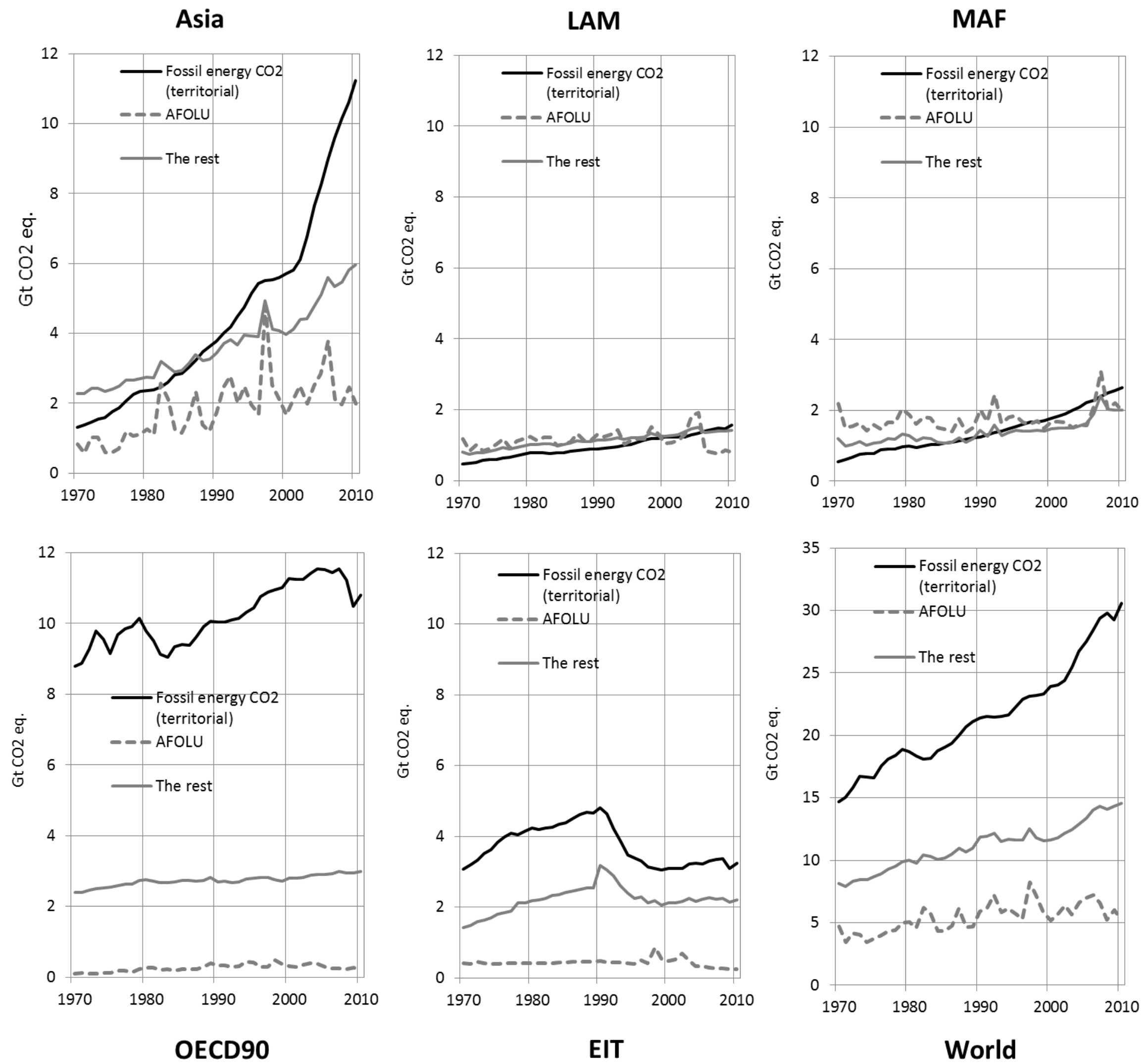


Figure 5.6. GHG emissions in GWP100 at regional level divided into fossil energy CO_2, AFOLU and the rest (1970 – 2010); note that only the bottom-right panel for the World has a different scale for its vertical axis (created using JRC/PBL (2012)). The direct emission data from JRC/PBL (2012) (see Annex II.8) represents land-based CO2 emissions from forest and peat fires and decay that approximate to net CO2 flux from the FOLU (Forestry and Other Land Use) sub-sector. For a more

detailed representation of AFOLU GHG flux (Agriculture and FOLU) see Section 11.2 and Figure 11.2 and 11.6.

Two GHG accounts are distinguished in the literature, namely territorial and consumption accounts (see Box 5.2 for the definition). The Kaya identity for territorial CO2 emissions can be written as

(1) $$\text{Territorial } CO_2 \text{ emission} = \textbf{populaton} \times \frac{\text{GDP}}{\text{people}} \times \frac{\text{Energy}}{\$\text{GDP}} \times \frac{CO_2 \text{ emission}}{\text{Energy}}$$

In other words, CO_2 emission is 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 emission/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) $$\text{Territorial } CO_2 \text{ emission} = \text{population} \times \frac{\text{GDP}}{\text{people}} \times \frac{CO_2 \text{ emission}}{\text{GDP}}.$$

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

(3)

$$\text{Consumption-based } CO_2 \text{ emission} = \text{number of people} \times \frac{\$\text{GNE}}{\text{people}} \times \frac{t \text{ consumption-based } CO_2 \text{ emission}}{\$\text{GNE}}$$

$$\text{Consumption-based } CO_2 \text{ emission} = \text{population} \times \frac{\text{GNE}}{\text{people}} \times \frac{\text{consumption-based } CO_2 \text{ emission}}{\text{GNE}}.$$

In this case, consumption-based CO_2 emissions are decomposed into (1) population, (2) per capita consumption (GNE/people; 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 emission and its contributing factors (Raupach et al., 2007).

5.3.1.1 Key drivers

Figure 5.6 shows that, globally AFOLU emissions have increased by 12% between 1970 and 2010. AFOLU emissions have been more pronounced in non-OECD-1990 regions and dominate total GHG emissions from Middle East and Africa (MAF) and Latin America (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 the last IPCC Assessment Report (Metz, 2007)

Figure 5.3.2 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 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 Economies in Transition (EIT), ASIA and OECD-1990 (39% to 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. EIT 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 2 folds (OECD-1990, EIT and LAM) to a remarkable 6 folds 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, the 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.

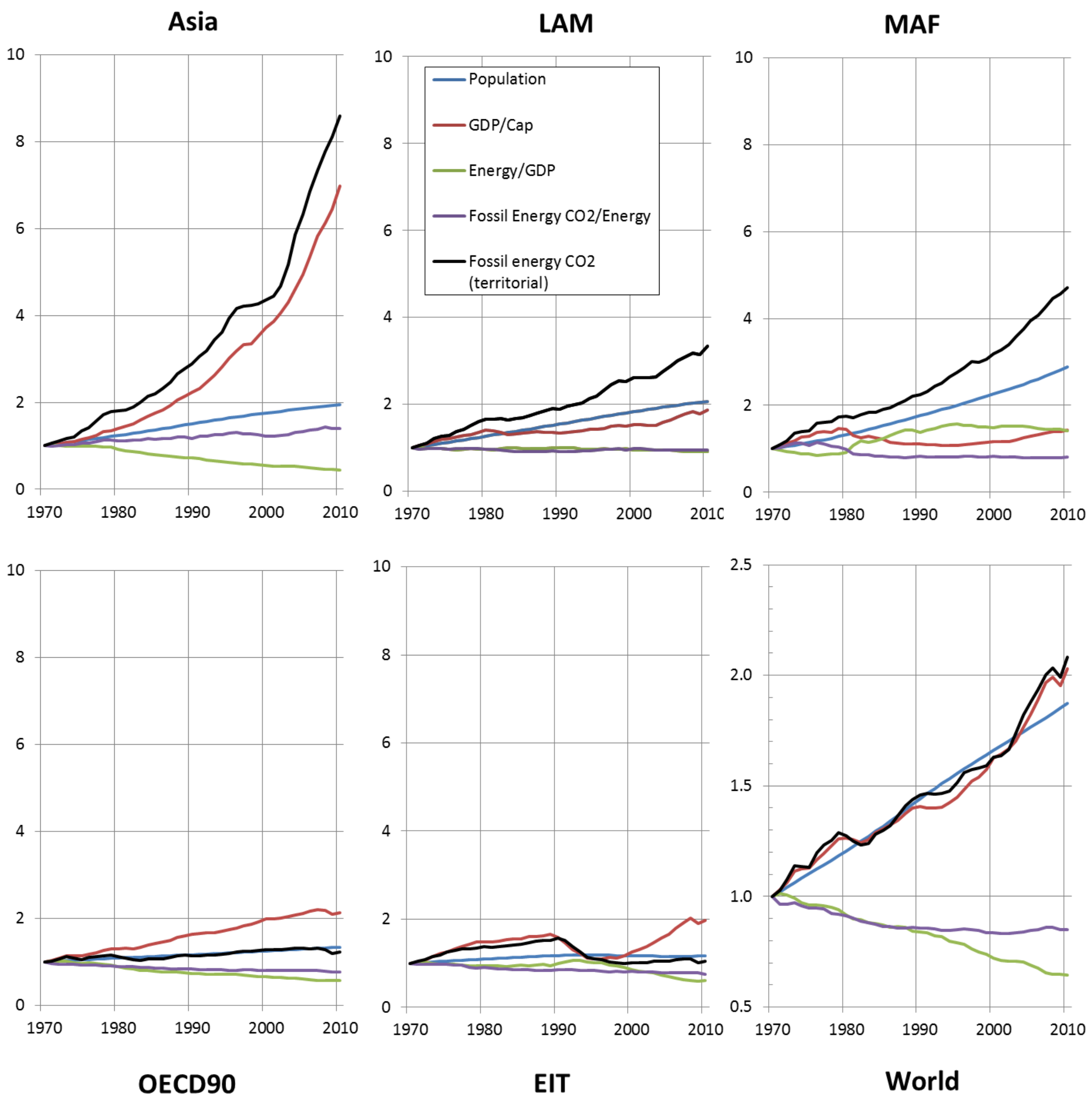


Figure 5.7. Four factor decomposition of territorial fossil energy CO_2 emission at regional level (1970 – 2010); note that only the bottom-right panel for the World has a different scale for its vertical axis (created using IEA and JRC/PBL (2012); based on PPP adjusted GDP).

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

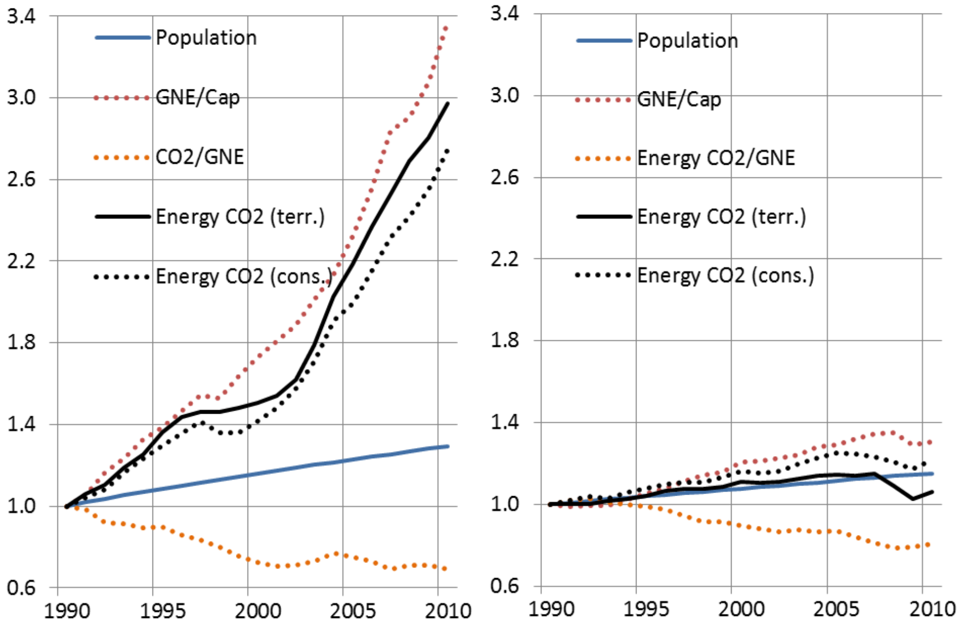


Figure 5.8. Three factor decomposition of consumption-based and territorial fossil energy CO_2 emission for Asia (left) and OECD (right) (1990 – 2010) (JRC/PBL, 2012).

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 energy-intensive, Asian economy.

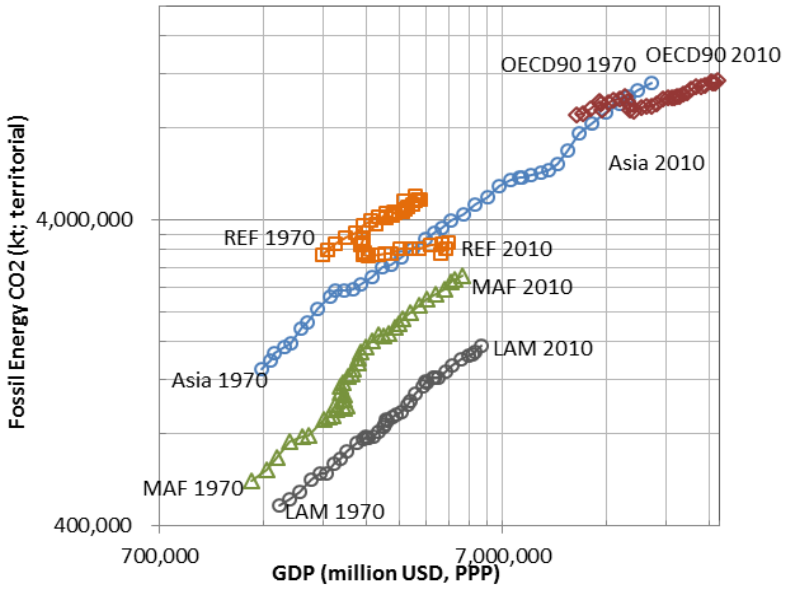


Figure 5.9. Historical regional trajectories of territorial fossil energy CO2 emission vs. GDP (1970 – 2010 (Drawn using data from JRC/PBL (2012)).

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

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.

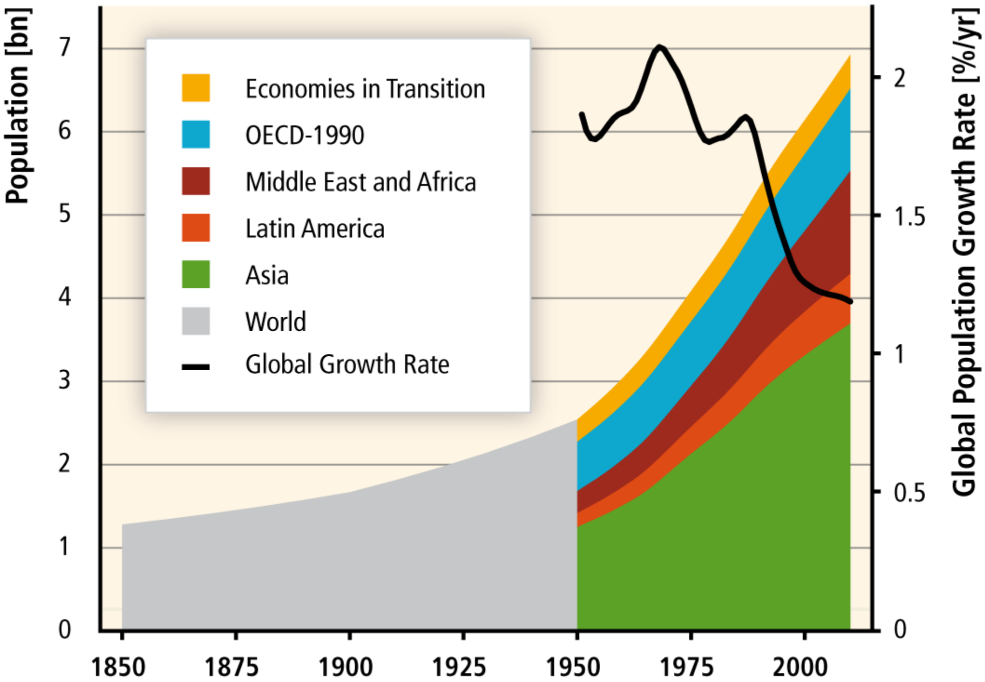


Figure 5.10. Trends in regional and global population growth 1850-2010. Global data up to 1950 (grey from (UN, 1999). Regional data from 1950 onwards from UN WPP (2012).

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 analysed by Raupach et al. (2007). Global CO2 emissions from fossil fuel combustion have been growing slightly below the growth rate of global population in most of the 1980-2005 interval but they have accelerated towards the end of the period.

Aggregating population and GHG emissions data according to the five IPCC Representative Concentration Pathways (RCP) regions (see Annex II.7), Figure 5.10 shows that between 1971 and 2010 population growth was fastest in Middle East and Africa (MAF); GHG emissions have increased most in ASIA while changes in population and emissions were modest in OECD-1990 and Economies in Transition (REF). The evolution of total population and per capita GHG emissions in the same period is shown in Figure 5.10. With some fluctuations, per capita emissions have declined slightly from rather high levels in the OECD1990 countries and the Economies in Transition, decreased somewhat from relatively lower levels in Latin America and especially in Middle East and Africa, while more than doubled in Asia. These trends raise concerns about the future: per capita emissions decline slowly in high-emission regions (OECD1990 and REF) while fast increasing per capita emissions are combined with relatively fast population and per-capita income growth in ASIA (JRC/PBL, 2012).

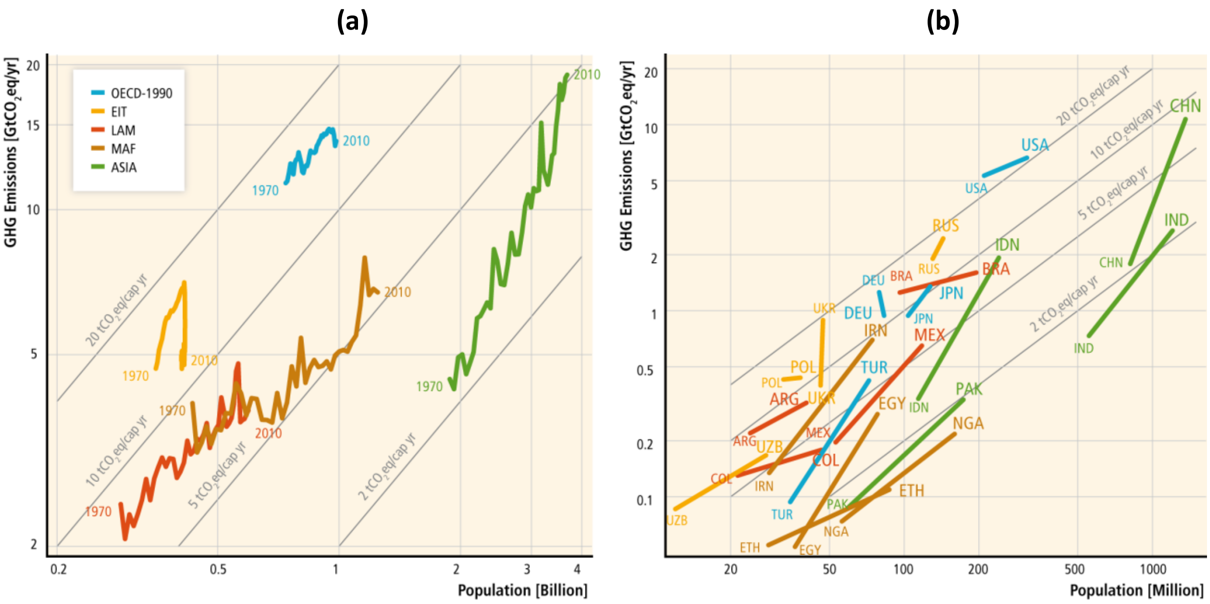


Figure 5.11. Trends in population and GHG emissions in the five IPCC RCP regions (panel a) and for each region the four most populous countries in 2010 (panel b). Grey diagonals connect points with constant emission intensity. Major GHG emitting regions or countries are in the upper half. A shift to 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. Panel (b): The small labels refer to 1970, the large labels to 2010; drawn using data from JRC/PBL (2012). (Note the log-log plot.)

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 percent increase in population size) vary widely: from 0.32 (Martínez-Zarzoso and Maruotti, 2011) to 2.78 (Martínez-Zarzoso et al., 2007)) (for the 8 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 countries) to 1.23 (middle income) to 1.75 (low-income) 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 which is 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 CO2 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 CO2 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 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, a set of multivariate decomposition studies reviewed by O'Neill et al. (forthcoming) 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. (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 ten 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, e.g. 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 obvious important determinant of urban GHG emissions in several global cities in the examined sample. Transport related aspects connectivity and accessibility of destination and origin, ability to use alternative transport 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 urbanisation-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 utilize much larger shares of commercial energy. Urbanization thereby involves radical increases in household electricity demand and in CO2 emissions as long as electricity supply comes from fossil, especially coal based power plants. Transition from coal to low-carbon electricity could mitigate the fast increasing CO2 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 urbanisation, 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 in 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 USA that aging tends to reduce long-term CO2 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 CO2 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 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 US) 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" EU 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 CO2 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 aging-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 & 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 Middle East and Africa 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 REF as well as globally and declined in MAF. The levels of the GDP and emissions per capita also vary tremendously globally as shown in Figure 5.12:

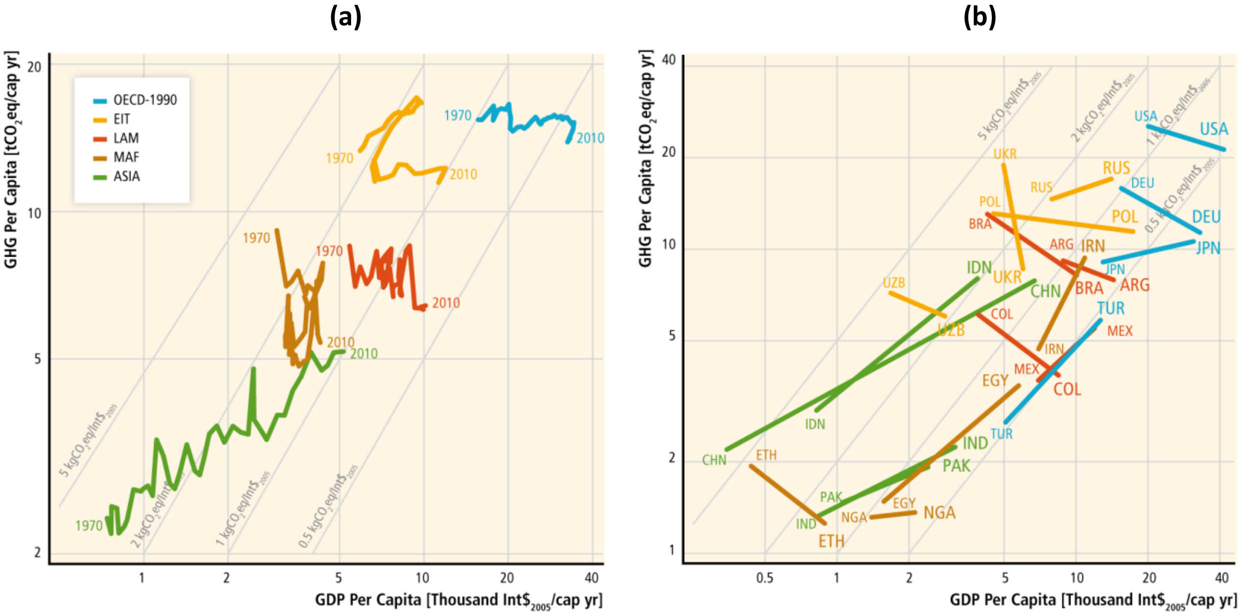


Figure 5.12. Trends in per capita production and GHG emissions in the five IPCC RCP regions (panel a) and for each region the four most populous countries in 2010 (panel b) (JRC/PBL, 2012). Grey diagonals connect points with constant emission intensity (emissions/GDP). A shift to the right presents income growth. A flat or downwards line presents a decrease in energy intensity, 1971 and 2010. Panel (b): 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 complemented with substantial emissions increase.

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 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, Figure 5.12). 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 2009-10 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.) that 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 bimodal 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 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 very varied and no firm conclusions can be drawn yet (Stern, 2011).

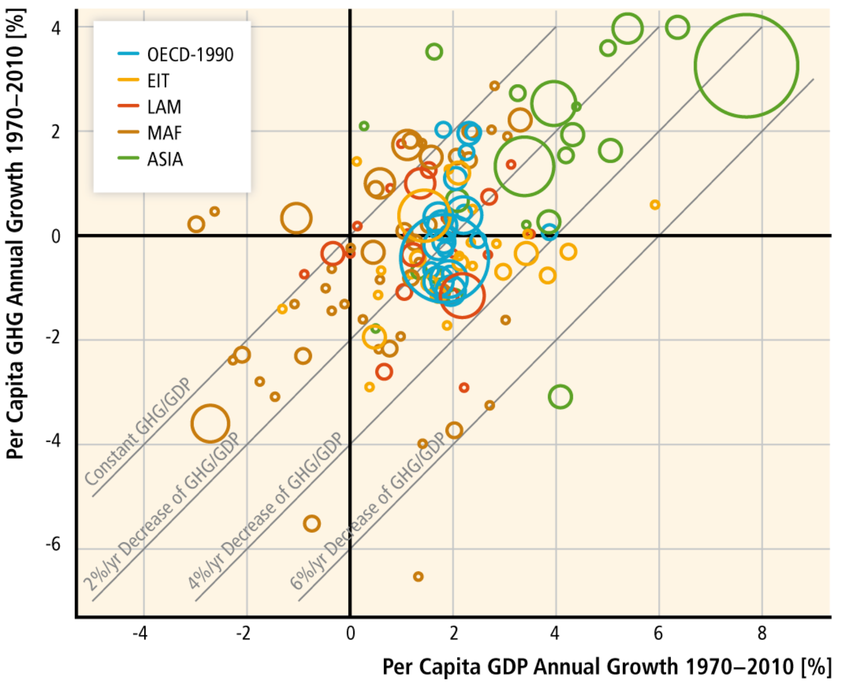


Figure 5.13. Growth rates of per capita income and emissions (JRC/PBL, 2012). The figure shows the correlation between the average annual growth rate of per capita income and per capita emissions from 1970 to 2010, for all countries with more than 1 million people by 2010. Points along the grey lines have either constant emissions intensity or emissions intensity declining at 2% or 5% 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).

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 been found to be not 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 there is strong positive correlation between the growth of the two variables. 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 greenhouse gas emissions, we find subtle but important differences. Box 5.2 presents two methods; one for allocating GHG emissions to production (territories), 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 with 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 Asian countries together surpassed those of the OECD countries in 2009, for consumption-based emissions, the OECD countries as a group contributed more than all 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 territorial per capita emissions declined over 1990-2010, while consumption-based emissions increased. By 2010, per capita territorial emissions for OCED countries are 3 times those for Asian countries, but per capita consumption-related emissions differ by a factor of 5. The overall picture shows a substantial gap between territorial and consumption-based emissions, due to emissions embedded in trade. For the OECD countries, the gap amounts to 2.6 Gt CO2 in 2010. The data shows that the reduction in territorial emissions that has been achieved in the OECD countries has been more than negated by an increase in emissions in other countries, but related with consumption in OECD 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., 2011a; Aichele and Felbermayr, 2012).

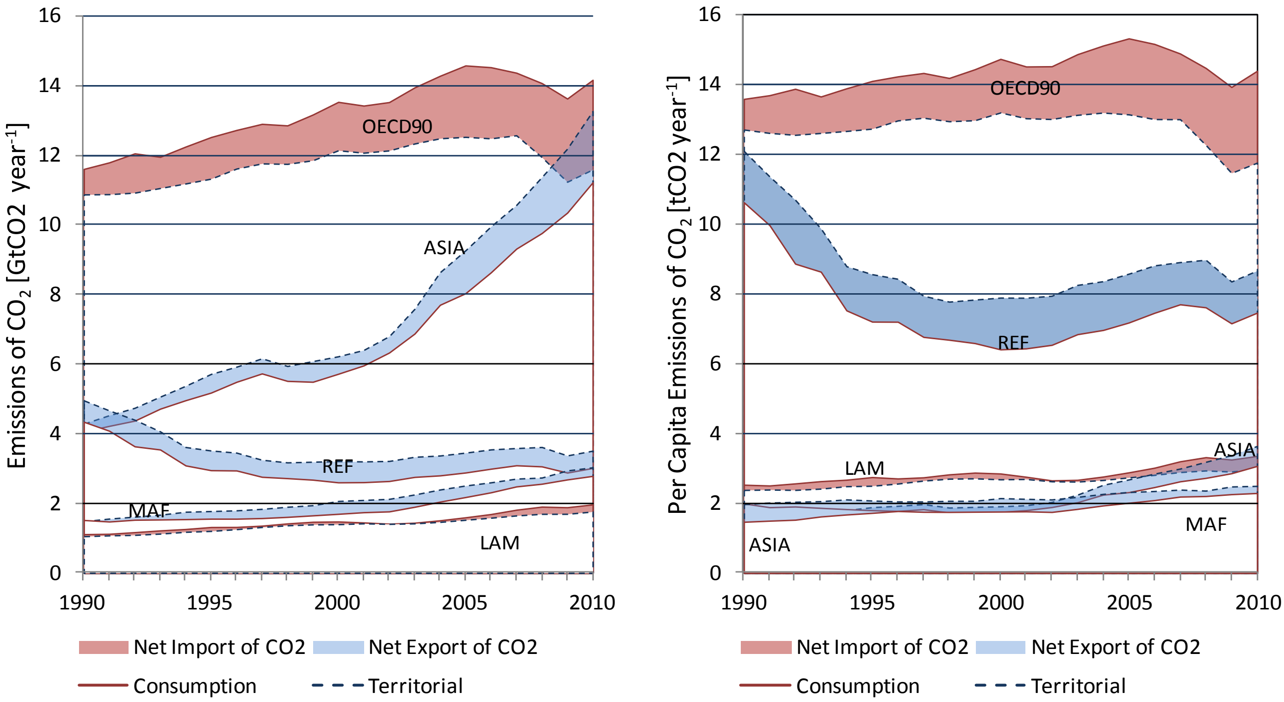


Figure 5.14. Territorial (blue dotted lines) versus consumption-based (red lines) emissions in five world regions, from 1990 to 2010. The left panel presents total emissions, while the right panel presents per capita emissions. The red areas indicate that a region is a net importer of embedded CO2 emissions. The blue area indicates a region is a net exporter of embedded CO2. Data from Lenzen et al. (2010).

Numerous studies have used a structural decomposition analysis to quantify the factors for changes in greenhouse gas 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 to 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 UK 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 in consumption-related emissions.

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 harmonisation 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.

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 to 2008. However, the elasticity of consumption-based emissions with respect to economic growth will have to be revised upwards for OECD countries, given that their consumption emissions grew at a faster rate than territorial ones (Peters et al., 2011a). In this sense, there is less decoupling in industrialised 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 follows an inverted-U 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 shape 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 manufacturing 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 UK 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 ten developed (USA, 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 Sue 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, 2010). An alternative perspective is provided by the literature on consumption-based emissions (see 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 reduce the global reduction in emissions from shifting towards the service sector in the UK. 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 greenhouse gas 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[1]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).

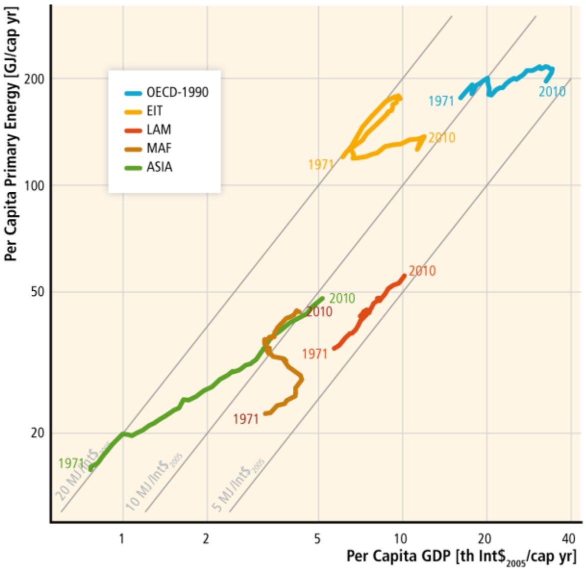
In conclusion, the role of an increase in share of the service sector in output in reducing emissions is probably quite small, but finer grained structural change could be important and economy wide reforms contribute much to the adoption of more energy and emissions efficient production processes.

5.3.4 Energy demand and supply

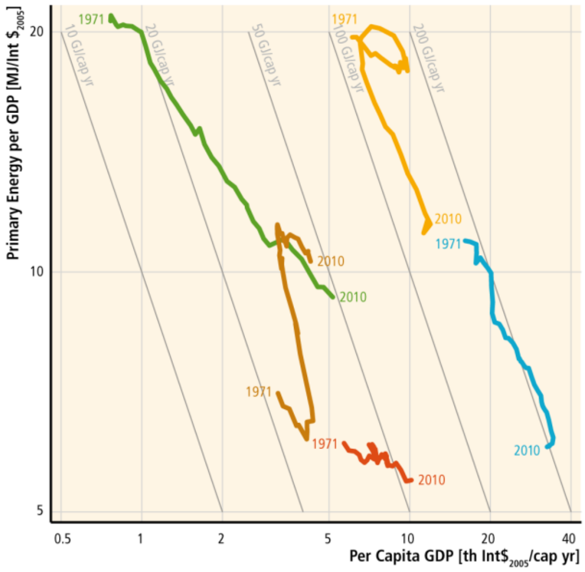
5.3.4.1 Energy demand

Globally, per capita primary energy use, as estimated by the IEA method (see Annex II.8), rose by 31% from 1971 to 2010; however the five world regions exhibited two different pathways during this period, as seen in Figure 5.15.a. In the OECD and transition economies (EIT), energy use per capita rose by 13-14%, while the other regions increased their per capita energy use at a much higher rate: Latin America (LAM) by 60%, Middle East and Africa (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 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.b). 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 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).



(a)



(b)

Figure 5.15. Historical trend (1971-2010) by Region in per capita primary energy (a) and primary energy intensity of GDP (b) against GDP per Capita on the horizontal axis. Note that both axes are logarithmic. Source: (IEA, 2012; UN WPP, 2012; World Bank, 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 (Grubler, 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, using by proxy GDP per capita, 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; Grubler, 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)(Filippini and Hunt, 2011)(Nakicenovic et al., 1996).

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 and 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 below, and is not an appropriate proxy of actual energy (conversion) efficiency (Ang, 2006), (Filippini and Hunt, 2011), (Stern, 2012) (Grübler et al., 2012)

Energy intensity metrics yield valuable insights into potentials for efficiency improvements related to various activities (Fisher et al., 2007)(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[4] 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 US as an example, as PPP and MER GDP are the same by definition. The thin green curve shows U.S. 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 starting energy intensity between the investigated countries, they all exhibit very similar rates of energy improvements independent of whether they are on a more or less energy-intensive development trajectory.

[4] 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.

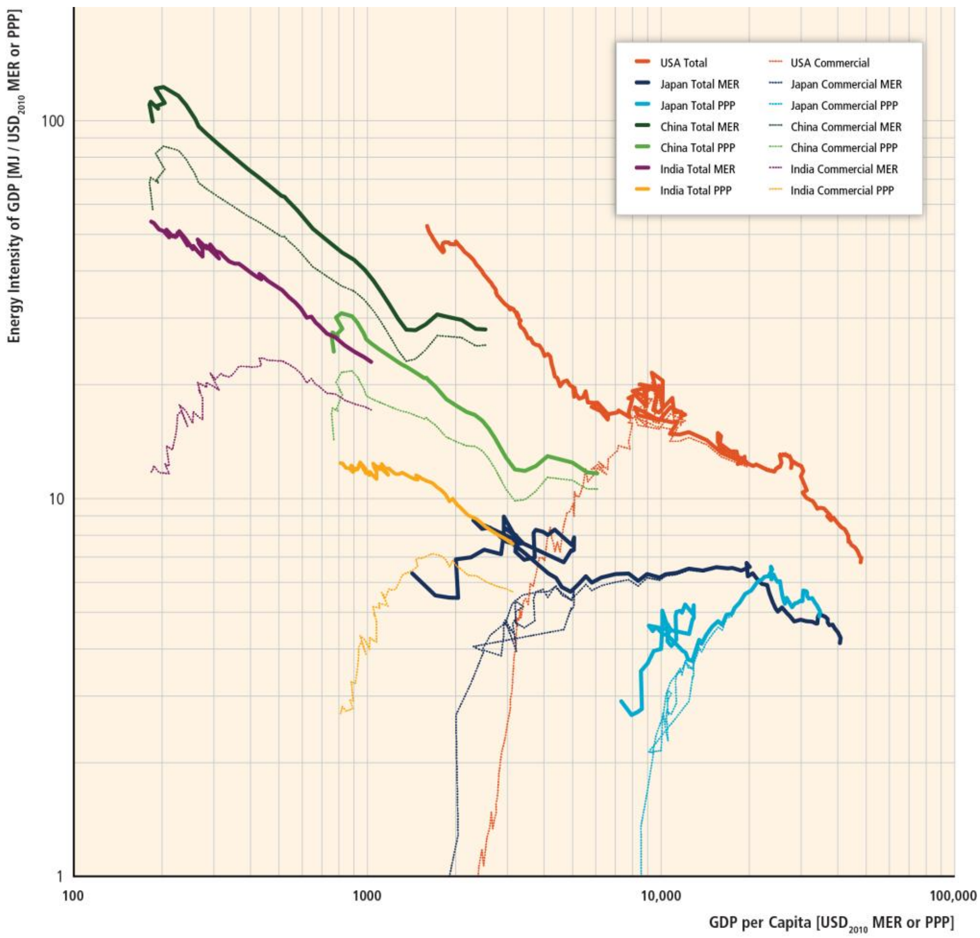


Figure 5.16. Energy intensity improvements and per capita GDP - US (1800–2008), Japan (1885–2008), India (1950–2008), and China (1970–2008). Source: (Grübler et al., 2012). Note: Energy intensities (in MJ per US$) are always shown for total primary energy (bold lines) and commercial primary energy only (thin lines) and per unit of GDP expressed at market exchange rates (MER in 2010US$) and for China, India, and Japan also at purchasing power parities (PPP in 2010 International$). For the United States, MER and PPP are identical.

For GDP, the most important accounting factor are the exchange rates used for converting income measured in local national currencies to internationally comparable currency units based on either market exchange rates (MER) or purchasing power parity (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. 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, i.e., 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 but 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 causes for 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 20^{th} 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[5], as well as the introduction of near-zero carbon energy sources, such as renewables, including sustainably managed biomass (biogenic carbon is reabsorbed through new growth), and nuclear, and consequently further decarbonization of energy systems (Grübler and Nakićenović, 1996), (Grubler, 2008). Decarbonization can also affect the emissions of other GHGs and radiatively active substances such as aerosols. Figure 5.17.a 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.

(a) **(b)**

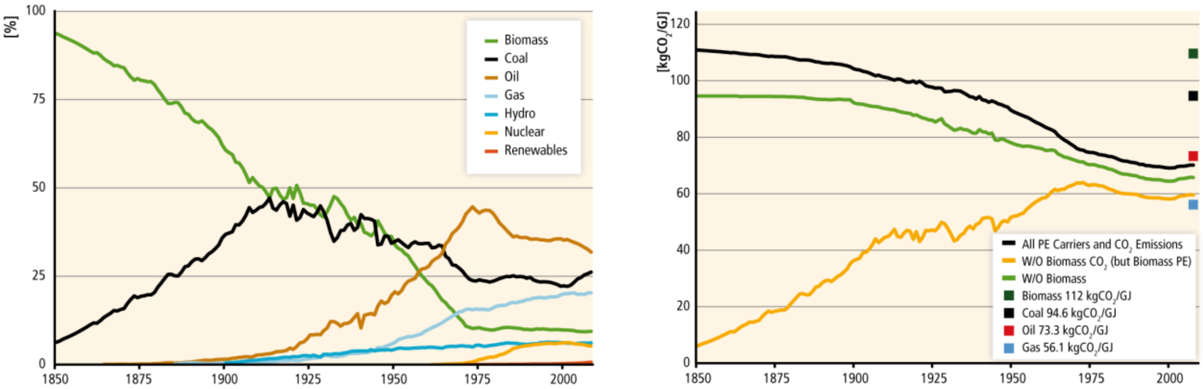


Figure 5.17. (a) Structural change in world primary energy (in percent) illustrating the substitution of traditional biomass (mostly non-commercial) by coal and later by oil and gas. The emergence of hydro, nuclear and new renewables is also shown. Source: Nakicenovic et al. (1998) and Grubler (2008). **(b)** Decarbonization of primary energy (PE) use worldwide since 1850 (kg of CO2 emitted per GJ). The solid line shows carbon intensities of all primary energy sources, dashed 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 CO2 released from biomass burning) and the dotted line shows global decarbonization without biomass and its CO_2 emissions. Note: For comparison, the specific emission factors (OECD/IPCC default emission factors, LHV basis) for biomass (wood fuel), coal, crude oil, and natural gas are also shown (coloured squares). Source: updated from Grübler et al. (2012).

Figure 5.17.b 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 land-use changes, 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

[5] For further detailed information on carbon emissions for various combustible fuels, see IPCC, 1995 and IPCC, 2006.

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 ICT technologies 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 the 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 the current production. However, the global resources are unevenly distributed and are often 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 assurance for limiting the global CO2 emissions. For example, the carbon embedded in oil and gas reserves exceeds the carbon of the atmosphere. The emissions budget for stabilizing climate change at 2 degrees Celsius above pre-industrial levels is about the same as the current 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

Here we describe shortly the GHG emission trends for the main economic sectors (energy, transport, buildings, industry, AFOLU, and waste) and the correlation between emissions and income, showing marked differences between sectors and countries. The following subsections provide short discussions of trends and drivers per sector, while the following chapters (7-11) provide the detailed analyses. Note that in Chapter 5, we consider direct emissions for the buildings sector, whereas chapter 9 provides the more elaborate view including indirect emissions.

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 (ch11). Over 2000-2010, emissions by upper-middle income countries for energy (+3.5 GtCO2e/yr) and industry (+2.4 GtCO2e/yr) more than doubled, and by 2010 emissions from industries in upper-middle income countries have passed those from high-income countries. For transport, emissions start to increase at higher income levels.

The large increase in energy and industry emissions in upper-middle income countries is consistent with the observed income growth and 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 up to 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_2e/cap yr, while per capita emissions in the typical low income country reached to about one tenths of that value, at 1.4 tCO_2e/cap yr. But, there is a large variety between 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 1.2 th Int$2005/cap) have low per capita emissions (median of 1.4 tCO_2e/yr), but for the low-income country group, average per capita emissions (4.3 tCO_2e/yr) are pulled up by a few countries with very high emissions associated with land-use.

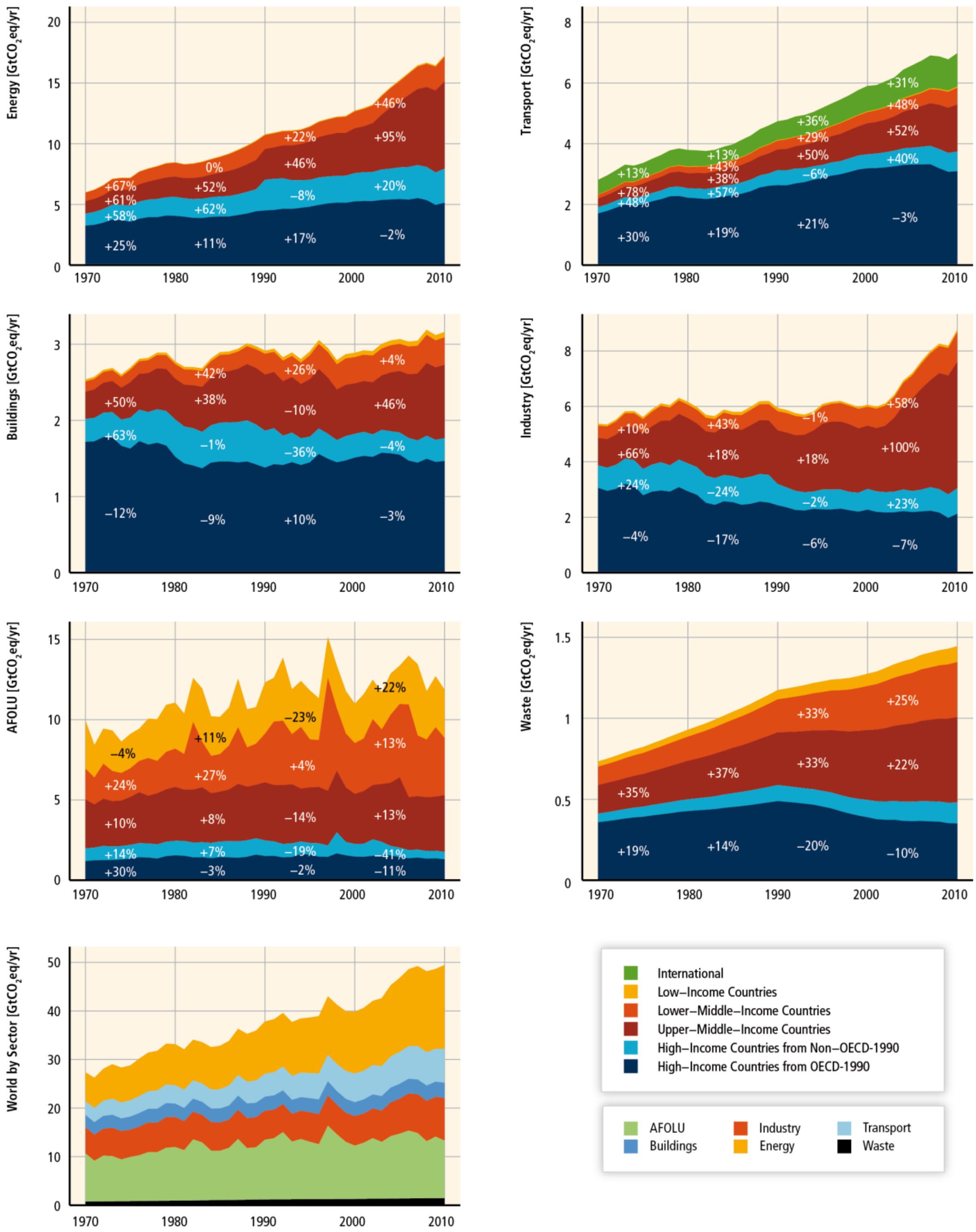


Figure 5.18. Regional and sector distribution of emission trends. The figure shows annual GHG emissions for the 6 key sectors discussed in Section 5.3.4 and 5.3.5. The left-lower panel presents global sector-emissions to assess the relative contribution. Decadal growth rates are projected on the charts for emissions exceeding 0.2 GtCO2eq/yr. The direct emission data from JRC/PBL (JRC/PBL, 2012) (see Annex II.8) represents land-based CO2 emissions from forest and peat fires and decay that approximate to net CO2 flux from the FOLU (Forestry and Other Land Use) sub-sector. For a more detailed representation of AFOLU GHG flux (Agriculture and FOLU) see Section 11.2 and Figure 11.2 and 11.6.

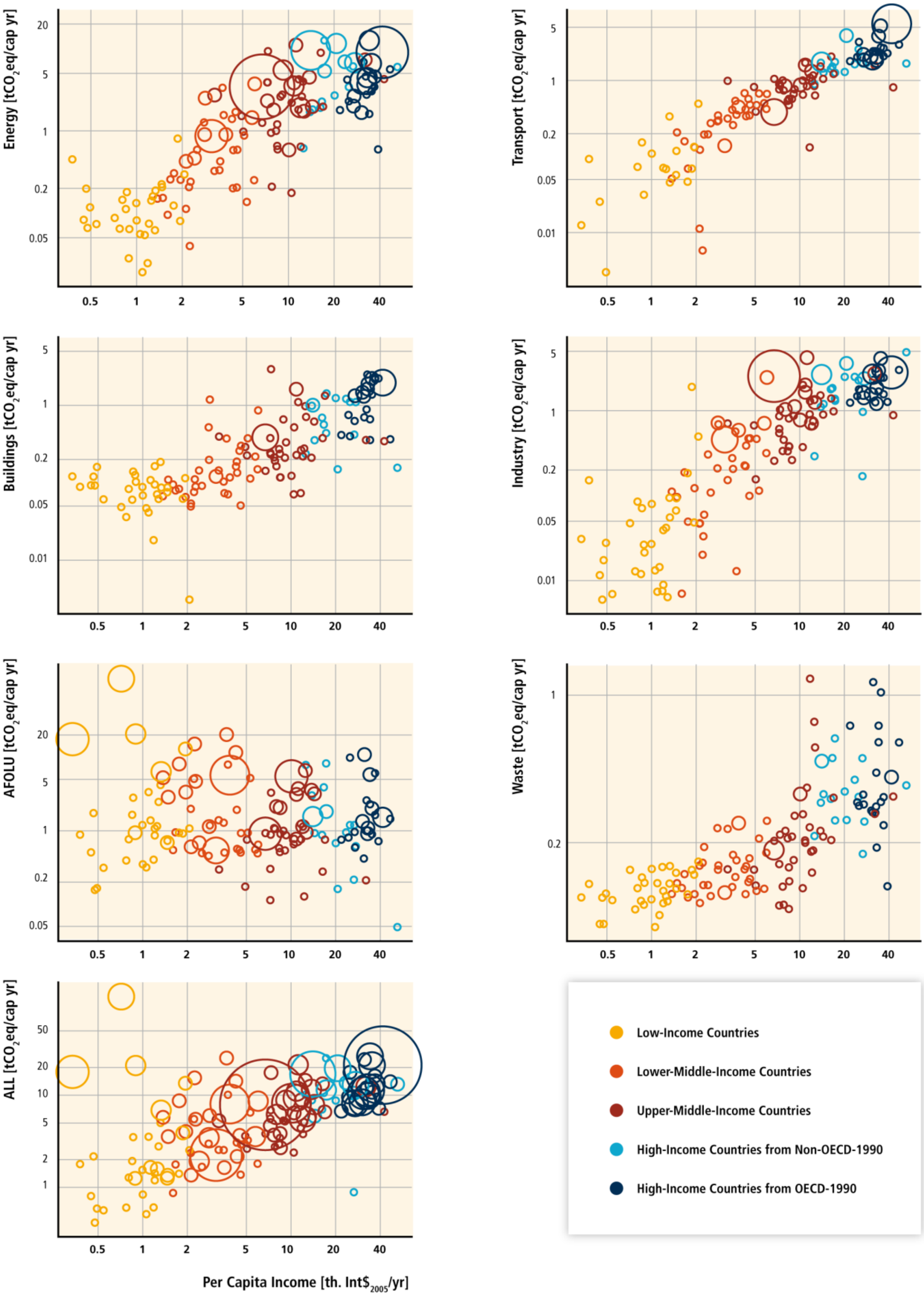


Figure 5.19. The relation between income and emissions for the 6 key sectors discussed in Section 5.3.4 and 5.3.5. The left-lower panel presents the relation for emissions aggregated over all sectors. Each circle is one country, for the year 2010. The area of a circle is proportional to the aggregate 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. Based on data from JRC/PBL (2012). The direct emission data from JRC/PBL (2012) (see Annex II.8) represents land-based CO2 emissions from forest and peat fires and decay that approximate to net CO2 flux from the FOLU (Forestry and Other Land Use) sub-sector. For a more detailed representation of AFOLU GHG flux (Agriculture and FOLU) see Section 11.2 and Figure 11.2 and 11.6.

5.3.5.1 Transport

The global transport GHG emissions[6] grew from 2.8 $GtCO_2eq$ in 1970 to 7 Gt CO_2eq in 2010[7]. The OECD countries contributed the largest share of the emissions (i.e. 60% in 1970, 56% in 1990 and 46% in 2010) but the highest growth rate in transport emissions was in the Upper Middle Income 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; high fuel consuming stock fleet of vehicles; relatively low oil prices; and the limited availability of low-carbon fuels have been the principle drivers of transport sector CO2 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 suggesting an influence of trade policies and world trade agreements on the 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 regions, with carbon dioxide emissions declining by 2.0% in 2008 and an estimated 6.3% in 2009. The greenhouse gas emissions in non- OECD emissions were not affected and even caused a 2.2% increase in total global transport emissions and an estimated 0.3% in 2009 (*US EIA,* 2011).

There is a strong correlation of per capita transport emissions and the per capita incomes and alignment of the two variables is sharper in the high income countries (Fig 5.3.15) as the demand for personal transportation increases as standards of living rise and increased economic activity as a result of high per capita income (US EIA, 2011).

5.3.5.2 Buildings

The building sector emissions grew from 2.5 Gt CO_2eq in 1970 to 3.2 Gt CO_2eq in 2010 with emissions growth rates in OECD countries being largely negative. Positive emission growth rates were registered in the Upper and Lower Middle Income countries, although the largest contribution to the buildings emissions were still from OECD countries (Figure 5.18).

There is correlation of per capita buildings emissions with per capita income attributed to high energy consumption. Considering life cycle analysis starting with manufacturing of building materials to demolition over 80% of greenhouse gas emissions take place during 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. The demand for energy in buildings for space heating was 58% in 1990 and 53% in 2005 while water heating was 17% to 16%, cooking and lighting about 5% and appliances 16-21% (International Energy Agency, 2008; *UNEP 2009*). In the low income countries, per capita emissions also tend to be high as a large proportion of operational energy is derived from polluting fuels mainly wood and other

[6] Consisting of direct CO2, CH4, N2O and F-gases (Freight Vision, 2009).

[7] (JRC/PBL, 2012)

biomass, such as dung and crop residues and that there is still a high number of people (2.4 billion) using biomass for cooking and heating (International Energy Agency, 2002, 2006)

5.3.5.3 Industry

The direct industry emissions (excluding waste water and AFOLU contributions[8]) grew from 6.1 in 1970 to 10.2 $GtCO_2eq/yr$ in 2010 and the contribution of OECD countries to the emissions dominated at the start of the period with over 61% of the emissions declining to 26% in 2010. The Middle income countries have become the major emitters particularly from after 2000 (Fig 5.3.14) when the annual growth rate in emissions increased by 165% in the Middle (Upper and Lower) income countries. There is positive correlation of industry per capita emissions and per capita income to about 10,000 Int$2005/cap. Beyond that income level, the correlation gradient flattens 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 the sector emissions has grown in both absolute and relative terms in all OECD regions and in relative terms in Economies in Transition (REF Region) countries driven by changes in income, demand of goods and services hence the level of industrial output, fuel switching and structural changes (International Energy Agency, 2003). There has also been a complex restructuring and relocation of production and consumption of goods and supply of services that have shaped the location of industrial emissions, hence the shift of major emissions to some Asian economies (De Backer and Yamano, 2012)(De Backer and Yamano, 2012) (Backer and Yamano, 2007).

The production of energy-intensive industrial goods that include 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 being located in developing nations (IPCC, 2007). 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 industry emissions such as PFC emissions have declined in many OECD countries, while SF6 emissions vary and HFC emissions have increased very rapidly driven more by use in refrigeration equipment rather than in manufacturing industries (International Energy Agency, 2003).

5.3.5.4 Agriculture, Forestry, Other Land Use (AFOLU)

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 the global emission in 2010 (JRC/PBL, 2013). Both the agriculture sub-sector and the forest and other land use (FOLU) sub-sector showed an increase in emissions during the period 1970-2010, but there is substantial uncertainty and variation between databases (see 5.2.3); Chapter 11 provides an overview of other estimates. In the agriculture sub-sector, methane from enteric fermentation and rice cultivation, and nitrous oxide mainly from soil and application of synthetic and manure fertilizer manure management had the largest contribution (≥80%) to total emission in 2010. Between 1970 and 2010, emission of methane increased by 20% whereas emission of nitrous oxide increased by 45-75%. Though total global emission increased but per capita emission went down from 2.5 ton in 1970 to 1.6 ton in 2010 because of growth in population. Per capita emission decreased in Latin America (LAM), Middle East and Africa (MAF) and Economies and Transition (REF) countries whereas in Asia and Organization for Economic Co-operation and Development (OECD-1990) countries it remained almost unchanged. There was no clear relation between emission in the AFOLU sector and per capita income (Figure 5.19).

[8] These emissions have been presented in other subsections

During 2000 and 2010, emission in the AFOLU sector marginally increased from 11 $GtCO_2eq$ to 11.9 $GtCO_2eq$ (Figure 5.18) but per capita emission marginally decreased from 1.8 ton to 1.7 tCO2eq/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 population of human and animal. 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 crop land 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 billion ton to 2.5 billion ton and 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 M ton in 1970 to 106 M ton 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 by 1.6 and 3.7-fold, respectively (FAOSTAT). This has increased GHGs emission directly and also through manure production (Davidson, 2009). Global daily per-capita food availability and consumption of animal products increased, particularly in Asia (FAOSTAT, 2013).

The emission 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. The details of emission, 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 Developing Countries

Almost 90% of 1970-2010 GHG emissions in the LDC countries are generated by agriculture, forestry and other land use activities- AFOLU (Fig 5.3.16), and emissions have increased by 0.6% per year in these countries during the last 4 decades. For the LDC, the primary activities within AFOLU include subsistence farming and herding, 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 5.29) 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 urbanisation and industrialisation 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 urbanisation and industrialization are associated with higher emissions than later stages (Martínez-Zarzoso and Maruotti, 2011).

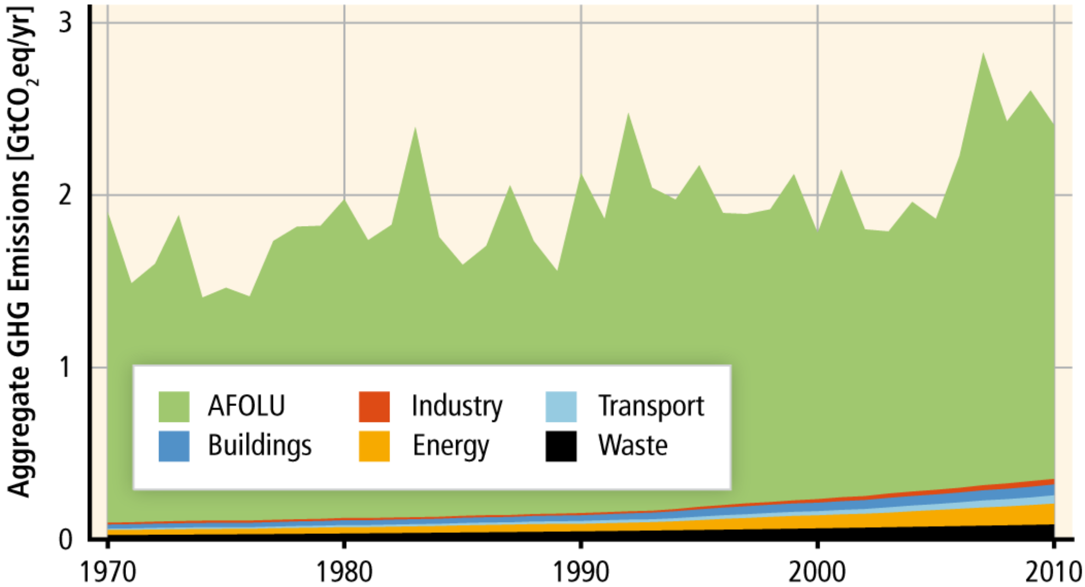


Figure 5.20. Historic fossil-fuel GHG emissions per sector in Least Developed Countries. The figure shows that for all sectors apart from AFOLU, emissions have increased sharply in relative terms. Yet AFOLU presents the largest share of emissions (JRC/PBL, 2012). The direct emission data from JRC/PBL (2012) (see Annex II.8) represents land-based CO2 emissions from forest and peat fires and decay that approximate to net CO2 flux from the FOLU (Forestry and Other Land Use) sub-sector. For a more detailed representation of AFOLU GHG flux (Agriculture and FOLU) see Section 11.2 and Figure 11.2 and 11.6.

5.3.5.5 Waste

Total global waste emissions for all gases (CH4, N2O, CO2) almost doubled from 1970 to 2010 (Figure 5.18) (JRC/PBL, 2012), while in the period 2000-2010 year the increment was 13% (1278MtCO2eq vs 1446 MtCO2eq) (JRC/PBL, 2012). Waste GHG emissions represented in 2010 the 3,0**%** of total GHG emissions from all sources (1446 MtCO2eq), compared to 2,6% in 1970 (734 MtCO2eq)(JRC/PBL, 2012). Main sources of waste GHG emissions were solid wastes disposal on land (46% of total waste

GHG emissions in 1970 year and 43% in 2010 year) and wastewater handling (51% of total waste GHG emissions in 1970 year and 54% in 2010 year), and in minor importance according to their GHG emission quantities waste incineration (mainly CO2), and other sources (JRC/PBL, 2012).

From 1998 year and forward waste GHG emissions in Asia are larger than in OECD countries (mainly in GHG wastewater emissions); while in 1970 year OECD's emissions represented 50% of emissions (364 MtCO2eq) and Asia 27% (199 MtCO2eq), in 2010 year Asia represented 41% of waste GHG emissions (596 MtCO2eq) and OECD 27% (391 MtCO2eq) (Figure 5.18) (JRC/PBL, 2012). The main GHG from waste is CH4 (methane) – mainly emitted from municipal solid wastes disposal on land and wastewaters - representing 91% in 1970 year, followed by N2O(7%); and 90% in 2010 year followed by N2O (8%) (Monni et al., 2006; JRC/PBL, 2012).

The waste generation is closely interrelated with population, urbanization and affluence. Waste-generation rates can be correlated with different indicators of affluence, as gross domestic product (GDP)/cap, energy consumption/cap, and private final consumption/cap (Monni et al., 2006; Bogner et al., 2008). In the same way Magnus Sjöström and Göran Östblom remarks in their article that waste quantities have grown steadily along with Gross Domestic Products (GDPs) over the last decades (Sjöström and Östblom, 2009), moreover they wrote that total quantity of municipal waste per capita increased by 29 per cent in North America, 35 per cent in OECD, and 54 per cent in the EU15 from 1980 to 2005 (Sjöström and Östblom, 2009)

The estimation of the past, current and future emissions as well as the mitigation potential in the waste sector has many uncertainties, the most important relating to the poor quality of 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 gross domestic product (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 billion tonnes. Statistics on CO2 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%. Asia is by far the most important exporting region in the developing country group, with a 10% share of world exports in 1990 (US$ 335 million) which increased to 21% (US$ 2,603 million) in 2009 (World Trade Organisation, 2011).

Box 5.4. Definition of Carbon Leakage

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 albeit 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 EU 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.

The consumption accounts presented in section 5.3.3.2 showed that between 1990 and 2000, global carbon dioxide emissions increased by about 10%, and by a further 29% between 2000 and 2008 (Le Quere et al., 2009), (Peters et al., 2011a). Over the full period, all of the growth in carbon dioxide emissions occurred in non-Annex B countries while CO2 emissions in Annex B countries stabilised. 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. 20% of the growth in CO2 emissions in non-Annex B countries can, through trade, be attributed to the increased demand for products by Annex B countries (Peters et al., 2011a).

In 1990, the global carbon dioxide emissions associated with exported products was 4.3 Gt CO2 (Peters et al., 2011a) This figure includes the carbon dioxide 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 Gt CO2, (average annual increase of 4.3%) (Peters et al., 2011a). Between 1990 and 2000 the growth in the embedded carbon dioxide emissions of products being traded grew by 10%. Between 2000 and 2008, carbon dioxide emissions embedded in trade grew by a further 26%, demonstrating a more recent and rapid increase (Peters et al., 2011a). In 2005, China accounted for 25% of the total global CO2 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., 2011b). In terms of total CO2 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., 2011b).

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” (Davis and Caldeira, 2010), (Rothman, 1998, 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 US (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., 2012). 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 greenhouse gas 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. (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 become the most skill-intensive sectors in developing countries (Zhu and Trefler, 2005; Meschi and Vivarelli, 2009) – which in turn can have 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 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 FDI (Foreign Direct Investment) 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, in order 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 US 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 Indian 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 tons 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 co-ordination 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, 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 Section 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[9] and the role of salience[10] (Fiske and Morling, 1996), priming (Richardson-Klavehn and Bjork, 1988), affect (Slovic et al., 2002), norms[11] (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.[12] Newell et al. (1999) provides evidence that the US room air conditioners energy efficiency gain since 1973, is for 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

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

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

[11] 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)

[12] 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 percent.

a supplement to property taxes (Ameli and Kammen, 2012). Various US and UK 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.[13] 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, 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 IPCC Fourth Assessment Report (AR4) acknowledged the importance of technological change as a driver for climate change mitigation (IPCC, 2007): p149-153; 218-219). 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 the energy intensity, e.g., (Fan and Xia; Sheinbaum et al., 2011; Wu et al., 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

[13] UK Cabinet Office (2012).

favour non-mitigation issues over reduction of greenhouse gas 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 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, 2010). 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, 2010). 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 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 EU ETS 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 effect. 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 disposal income that could be spent on an additional holiday. These could include substitution or income effect 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 generalise on their relative size and importance. Being context specific means that there is evidence of both negative rebound effects where further energy saving are 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 that 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, 2010; 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 generalisation is difficult, circumstances where rebounds are high is when energy costs forms 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 & 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 CO2 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 carbon dioxide–emitting devices, totalling to 500 (280 to 700) GtCO2 between 2010 and 2060, and an associated warming of 1.3°C (1.1° 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 1500km. 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 in order 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 US cities, 20%-30% of the land-area is used for roads, the corresponding share for major cities in Asia is 10% to 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 place 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 US 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 analysis can help to reduce undesired lock in effects with respect to the construction and operation of large physical infrastructure.

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).[14] 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

[14] Co-benefits and adverse side-effects describe co-effects without yet evaluating the net effect on overall social welfare. Please refer to the respective sections in the framing chapters as well as to the glossary in Annex I for concepts and definitions – particularly 2.4, 3.6.3, and 4.8.2.

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.

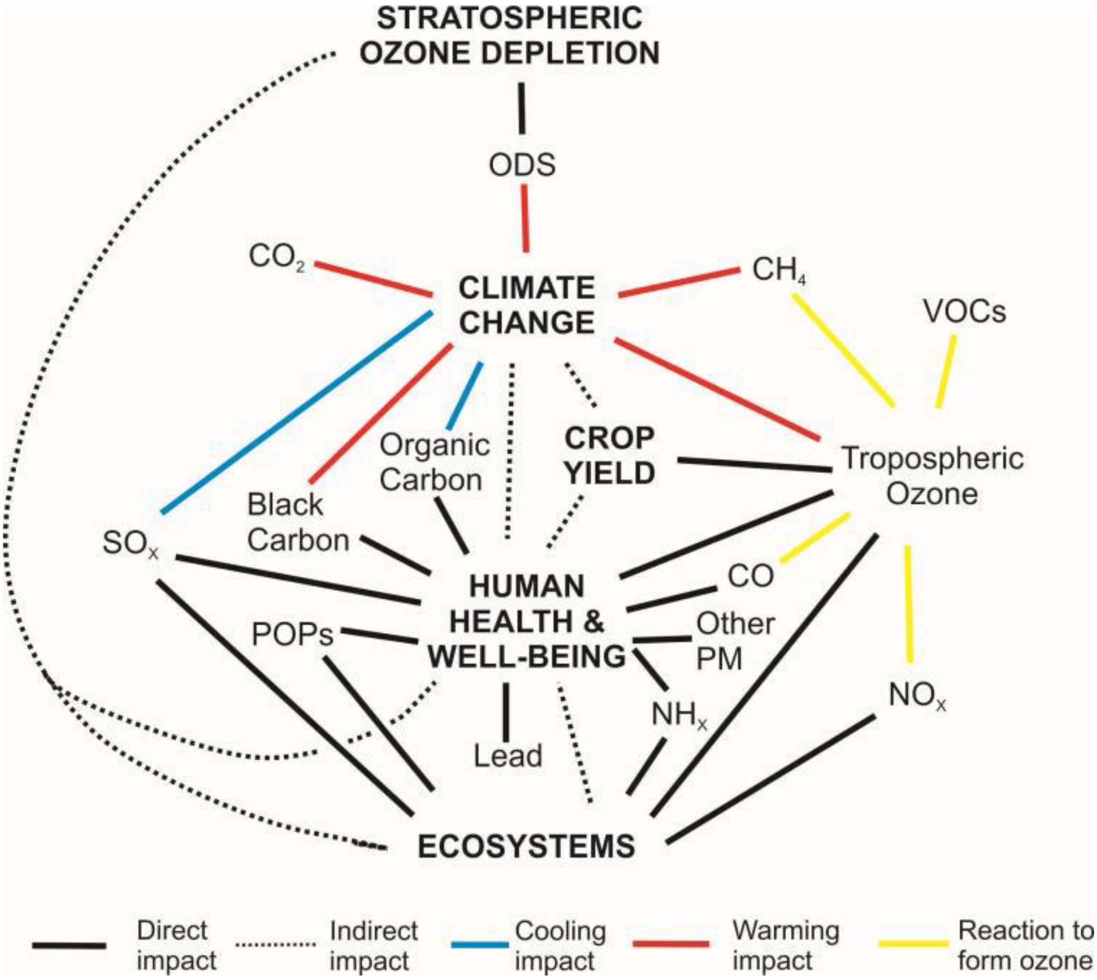


Figure 5.21. Impacts of and links between selected substances emitted to the atmosphere. Source: (UNEP, 2012)

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 (cf. Figure 7.8). Second, the policy costs of achieving air pollution objectives through direct control measures decrease as a result of climate 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.

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 380 USD/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 analyse 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 industrialising developing countries may follow the pattern of developed countries and adopt regulations to improve local air quality (and provide immediate local health and environmental benefits) before focusing upon climate policy (Nemet et al., 2010b; Klimont et al., 2013a) . 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, one cannot 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 (cf.(van Vuuren et al., 2006)).

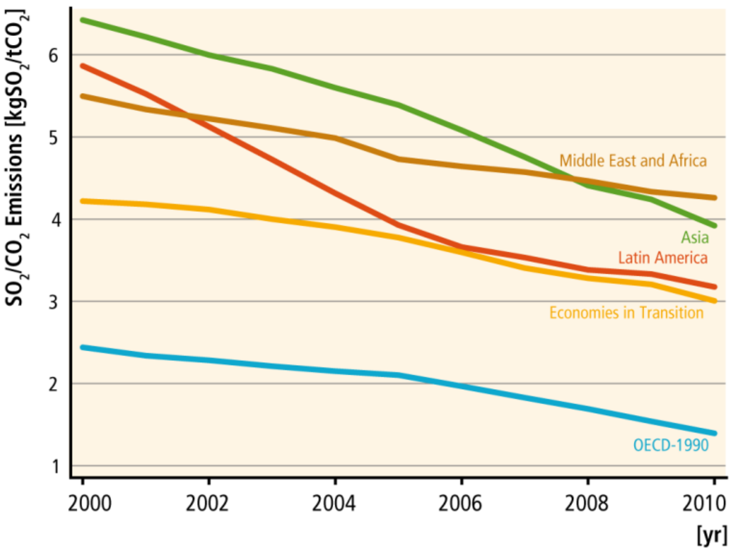


Figure 5.22. Trends for SO2 per CO2 emissions per region over 2000-2010. For CO2: territorial, excluding AFOLU and Waste: (Data Source: (JRC/PBL, 2012)). For SO2, data source: (Klimont et al., 2013b).

Box 5.5. The Chinese experience with co-benefits from a cross-sectoral perspective (see Sections 7.9, 8.7, 9.7, 10.9 and 11.8 for sectoral effects)

(Pan et al., 2011) estimate the amount of green jobs in three sectors (energy, transportation, and forestry) and the result suggest 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 ambitious metro-system plan that includes 660 kilometers by 2015 and another 340 kilometers during 2016–20, 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 2011–20 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). 12 out 17 mandatory targets in the 12th 5-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 5-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)

5.7.2 Adverse side-effects

There are also adverse side-effects associated with mitigation. A comprehensive discussion is given in 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 sulphur dioxide (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 CO2 emissions for a given electricity output (Pan, 2013). While carbon dioxide capture processes reduce SO_2 emissions at the same time, some CCS technologies would imply an increase in NOx and/or 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 NOx 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 complicated, 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 underestimated 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 [….fill in regional variation]

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 CO2 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 CO2 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 CO2 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 kgCO2eq/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 [add numbers] but per capita GHG emissions in OECD-1990 and EIT are still higher by a factor of 2 to 3 [add numbers]. 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 Latin American 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 Economies in Transition 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. Middle East and Africa also show 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 2 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 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 land-use change, fugitive emissions, and gas flaring. Formally estimating uncertainty for land-use change 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 greenhouse gases 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 Section 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. (5.3.2; 5.6; 5.7)
- **It is debated whether greenhouse gas emissions have an 'autonomous' tendency to stabilize at higher income levels** (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 (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** (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 (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 (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 (5.6.3). Finally, most if not all of the literature on co-benefits and risk trade-offs focuses on future potential gains. There is a total absence of empirical assessment about the role that co-benefits and adverse side-trade-offs have played, historically, in policy formation and GHG emissions (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 gigatonnes of GHG to over 50 gigatonnes (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 make 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).

References

Abrahamse W., L. Steg, C. Vlek, and T. Rothengatter (2005). A review of intervention studies aimed at household energy conservation. *Journal of Environmental Psychology* **25**, 273–291.

Ackerman F., M. Ishikawa, and M. Suga (2007). The carbon content of Japan-US trade. *Energy Policy* **35**, 4455–4462.

Ackerman K.V., and E.T. Sundquist (2008). Comparison of two US power-plant carbon dioxide emissions data sets. *Environmental Science & Technology* **42**, 5688–5693. (DOI: 10.1021/Es800221q). Available at: http://pubs.acs.org/doi/pdf/10.1021/es800221q.

Aghion P., A. Dechezleprêtre, D. Hemous, R. Martin, and J. Van Reenen (2012). *Carbon Taxes, Path Dependency and Directed Technical Change: Evidence from the Auto Industry*. London, UK. 76 pp.

Aghion P., and P. Howitt (2009). *The economics of growth*. MIT Press, Cambridge Mass., (ISBN: 9780262012638).

Aichele R., and G. Felbermayr (2012). Kyoto and the carbon footprint of nations. *J. Environmental Economics and Management* **63**, 336–354.

Aichele R., and G. Felbermayr (2013). Estimating the effects of Kyotot on bilateral trade flows using matching econometrics. *The World Economy*. (DOI: 0.1111/twec.12053).

Akerlof G.A. (1970). The Market for “Lemons”: Quality Uncertainty and the Market Mechanism. *The Quarterly Journal of Economics* **84**, 488–500. (DOI: 10.2307/1879431). Available at: http://www.jstor.org/stable/1879431.

Alam S.S., A. Khatibi, M.I.S. Ahmad, and H.B. Ismail (2008). Factors affecting e-commerce adoption in the electronic manufacturing companies in Malaysia. *International Journal of Commerce and Management* **17**, 125–139. (DOI: 10.1108/10569210710776503). Available at: http://www.emeraldinsight.com/journals.htm?articleid=1617216.

Allcott H. (2011). Social norms and energy conservation. *Journal of Public Economics* **95**, 1082–1095. (DOI: 10.1016/j.jpubeco.2011.03.003). Available at: http://www.sciencedirect.com/science/article/pii/S0047272711000478.

Allcott H., and M. Greenstone (2012). *Is there an energy efficiency gap?* National Bureau of Economic Research. Available at: http://www.nber.org/papers/w17766.

Allen R. (2009). *The British industrial revolution in global perspective*. Cambridge Univ. Press, Cambridge [u.a.], (ISBN: 9780521687850).

Ameli N., and D.M. Kammen (2012). Clean energy deployment: addressing financing cost. *Environmental Research Letters* **7**, 034008. (DOI: 10.1088/1748-9326/7/3/034008). Available at: http://iopscience.iop.org/1748-9326/7/3/034008.

Andres R.J., T.A. Boden, F.-M. Bréon, P. Ciais, S. Davis, D. Erickson, J.S. Gregg, A. Jacobson, G. Marland, J. Miller, T. Oda, J.G.J. Olivier, M.R. Raupach, P. Rayner, and K. Treanton (2012). A synthesis of carbon dioxide emissions from fossil-fuel combustion. *Biogeosciences* **9**, 1845–1871. (DOI: 10.5194/bg-9-1845-2012). Available at: http://www.biogeosciences.net/9/1845/2012/.

Andrew R.M., and G.P. Peters (2013). A Multi-Region Input–Output Table Based on the Global Trade Analysis Project Database (gtap-Mrio). *Economic Systems Research* **25**, 99–121. (DOI: 10.1080/09535314.2012.761953). Available at: http://www.tandfonline.com/doi/abs/10.1080/09535314.2012.761953.

Ang B.W. (2006). Monitoring changes in economy-wide energy efficiency: From energy-GDP ratio to composite efficiency index. *Energy Policy* **34**, 574–582. (DOI: 16/j.enpol.2005.11.011). Available at: http://www.sciencedirect.com/science/article/pii/S0301421505003125.

Angel D.P., S. Attoh, D. Kromm, J. Dehart, R. Slocum, and S. White (1998). The drivers of greenhouse gas emissions: what do we learn from local case studies? *Local environment* **3**, 263–277.

Arrow et al K. (1996). Economic Growth, Carrying Capacity, and the Environment. *Ecological Applications* **6**, 13–15. Available at: http://www.jstor.org/stable/2269539.

Axelrod R. (2006). Robert Axelrod. 1986. "An Evolutionary Approach to Norms." "American Political Science Review" 80 (December): 1095-1111. *The American Political Science Review* **100**, 682–683. (DOI: 10.2307/27644412). Available at: http://www.jstor.org/stable/27644412.

Ayres I., S. Raseman, and A. Shih (2009). *Evidence from Two Large Field Experiments that Peer Comparison Feedback Can Reduce Residential Energy Usage*. National Bureau of Economic Research. Available at: http://www.nber.org/papers/w15386.

Ayres R., and B. Warr (2009). *The economic growth engine : how energy and work drive material prosperity*. Edward Elgar, Cheltenham, (ISBN: 9781848441828).

Azar C., and H. Dowlatabadi (1999). A REVIEW OF TECHNICAL CHANGE IN ASSESSMENT OF CLIMATE POLICY. *Annual Review of Energy and the Environment* **24**, 513–544. (DOI: 10.1146/annurev.energy.24.1.513). Available at: http://www.annualreviews.org/doi/abs/10.1146/annurev.energy.24.1.513.

Babiker M.H. (2005). Climate change policy, market structure, and carbon leakage. *Journal of International Economics* **65**, 421–445. Available at: http://ideas.repec.org/a/eee/inecon/v65y2005i2p421-445.html.

De Backer K., and N. Yamano (2012). *International Comparative Evidence on Global Value Chains*. Organisation for Economic Co-operation and Development, Paris. Available at: http://www.oecd-ilibrary.org/content/workingpaper/5k9bb2vcwv5j-en.

Backer K.D., and N. Yamano (2007). *The Measurement of Globalisation using International Input-Output Tables*. OECD Publishing. Available at: http://ideas.repec.org/p/oec/stiaaa/2007-8-en.html.

Baiocchi G., and J.C. Minx (2010). Understanding Changes in the UK's CO2 Emissions: A Global Perspective. *Environ. Sci. Technol.* **44**, 1177–1184. (DOI: 10.1021/es902662h). Available at: http://dx.doi.org/10.1021/es902662h.

Ballantyne A.P., C.B. Alden, J.B. Miller, P.P. Tans, and J.W.C. White (2012). Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years. *Nature* **488**, 70–72. (DOI: 10.1038/nature11299). Available at: http://www.nature.com/nature/journal/v488/n7409/full/nature11299.html.

Ballantyne A.P., D.R. Greenwood, J.S.S. Damsté, A.Z. Csank, J.J. Eberle, and N. Rybczynski (2010). Significantly warmer Arctic surface temperatures during the Pliocene indicated by multiple independent proxies. *Geology* **38**, 603–606. (DOI: 10.1130/G30815.1). Available at: http://geology.gsapubs.org/content/38/7/603.

Ballesteros A., S. Nakhooda, J. Werksman, and K. Hurlburt (2010). Power, responsibility, and accountability: Rethinking the legitimacy of institutions for climate finance. *Climate law* **1**, 261–312. (DOI: 10.3233/CL-2010-013). Available at: http://dx.doi.org/10.3233/CL-2010-013.

Banister D. (2011a). The trilogy of distance, speed and time. *Journal of Transport Geography* **19**, 950–959. (DOI: 10.1016/j.jtrangeo.2010.12.004). Available at: http://www.sciencedirect.com/science/article/pii/S0966692310001973.

Banister D. (2011b). Cities, mobility and climate change. *Journal of Transport Geography* **19**, 1538–1546. (DOI: 10.1016/j.jtrangeo.2011.03.009). Available at: http://www.sciencedirect.com/science/article/pii/S0966692311001244.

Banister D., and M. Thurstain-Goodwin (2011). Quantification of the non-transport benefits resulting from rail investment. *Journal of Transport Geography* **19**, 212–223. (DOI: 10.1016/j.jtrangeo.2010.05.001). Available at: http://www.sciencedirect.com/science/article/pii/S0966692310000712.

Barker T., A. Alharthi, M. Amann, L. Cifuentes, J. Drexhage, R. Duan, O. Edenhofer, B. Flannery, M. Grubb, M. Hoogwijk, F.I. Ibitoye, C.J. Jepma, W.A. Pizer, and K. Yamaji (2008). Mitigation from a cross-sectoral perspective. In: *Climate Change 2007: Mitigation; Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer, (eds.), Cambridge University Press, Cambridge, United Kingdom.

Barker T., P. Ekins, and T. Foxon (2007). The macro-economic rebound effect and the UK economy. *Energy Policy* **35**, 4935–4946. (DOI: 10.1016/j.enpol.2007.04.009). Available at: http://www.sciencedirect.com/science/article/pii/S0301421507001565.

Barrett J., K. Roelich, T. Wiedmann, J. Minx, and A. Owen (2013). Learning from the Past, Evaluating Futures ? Sustainable Consumption and Production Evidence and Applications in the UK. *Environment and Planning (forthcoming)*.

Becker L.J., C. Seligman, R.H. Fazio, and J.M. Darley (1981). Relating Attitudes to Residential Energy Use. *Environment and Behavior* **13**, 590–609. (DOI: 10.1177/0013916581135004). Available at: http://eab.sagepub.com/content/13/5/590.

Bednar-Friedl B., T. Schinko, and K.W. Steininger (2012). The relevance of process emissions for carbon leakage: A comparison of unilateral climate policy options with and without border carbon adjustment. *Energy Economics* **34, Supplement 2**, S168–S180. (DOI: 10.1016/j.eneco.2012.08.038).

Bell M.L., D.L. Davis, L.A. Cifuentes, A.J. Krupnick, R.D. Morgenstern, and G.D. Thurston (2008). Ancillary human health benefits of improved air quality resulting from climate change mitigation. *Environmental Health* **7**, 41. (DOI: 10.1186/1476-069X-7-41). Available at: http://www.ehjournal.net/content/7/1/41/abstract.

Bentzen J. (2004). Estimating the rebound effect in US manufacturing energy consumption. *Energy Economics* **26**, 123–134. (DOI: 10.1016/S0140-9883(03)00047-1). Available at: http://www.sciencedirect.com/science/article/pii/S0140988303000471.

Van den Bergh J.C.J.M. (2010). Energy Conservation More Effective With Rebound Policy. *Environmental and Resource Economics* **48**, 43–58. (DOI: 10.1007/s10640-010-9396-z). Available at: http://www.springerlink.com/content/n2n58h744078x2gp/.

Berkhout P.H.G., J.C. Muskens, and J. W. Velthuijsen (2000). Defining the rebound effect. *Energy Policy* **28**, 425–432. (DOI: 10.1016/S0301-4215(00)00022-7). Available at: http://www.sciencedirect.com/science/article/pii/S0301421500000227.

Biel A., and L.J.J. Lundqvist (2012). *From Kyoto to the Town Hall: Making International and National Climate Policy Work at the Local Level*. Routledge, 152 pp., (ISBN: 9781136565182).

Black C., A. Collins, and M. Snell (2001). Encouraging Walking: The Case of Journey-to-school Trips in Compact Urban Areas. *Urban Studies* **38**, 1121–1141. (DOI: 10.1080/00420980124102). Available at: http://usj.sagepub.com/content/38/7/1121.

Blodgett J., and L. Parker (2010). Greenhouse Gas Emission Drivers: Population, Economic Development and Growth, and Energy Use. CRS Report for Congress. Available at: http://www.cnie.org/NLE/CRSreports/10Apr/RL33970.pdf.

Blundell R., R. Griffith, and J. van Reenen (1999). Market Share, Market Value and Innovation in a Panel of British Manufacturing Firms. *Review of Economic Studies* **66**, 529–554.

Boden T.A., G. Marland, and R.J. Andres (2012). *Global, Regional, and National Fossil-Fuel CO2 Emissions.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Boehringer C., T. Rutherford, and E. Balistreri (2012). The Role of Border Carbon Adjustment in Unilateral Climate Policy, Insights From An EMF Model Comparison. *Energy Economics (forthcoming)*.

Bogner J., R. Pipatti, S. Hashimoto, C. Diaz, K. Mareckova, L. Diaz, P. Kjeldsen, S. Monni, A. Faaij, Q. Gao, T. Zhang, M.A. Ahmed, R.T.M. Sutamihardja, and R. Gregory (2008). Mitigation of global greenhouse gas emissions from waste: conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. Working Group III (Mitigation). *Waste Management & Research* **26**, 11–32. (DOI: 10.1177/0734242X07088433). Available at: http://wmr.sagepub.com/content/26/1/11.

Bolla V., and V. Pendolovska (2011). Driving forces behind EU-27 greenhouse gas emissions over the decade 1999-2008. Eurostat. Available at: http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-SF-11-010/EN/KS-SF-11-010-EN.PDF.

Bollen J., B. Guay, S. Jamet, and J. Corfee-Morlot (2009). *Co-Benefits of Climate Change Mitigation Policies: Literature Review and New Results*. OECD Publishing. Available at: http://ideas.repec.org/p/oec/ecoaaa/693-en.html.

Bond T.C., E. Bhardwaj, R. Dong, R. Jogani, S.K. Jung, C. Roden, D.G. Streets, and N.M. Trautmann (2007). Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850-2000. *Global Biogeochemical Cycles* **21**. (DOI: 10.1029/2006gb002840). Available at: http://onlinelibrary.wiley.com/doi/10.1029/2006GB002840/pdf.

Bond T.C., S.J. Doherty, D.W. Fahey, P.M. Forster, T. Berntsen, B.J. DeAngelo, M.G. Flanner, S. Ghan, B. Karcher, D. Koch, S. Kinne, Y. Kondou, P.K. Quinn, M.C. Sarofim, M.G. Schultz, C. Venkataraman, H. Zhang, S. Zhang, N. Bellouin, S.K. Guttikunda, P.K. Hopke, M.Z. Jacobson, J.W. Kaiser, Z. Klimont, U. Lohmann, J.P. Schwarz, D. Shindell, T. Storelvmo, S.G. Warren, and C.S.

Zender (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *J. Geophys. Res.*

Bond T.C., D.G. Streets, K.F. Yarber, S.M. Nelson, J.-H. Woo, and Z. Klimont (2004). A technology-based global inventory of black and organic carbon emissions from combustion. *Journal of Geophysical Research* **109**, D14203.

Bosetti V., and E. Verdolini (2012). Heterogeneous Firms Trading In Ideas: An Application to Energy Technologies. Available at: http://graduateinstitute.ch/files/live/sites/iheid/files/sites/cies/shared/publications/InnovationWorkshop/VB_EV_Heterogenous_Geneva.pdf.

Boucher O., and D. Randall (2013). *Chapter 7: Clouds and Aerosols*. WORKING GROUP I CONTRIBUTION TO THE IPCC FIFTH ASSESSMENT REPORT CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS.

BP (2013). *BP Statistical Review of World Energy*. BP. Available at: http://www.bp.com/content/dam/bp/pdf/statistical-review/statistical_review_of_world_energy_2013.pdf.

Brock W., and M. Taylor (2010). The Green Solow model. *Journal of Economic Growth* **15**, 127–153. (DOI: 10.1007/s10887-010-9051-0). Available at: http://www.springerlink.com/content/m026226r432312m4/abstract/.

Bruckner T., O. Edenhofer, H.S. Matthews, M. Haller, M. Lüken, N. Bauer, and N. Nakicenovic (2010). Robust options for decarbonization. In: *Global Sustainability: A Nobel Cause*. H.-J. Schellnhuber, M. Molina, N. Stern, V. Huber, S. Kadner, (eds.), Cambridge University Press, pp.189–204, .

Bryan J.E., P.L. Shearman, G.P. Asner, D.E. Knapp, G. Aoro, and B. Lokes (2013). Extreme differences in forest degradation in Borneo: comparing practices in Sarawak, Sabah, and Brunei. *PloS one* **8**, e69679. (DOI: 10.1371/journal.pone.0069679). Available at: http://www.plosone.org/article/fetchObject.action?uri=info%3Adoi%2F10.1371%2Fjournal.pone.0069679&representation=PDF.

Burtraw D., and D. Evans (2003). *The Evolution of NOx Control Policy for Coal-Fired Power Plants in the United States*. Resources For the Future. Available at: http://ideas.repec.org/p/rff/dpaper/dp-03-23.html.

Cai H., Y. Chen, and H. Fang (2009). Observational Learning: Evidence from a Randomized Natural Field Experiment. *American Economic Review* **99**, 864–82. Available at: http://ideas.repec.org/a/aea/aecrev/v99y2009i3p864-82.html.

Caldeira K., and S.J. Davis (2011). Accounting for carbon dioxide emissions: A matter of time. *Proceedings of the National Academy of Sciences* **108**, 8533 –8534. (DOI: 10.1073/pnas.1106517108). Available at: http://www.pnas.org/content/108/21/8533.short.

Calel R., and A. Dechezleprêtre (2012). *Environmental Policy and Directed Technological Change: Evidence from the European carbon market*. Centre for Climate Change Economics and Policy / Grantham Research Institute on Climate Change and the Environment, London, UK. 35 pp. Available at: http://www.lse.ac.uk/GranthamInstitute/publications/WorkingPapers/Papers/70-79/WP75_environmental-policy-european-carbon-market.pdf.

Carley S. (2011a). Historical analysis of U.S. electricity markets: Reassessing carbon lock-in. *Energy Policy* **39**, 720–732. (DOI: 10.1016/j.enpol.2010.10.045). Available at: http://www.sciencedirect.com/science/article/pii/S0301421510007962.

Carley S. (2011b). Historical analysis of U.S. electricity markets: Reassessing carbon lock-in. *Energy Policy* **39**, 720–732. (DOI: 10.1016/j.enpol.2010.10.045). Available at: http://www.sciencedirect.com/science/article/pii/S0301421510007962.

Carson R.T. (2010). The Environmental Kuznets Curve: Seeking Empirical Regularity and Theoretical Structure. *Review of Environmental Economics and Policy* **4**, 3 –23. (DOI: 10.1093/reep/rep021). Available at: http://reep.oxfordjournals.org/content/4/1/3.abstract.

Caselli F. (2005). Chapter 9 Accounting for Cross-Country Income Differences. In: *Handbook of Economic Growth*. P. Aghion, S. Durlauf, (eds.), Elsevier, pp.679–741, (ISBN: 978-0-444-52041-8). Available at: http://linkinghub.elsevier.com/retrieve/pii/S1574068405010099.

Chakravarty D., S. Dasgupta, and J. Roy (2013). Rebound effect: how much to worry? *Current Opinion in Environmental Sustainability* **5**, 216–228. (DOI: 10.1016/j.cosust.2013.03.001). Available at: http://www.sciencedirect.com/science/article/pii/S1877343513000134.

Change I.P. on C., and O. for E.C.-O. and Development (2000). *Ancillary Benefits and Costs of Greenhouse Gas Mitigation: Proceedings of an IPCC Co-Sponsored Workshop, Held on 27-29 March 2000, in Washington*. OECD Publishing, 584 pp., (ISBN: 9789264185425).

Chavez A., and A. Ramaswami (2013). Articulating a trans-boundary infrastructure supply chain greenhouse gas emission footprint for cities: Mathematical relationships and policy relevance. *Energy Policy* **54**, 376–384. (DOI: 10.1016/j.enpol.2012.10.037).

Chawla L. (1998). Significant Life Experiences Revisited: A Review of Research on Sources of Environmental Sensitivity. *The Journal of Environmental Education* **29**, 11–21. (DOI: 10.1080/00958969809599114). Available at: http://www.tandfonline.com/doi/abs/10.1080/00958969809599114.

Chawla L. (1999). Life Paths Into Effective Environmental Action. *The Journal of Environmental Education* **31**, 15–26. (DOI: 10.1080/00958969909598628). Available at: http://www.tandfonline.com/doi/abs/10.1080/00958969909598628.

Chetty R., A. Looney, and K. Kroft (2009). *Salience and taxation: theory and evidence*. Board of Governors of the Federal Reserve System (U.S.). Available at: http://ideas.repec.org/p/fip/fedgfe/2009-11.html.

Chitnis M., and L.C. Hunt (2012). What drives the change in UK household energy expenditure and associated CO2 emissions? Implication and forecast to 2020. *Applied Energy* **94**, 202–214. Available at: http://ideas.repec.org/a/eee/appene/v94y2012icp202-214.html.

Ciais P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J. Galloway, M. Heimann, C. Jones, C. Le Quéré, R. Myneni, S. Piao, and P. Thornton (2013). Carbon and Other Biochemical Cycles. In: *IPCC Working Group 1 Fifth Assessment Report*.

Cialdini R.B., N.J. Goldstein, and V. Griskevicius (2006). SOCIAL NORMS. Available at: http://143.236.32.231/cnr-ap/UWEXLAKES/Documents/ecology/shoreland/marketing/social_norms_griskevicius.pdf.

Cian D., Enrica, M. Schymura, E. Verdolini, and S. Voigt (2013). *Energy Intensity Developments in 40 Major Economies: Structural Change or Technology Improvement?* Social Science Research Network, Rochester, NY. Available at: http://papers.ssrn.com/abstract=2264708.

Cloete B., and F. Venter (2012). Carbon lock-in: Infrastructure Investment Research Piece. NPC low carbon economy work programme. Available at: http://www.dnaeconomics.com/assets/Usematthew/Infrastructure_Lock_In_Paper_June_2012_final2.pdf.

Coe D., and E. Helpman (1995). International R&D spillovers. *European Economic Review* **39**, 859–887.

Coller M., and M.B. Williams (1999). Eliciting individual discount rates. *Experimental Economics* **2**, 107–127. (DOI: 10.1007/BF01673482). Available at: http://link.springer.com/article/10.1007/BF01673482.

Cox M., M.A. Brown, and X. Sun (2013). Energy benchmarking of commercial buildings: a low-cost pathway toward urban sustainability. *Environmental Research Letters* **8**, 035018. (DOI: 10.1088/1748-9326/8/3/035018). Available at: http://iopscience.iop.org/1748-9326/8/3/035018.

Dalton M., B. O'Neill, A. Prskawetz, L. Jiang, and J. Pitkin (2008). Population aging and future carbon emissions in the United States. *Energy Economics* **30**, 642–675. (DOI: 10.1016/j.eneco.2006.07.002). Available at: http://www.sciencedirect.com/science/article/pii/S0140988306000892.

Dauvergne P., and K.J. Neville (2010). Forests, food, and fuel in the tropics: the uneven social and ecological consequences of the emerging political economy of biofuels. *The Journal of peasant studies* **37**, 631–660. (DOI: 10.1080/03066150.2010.512451).

Davidsdottir B., and M. Fisher (2011). The odd couple: The relationship between state economic performance and carbon emissions economic intensity. *Energy Policy* **39**, 4551–4562. (DOI: 10.1016/j.enpol.2011.04.030). Available at: http://www.sciencedirect.com/science/article/pii/S0301421511003132.

Davidson E.A. (2009). The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geoscience* **2**, 659–662. (DOI: 10.1038/ngeo608). Available at: http://www.nature.com/ngeo/journal/v2/n9/abs/ngeo608.html.

Davies J., M. Grant, J. Venezia, and J. Aamidor (2007). US Transportation Sector Greenhouse Gas Emissions: Trends, Uncertainties and Methodological Improvements. In Proceedings: *TRB 2007 Annual Meeting*.2007, .Available at: http://www.uvm.edu/~transctr/pdf/email/Davies%20Article.pdf.

Davis S.J., and K. Caldeira (2010). Consumption-based accounting of CO2 emissions. *Proceedings of the National Academy of Sciences* **107**, 5687–5692. (DOI: 10.1073/pnas.0906974107). Available at: http://www.pnas.org/gca?gca=pnas%3B107%2F12%2F5687&allch=&submit=Go.

Davis S.J., K. Caldeira, and H.D. Matthews (2010). Future CO2 Emissions and Climate Change from Existing Energy Infrastructure. *Science* **329**, 1330–1333. (DOI: 10.1126/science.1188566). Available at: http://www.sciencemag.org/content/329/5997/1330.

Dechezleprêtre A., M. Glanchant, I. Hascic, N. Johnstone, and Y. Meniere (2008). *Invention and Transfer of Climate Change Mitigation Technologies on a Global Scale: A Study Drawing on Patent*

Data. MPT, Cerna and AFD, France. 48 pp. Available at: http://www.cerna.ensmp.fr/images/stories/file/Poznan/final_report_090112.pdf.

DEFRA (2012). *2012 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors*. Department for Environment Food and Rural Affairs (DEFRA). Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69568/pb13792-emission-factor-methodology-paper-120706.pdf.

DellaVigna S. (2009). Psychology and Economics: Evidence from the Field. *Journal of Economic Literature* **47**, 315–72. Available at: http://ideas.repec.org/a/aea/jeclit/v47y2009i2p315-72.html.

Dhakal S. (2009). Urban energy use and carbon emissions from cities in China and policy implications. *Energy Policy* **37**, 4208–4219. (DOI: doi: 10.1016/j.enpol.2009.05.020). Available at: http://www.sciencedirect.com/science/article/pii/S0301421509003413.

Dietz T., and E.A. Rosa (1997). Effects of population and affluence on CO2 emissions. *Proceedings of the National Academy of Sciences* **94**, 175 –179. Available at: http://www.pnas.org/content/94/1/175.abstract.

Dietzenbacher E., and A.R. Hoen (1998). Deflation of Input-Output Tables from the User's Point of View: A Heuristic Approach. *Review of Income and Wealth* **44**, 111–22. Available at: http://ideas.repec.org/a/bla/revinw/v44y1998i1p111-22.html.

Dietzenbacher E., and H.-J. Wagener (1999). Prices in the Two Germanies. *Journal of Comparative Economics* **27**, 131–149. Available at: http://ideas.repec.org/a/eee/jcecon/v27y1999i1p131-149.html.

Dittrich M., and S. Bringezu (2010). The physical dimension of international trade: Part 1: Direct global flows between 1962 and 2005. *Ecological Economics* **69**, 1838–1847.

Dolan P., M. Hallsworth, D. Halpern, D. King, R. Metcalfe, and I. Vlaev (2012). Influencing behaviour: The mindspace way. *Journal of Economic Psychology* **33**, 264–277. (DOI: 10.1016/j.joep.2011.10.009). Available at: http://www.sciencedirect.com/science/article/pii/S0167487011001668.

Durlauf S., P. Johnson, and J. Temple (2005). Chapter 8 Growth Econometrics. In: *Handbook of Economic Growth*. P. Aghion, S. Durlauf, (eds.), Elsevier, pp.555–677, (ISBN: 978-0-444-52041-8). Available at: http://linkinghub.elsevier.com/retrieve/pii/S1574068405010087.

Dwyer W.O., and F.C. Leeming (1993). Critical review of Behavioral interventions to preserve the environment research since 1980. *Environment and Behavior*.

Eberhardt M., and F. Teal (2011). Econometrics for Grumblers: A New Look at the Literature on Cross-country Growth Empirics. *Journal of Economic Surveys* **25**, 109–155. (DOI: 10.1111/j.1467-6419.2010.00624.x). Available at: http://onlinelibrary.wiley.com/doi/10.1111/j.1467-6419.2010.00624.x/abstract.

Edenhofer O., K. Seyboth, F. Creutzig, and S. Schlömer (2013). On the Sustainability of Renewable Energy Sources. *Annual Review of Environment and Resources* **38**, 169–200. (DOI: 10.1146/annurev-environ-051012-145344).

Edwards S. (2001). Openness, Productivity and Growth: What Do We Really Know? *The Economic Journal* **108**, 383–398.

Ehrlich P.R., and J.P. Holdren (1971). Impact of Population Growth. *Science* **171**, 1212–1217. (DOI: 10.1126/science.171.3977.1212). Available at: http://www.sciencemag.org/content/171/3977/1212.

Elzen M.G.J., J.G.J. Olivier, N. Höhne, and G. Janssens-Maenhout (2013). Countries' contributions to climate change: effect of accounting for all greenhouse gases, recent trends, basic needs and technological progress. *Climatic Change*. (DOI: 10.1007/s10584-013-0865-6).

Erb K.-H., H. Haberl, and C. Plutzar (2012). Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. *Energy Policy* **47**, 260–269. (DOI: 10.1016/j.enpol.2012.04.066). Available at: http://www.sciencedirect.com/science/article/pii/S0301421512003710.

Etheridge D.M., L.P. Steele, R.J. Francey, and R.L. Langenfelds (2002). *Historical CH4 Records Since About 1000 A.D. From Ice Core Data.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy.

Etheridge D.M., L.P. Steele, R.L. Langenfelds, R.J. Francey, J.-M. Barnola, and V.I. Morgan (1996). Natural and anthropogenic changes in atmospheric CO2 over the last 1000 years from air in Antarctic ice and firn. *Journal of Geophysical Research: Atmospheres* **101**, 4115–4128. (DOI: 10.1029/95JD03410). Available at: http://onlinelibrary.wiley.com/doi/10.1029/95JD03410/abstract.

European Environment Agency (2009). *Greenhouse gas emission trends and projections in Europe 2009*. EEA – European Environment Agency. Available at: http://www.eea.europa.eu/publications/eea_report_2009_9.

Ewing M., and S. Msangi (2009). Biofuels production in developing countries: assessing tradeoffs in welfare and food security. *Environmental Science & Policy* **12**, 520–528. (DOI: 10.1016/j.envsci.2008.10.002). Available at: http://www.sciencedirect.com/science/article/pii/S1462901108001123.

Exley S., and I. Christie (2002). Off the Buses? In: *British Social Attitudes: The 19th Report British social attitudes: The 19th report*. SAGE Publications Ltd, 1 Oliver's Yard, 55 City Road, London EC1Y 1SP United Kingdom pp.1–26, (ISBN: 9780761974543, 9781849208659). Available at: http://knowledge.sagepub.com/cite/british-social-attitudes-19th$002fn1.xml;jsessionid=1AF1FD7B8BE21B58CE30650BE38B756E?nojs=true.

Eyring V., I.S.A. Isaksen, T. Berntsen, W.J. Collins, J.J. Corbett, O. Endresen, R.G. Grainger, J. Moldanova, H. Schlager, and D.S. Stevenson (2010). Transport impacts on atmosphere and climate: Shipping. *Atmospheric Environment* **44**, 4735–4771. (DOI: 10.1016/j.atmosenv.2009.04.059). Available at: http://www.sciencedirect.com/science/article/pii/S1352231009003379.

Faber J., A. Schroten, M. Bles, M. Sevenster, and A. Markowska (2012). *Behavioural Climate Change Mitigation Options and Their Appropriate Inclusion in Quantitative Longer Term Policy Scenarios*. Available at: http://ec.europa.eu/clima/policies/roadmap/docs/main_report_en.pdf.

Fan Y., L.-C. Liu, G. Wu, and Y.-M. Wei (2006). Analyzing impact factors of CO2 emissions using the STIRPAT model. *Environmental Impact Assessment Review* **26**, 377–395. (DOI: doi: 10.1016/j.eiar.2005.11.007). Available at: http://www.sciencedirect.com/science/article/pii/S0195925506000059.

Fan Y., and Y. Xia Exploring energy consumption and demand in China. *Energy* **40**, 23–30.

FAOSTAT *Food and Agriculture Organization of the United Nations*. Available at: faostat.fao.org.

Ferraro P.J., and M.K. Price (2011). *Using Non-Pecuniary Strategies to Influence Behavior: Evidence from a Large Scale Field Experiment*. National Bureau of Economic Research. Available at: http://www.nber.org/papers/w17189.

Filippini M., and L.C. Hunt (2011). Energy Demand and Energy Efficiency in the OECD Countries: A Stochastic Demand Frontier Approach. *The Energy Journal* **32**. (DOI: 10.5547/ISSN0195-6574-EJ-Vol32-No2-3). Available at: http://www.iaee.org/en/publications/ejarticle.aspx?id=2417.

Fisher B.S., and N. Nakicenovic (2008). Issues related to mitigation in the long term context. In: *Climate Change 2007: Mitigation; Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer, (eds.), Cambridge University Press, .

Fisher-Vanden K., and M.S. Ho (2010). Technology, development, and the environment. *Journal of Environmental Economics and Management* **59**, 94–108. (DOI: 10.1016/j.jeem.2009.08.002). Available at: http://www.sciencedirect.com/science/article/pii/S0095069609000849.

Fiske S.T., and B. Morling (1996). Stereotyping as a function of personal control motives and capacity constraints: The odd couple of power and anxiety. Handbook of motivation and cognition. In: *Handbook of motivation and cognition, Vol. 3: The interpersonal context*. R.M. Sorrentino, E.T. Higgins, (eds.), Guilford Press, New York, NY, US pp.322–346, (ISBN: 1-57230-052-3 (Hardcover)).

Foley J.A., R. DeFries, G.P. Asner, C. Barford, G. Bonan, S.R. Carpenter, F.S. Chapin, M.T. Coe, G.C. Daily, H.K. Gibbs, J.H. Helkowski, T. Holloway, E.A. Howard, C.J. Kucharik, C. Monfreda, J.A. Patz, I.C. Prentice, N. Ramankutty, and P. Snyder (2005). Global Consequences of Land Use. *Science* **309**, 570–574.

Fouquet R. (2008). *Heat, Power and Light: Revolutions in Energy Services*. Edward Elgar, (ISBN: 978 1 84542 660 6).

Fouquet R. (2012). Trends in income and price elasticities of transport demand (1850–2010). *Energy Policy* **50**, 62–71. (DOI: 10.1016/j.enpol.2012.03.001). Available at: http://www.sciencedirect.com/science/article/pii/S0301421512002066.

Fredriksson P.G., H.R.J. Vollebergh, and E. Dijkgraaf (2004). Corruption and Energy Efficiency in OECD Countries: Theory and Evidence. *Journal of Environmental Economics and Management* **47**, 207–231. Available at: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=703969.

Freight Vision (2009). *Freight Transport foresight 2050. Transport related emission trends 2000-2050: Deliverable 4.4*. 7th Research Framework Program, DG TREN. Available at: http://www.freightvision.eu/files/D4.4.pdf.

Freire González J. (2010). Empirical evidence of direct rebound effect in Catalonia. *Energy Policy* **38**, 2309–2314. (DOI: 10.1016/j.enpol.2009.12.018). Available at: http://www.sciencedirect.com/science/article/pii/S0301421509009744.

Frey B.S., and S. Meier (2004). Pro-social behavior in a natural setting. *Journal of Economic Behavior & Organization* **54**, 65–88. Available at: http://ideas.repec.org/a/eee/jeborg/v54y2004i1p65-88.html.

Frondel M., N. Ritter, and C. Vance (2012). Heterogeneity in the rebound effect: Further evidence for Germany. *Energy Economics* **34**, 461–467. (DOI: 10.1016/j.eneco.2011.10.016). Available at: http://www.sciencedirect.com/science/article/pii/S0140988311002660.

Fuhrer U., F.G. Kaiser, J. Seiler, and M. Maggi (1995). From social representations to environmental concern: the influence of face to face versus mediated communication. *Fuhrer U (ed.) Ökologisches Handeln als sozialer Prozess*, 61–75.

Gales B., A. Kander, P. Malanima, and M. Rubio (2007). North Versus South: Energy Transition and Energy Intensity in Europe Over 200 Years. *European Review of Economic History* **11**, 219–253. (DOI: 10.1017/S1361491607001967).

Gallagher K.P. (2009). Economic Globalization and the Environment. *Annual Review of Environment and Resources* **34**, 279–304. (DOI: 10.1146/annurev.environ.33.021407.092325). Available at: http://www.annualreviews.org/doi/abs/10.1146/annurev.environ.33.021407.092325.

Gardner G.T., and P.C. Stern (1996). *Environmental problems and human behavior*. Allyn and Bacon, 392 pp., (ISBN: 9780205156054).

GEA (2012). *Global Energy Assessment, Toward a More Sustainable Future*. Cambridge University Press, 1885 pp., (ISBN: 9780521182935).

Geist H., and E. Lambin (2002). Proximate causes and underlying driving forces of tropical deforestation. *BioScience* **52**, 143–150. Available at: http://dx.doi.org/10.1641/0006-3568(2002)052%5B0143:PCAUDF%5D2.0.CO;2.

Geller E.. (2002). The challenge of increasing proenvironmental behavior. *Handbook of environmental psychology*.

Ghosh P. (2006). A partnership for a decarbonised energy future. *World affairs the Journal of International Issues* **10**.

Gilli P.V., N. Nakicenovic, A. Grubler, and F.L. Bodda (1990). *Technischer Fortschritt, Strukturwandel und Effizienz der Energieanwendung: Trends weltweit und in Österreich*. Österreichische Elektrizitätswirtschafts-AG Verbundgesellschaft, 331 pp.

Gillingham K., M.J. Kotchen, D.S. Rapson, and G. Wagner (2013). Energy policy: The rebound effect is overplayed. *Nature* **493**, 475–476. (DOI: 10.1038/493475a). Available at: http://www.nature.com/nature/journal/v493/n7433/full/493475a.html.

Gillingham K., R.G. Newell, and K. Palmer (2009). Energy Efficiency Economics and Policy. *Annual Review of Resource Economics* **1**, 597–620. (DOI: 10.1146/annurev.resource.102308.124234). Available at: http://econpapers.repec.org/article/anrreseco/v_3a1_3ay_3a2009_3ap_3a597-620.htm.

Goldstein N.J., R.B. Cialdini, and V. Griskevicius (2008). A Room with a Viewpoint: Using Social Norms to Motivate Environmental Conservation in Hotels. *Journal of Consumer Research* **35**, 472–482. Available at: http://ideas.repec.org/a/ucp/jconrs/v35y2008i3p472-482.html.

Golub A., T. Hertel, and B. Sohngen (2008). *Land use modeling in recursively-dynamic GTAP framework*. Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University. Available at: https://www.gtap.agecon.purdue.edu/resources/download/3679.pdf.

Greene D.L. (2011). Uncertainty, loss aversion, and markets for energy efficiency. *Energy Economics* **33**, 608–616. (DOI: 10.1016/j.eneco.2010.08.009). Available at: http://www.sciencedirect.com/science/article/pii/S0140988310001301.

Greening L.A., D.L. Greene, and C. Difiglio (2000). Energy efficiency and consumption -- the rebound effect -- a survey. *Energy Policy* **28**, 389–401. Available at: http://econpapers.repec.org/article/eeeenepol/v_3a28_3ay_3a2000_3ai_3a6-7_3ap_3a389-401.htm.

Gregg J.S., R.J. Andres, and G. Marland (2008). China: Emissions pattern of the world leader in CO2 emissions from fossil fuel consumption and cement production. *Geophysical Research Letters* **35**. (DOI: 10.1029/2007gl032887). Available at: http://onlinelibrary.wiley.com/doi/10.1029/2007GL032887/pdf.

Grossman G.M., and A.B. Krueger (1994). *Economic Growth and the Environment*. National Bureau of Economic Research. Available at: http://www.nber.org/papers/w4634.

Grubb M., J.C. Hourcade, and K. Neuhoff (2013). *Planetary economics: energy, climate change and the three domains of sustainable development*. (ISBN: 9780415518826 0415518822).

Grubler A. (2008). Energy Transitions. *Encyclopedia of Earth*. Environmental Information Coalition, National Council for Science and the Environment, Washington, DC. Available at: http://www.eoearth.org/article/Energy_transitions.

Grübler A., T.B. Johansson, L. Mundaca, N. Nakicenovic, S. Pachauri, K. Riahi, H.H. Rogner, and L. Strupeit (2012). Chapter 1 - Energy primer. In: *Global Energy Assessment*. IIASA and Cambridge University Press, Cambridge, UK(ISBN: 9781107005198).

Grübler A., and N. Nakićenović (1996). Decarbonizing the global energy system. *Technological Forecasting and Social Change* **53**, 97–110. (DOI: 10.1016/0040-1625(96)00049-2). Available at: http://www.sciencedirect.com/science/article/pii/0040162596000492.

Grübler A., N. Nakicenovic, and D.G. Victor (1999). Modeling technological change: implications for the global environment. *Annual Review of Energy and the Environment* **24**, 545–569. Available at: http://www.annualreviews.org/doi/abs/10.1146/annurev.energy.24.1.545.

Guan D.B., Z. Liu, Y. Geng, S. Lindner, and K. Hubacek (2012). The gigatonne gap in China's carbon dioxide inventories. *Nature Climate Change* **2**, 672–675. (DOI: 10.1038/Nclimate1560). Available at: http://www.nature.com/nclimate/journal/v2/n9/full/nclimate1560.html.

Gustavsson J., C. Cederberg, U. Sonesson, R. van Otterdijk, and A. Meybeck (2011). *Global food losses and food waste-FAO report*. Food and Agriculture Organization (FAO) of the United Nations. Available at: http://www.2degreesnetwork.com/preview/resource/global-food-losses-and-food-waste-fao-report/.

De Haan M. (2001). A Structural Decomposition Analysis of Pollution in the Netherlands. *Economic Systems Research* **13**, 181–196. (DOI: 10.1080/09537320120052452). Available at: http://dx.doi.org/10.1080/09537320120052452.

Haas R., and P. Biermayr (2000). The rebound effect for space heating Empirical evidence from Austria. *Energy Policy* **28**, 403–410. Available at: http://ideas.repec.org/a/eee/enepol/v28y2000i6-7p403-410.html.

Hamilton J.D. (2009). Causes and consequences of the oil shock of 2007-08. *Brookings Papers on Economic Activity* **2009**, 215–284. Available at: http://www.brookings.edu/~/media/Projects/BPEA/Spring%202009/2009a_bpea_hamilton.PDF.

Hartmann J., A.J. West, P. Renforth, P. Köhler, C.L. De La Rocha, D.A. Wolf-Gladrow, H.H. Dürr, and J. Scheffran (2013). Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification: ENHANCED WEATHERING. *Reviews of Geophysics* **51**, 113–149. (DOI: 10.1002/rog.20004). Available at: http://www.climate-engineering.eu/single/items/hartmann-jens-et-al-2013-enhanced-chemical-weathering-as-a-geoengineering-strategy-to-reduce-atmospheric-carbon-dioxide-a-nutrie.html.

Hausman J.A. (1979). Individual discount rates and the purchase and utilization of energy-using durables. *The Bell Journal of Economics* **10**, 33–54.

Havrylyshyn O. (1990). Trade Polic and Productivity Gains in Developing Countries: A Survey of the Literature. *The World Bank Research Observer* **5**, 1–24. (DOI: 10.1093/wbro/5.1.1).

Hayhoe K., H.S. Kheshgi, A.K. Jain, and D.J. Wuebbles (2002). Substitution of natural gas for coal: Climatic effects of utility sector emissions. *Climatic Change* **54**, 107–139. (DOI: 10.1023/A:1015737505552). Available at: http://link.springer.com/article/10.1023/A%3A1015737505552.

Heitmann N., and S. Khalilian (2011). Accounting for carbon dioxide emissions from international shipping: Burden sharing under different UNFCCC allocation options and regime scenarios. *Marine Policy* **35**, 682–691. (DOI: 10.1016/j.marpol.2011.02.009). Available at: http://www.sciencedirect.com/science/article/pii/S0308597X11000443.

Henriksen C., K. Hussey, and P. Holm (2011). Exploiting Soil-Management Strategies for Climate Mitigation in the European Union: Maximizing "Win-Win" solutions across Poliyc Regimes. *Ecology and Society* **16**, 22.

Henriques S.T., and A. Kander (2010). The modest environmental relief resulting from the transition to a service economy. *Ecological Economics* **70**, 271–282. (DOI: 10.1016/j.ecolecon.2010.08.010). Available at: http://www.sciencedirect.com/science/article/pii/S0921800910003344.

Hertwich E.G., and G.P. Peters (2009). Carbon Footprint of Nations: A Global, Trade-Linked Analysis. *Environ. Sci. Technol.* **43**, 6414–6420. (DOI: 10.1021/es803496a). Available at: http://dx.doi.org/10.1021/es803496a.

Hettige H., M. Mani, and D. Wheeler (2000). Industrial pollution in economic development: the environmental Kuznets curve revisited. *Journal of Development Economics* **62**, 445–476. (DOI: 10.1016/S0304-3878(00)00092-4). Available at: http://www.sciencedirect.com/science/article/pii/S0304387800000924.

Hill J., S. Polasky, E. Nelson, D. Tilman, H. Huo, L. Ludwig, J. Neumann, H. Zheng, and D. Bonta (2009). Climate change and health costs of air emissions from biofuels and gasoline. *Proceedings of the National Academy of Sciences*, pnas.0812835106. (DOI: 10.1073/pnas.0812835106). Available at: http://www.pnas.org/content/early/2009/02/02/0812835106.

Höglund-Isaksson L., W. Winiwarter, P. Purohit, P. Rafaj, W. Schöpp, and Z. Klimont (2012). EU low carbon roadmap 2050: Potentials and costs for mitigation of non-CO2 greenhouse gas emissions. *Energy Strategy Reviews* **1**, 97–108. (DOI: 10.1016/j.esr.2012.05.004). Available at: http://www.sciencedirect.com/science/article/pii/S2211467X12000168.

Holland S.P. (2010). *Spillovers from Climate Policy*. National Bureau of Economic Research. Available at: http://www.nber.org/papers/w16158.

Holtedahl P., and F.L. Joutz (2004). Residential electricity demand in Taiwan. *Energy Economics* **26**, 201–224. Available at: http://ideas.repec.org/a/eee/eneeco/v26y2004i2p201-224.html.

Hong L., Z. Pei Dong, H. Chunyu, and W. Gang (2007). Evaluating the effects of embodied energy in international trade on ecological footprint in China. *Ecological Economics* **62**, 136–148.

Houghton R.A. (2007). Balancing the Global Carbon Budget. *Annual Review of Earth and Planetary Sciences* **35**, 313–347. (DOI: 10.1146/annurev.earth.35.031306.140057). Available at: http://www.annualreviews.org/doi/abs/10.1146/annurev.earth.35.031306.140057.

Houghton R.A. (2008). Carbon Flux to the Atmosphere from Land-Use Changes: 1850-2005. *TRENDS: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.*

Houghton R.A., G.R. van der Werf, R.S. DeFries, M.C. Hansen, J.I. House, C. Le Quéré, J. Pongratz, and N. Ramankutty (2012). Chapter G2 Carbon emissions from land use and land-cover change. *Biogeosciences Discussions* **9**, 835–878. (DOI: 10.5194/bgd-9-835-2012). Available at: http://www.biogeosciences-discuss.net/9/835/2012/.

Hourcade J., D. Demailly, K. Neuhoff, and M. Sato (2008). *Differentiation and dynamics of EU ETS industrial competitiveness impacts: Final Report*. Available at: http://www.iddri.org/Evenements/Interventions/070622_workshopberlin_Competitiveness_interim_report.pdf.

House of Commons (2012). *Consumption-Based Emissions Reporting. Twelfth Report of Session 2010–12*. House of Commons Energy and Climate Change Committee. Available at: http://www.publications.parliament.uk/pa/cm201012/cmselect/cmenergy/1646/1646vw.pdf.

Van Houwelingen J.H., and W.F. Van Raaij (1989). The Effect of Goal-Setting and Daily Electronic Feedback on In-home energy use. *Journal of consumer research* **16**, 98–105.

Howarth R.B. (1997). Energy Efficiency and Economic Growth. *Contemporary Economic Policy* **XV**. Available at: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=49080.

Hummels D., J. Ishii, and K.-M. Yi (2001). The nature and growth of vertical specialization in world trade. *Journal of International Economics* **54**, 75–96.

Hunt A., and M. Sendhil (2010). Behavior and Energy Policy. *Science* **327**, 1204–1205. Available at: www.sciencemag.org.

IEA (2009). *World Energy Outlook 2009*. OECD, Paris, (ISBN: 978-92-64-06130-9).

IEA (2012). CO2 Emissions from Fuel Combustion. Beyond 2020 Online Database. Available at: http://data.iea.org.

International Energy Agency (2002). *World Energy Outlook 2002*. Organisation for Economic Co-operation and Development, Paris, (ISBN: 9789264198357). Available at: http://www.oecd-ilibrary.org/content/book/weo-2002-en.

International Energy Agency (2003). *World Energy Outlook 2003*. Organisation for Economic Co-operation and Development, Paris, (ISBN: 9789264019065). Available at: http://www.oecd-ilibrary.org/content/book/weo-2003-en.

International Energy Agency (2006). *World Energy Outlook 2006*. Organisation for Economic Co-operation and Development, Paris, (ISBN: 9789264109896). Available at: http://www.oecd-ilibrary.org/content/book/weo-2006-en.

International Energy Agency (2008). *World Energy Outlook 2008*. Organisation for Economic Co-operation and Development, Paris, (ISBN: 9789264045606). Available at: http://www.oecd-ilibrary.org/content/book/weo-2008-en.

IPCC (1997). *IPCC Guidelines for National Greenhouse Gas Inventories. Vol.3. Greenhouse Gas Inventory Reference Manual. Revised 1996*. Intergovernmental Panel on Climate Change. Available at: http://www.ipcc-nggip.iges.or.jp/public/gl/invs6.html.

IPCC (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*. Intergovernmental Panel on Climate Change. Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm.

IPCC (2007). *Synthesis report*. Cambridge University Press, Cambridge, UK, 52 pp. Available at: www.ipcc.ch.

Ivy D.J., M. Rigby, M. Baasandorj, J.B. Burkholder, and R.G. Prinn (2012). Global emission estimates and radiative impact of C4F10, C5F12, C6F14, C7F16 and C8F18. *Atmospheric Chemistry and Physics* **12**, 7635–7645. (DOI: 10.5194/Acp-12-7635-2012). Available at: http://www.atmos-chem-phys.net/12/7635/2012/.

Jack D.W., and P.L. Kinney (2010). Health co-benefits of climate mitigation in urban areas. *Current Opinion in Environmental Sustainability* **2**, 172–177. (DOI: 10.1016/j.cosust.2010.06.007).

Jackson T. (2005). Live Better by Consuming Less?: Is There a “Double Dividend” in Sustainable Consumption? *Journal of Industrial Ecology* **9**, 19–36. (DOI: 10.1162/1088198054084734). Available at: http://onlinelibrary.wiley.com/doi/10.1162/1088198054084734/abstract.

Jakob M.A. (2011). Reframing International Climate Policy: Essays on Development Issues and Fragmented Regimes, Ein neuer Analyserahmen für die internationale Klimapolitik: Essays zu Entwicklungsfragen und fragmentierten Regimen. Available at: http://opus4.kobv.de/opus4-tuberlin/frontdoor/index/index/docId/2949.

Jakob M., M. Haller, and R. Marschinski (2012). Will history repeat itself? Economic convergence and convergence in energy use patterns. *Energy Economics* **34**, 95–104. (DOI: 10.1016/j.eneco.2011.07.008). Available at: http://www.sciencedirect.com/science/article/pii/S0140988311001381.

Jakob M., and R. Marschinski (2013). Interpreting trade-related CO2 emission transfers. *Nature Climate Change* **3**, 19–23. (DOI: 10.1038/nclimate1630). Available at: http://www.nature.com/nclimate/journal/v3/n1/full/nclimate1630.html.

Javorcik B.S. (2004). Does Foreign Direct Investment Increase the Productivity of Domestic Firms? In Search of Spillovers Through Backward Linkages. *American Economic Review* **94**, 605–627.

Jolley A. (2004). New Technologies, Industry Developments and Emission Trends in Key Sectors: The Land Transportation Sector. Victoria University. Available at: http://vuir.vu.edu.au/390/.

Jorgenson A.K., and B. Clark (2010). Assessing the temporal stability of the population/environment relationship in comparative perspective: a cross-national panel study of carbon dioxide emissions, 1960–2005. *Population and Environment* **32**, 27–41. (DOI: 10.1007/s11111-010-0117-x). Available at: http://www.springerlink.com/content/p067178140148623/.

Jorgenson D.W., and Z. Griliches (1967). The Explanation of Productivity Change. *The Review of Economic Studies* **34**, 249–283. (DOI: 10.2307/2296675). Available at: http://www.jstor.org/stable/2296675.

Jotzo F., P.J. Burke, P.J. Wood, A. Macintosh, and D.I. Stern (2012). Decomposing the 2010 global carbon dioxide emissions rebound. *Nature Climate Change* **2**, 213–214. (DOI: 10.1038/nclimate1450). Available at: http://www.nature.com/nclimate/journal/v2/n4/full/nclimate1450.html.

JRC/PBL (2012). European Commission, Joint Research Centre (JRC)/PBL Netherlands Environmental Assessment Agency. Emission Database for Global Atmospheric Research (EDGAR), release version 4.2 FT2010. Available at: http://edgar.jrc.ec.europa.eu/index.php.

JRC/PBL (2013). European Commission, Joint Research Centre (JRC)/PBL Netherlands Environmental Assessment Agency. Emission Database for Global Atmospheric Research (EDGAR), release version 4.2 FT2010. Available at: http://edgar.jrc.ec.europa.eu/index.php.

Kahneman D., P. Slovic, and A. Tversky (Eds.) **(1982).** *Judgment under Uncertainty: Heuristics and Biases*. Cambridge University Press, 544 pp., (ISBN: 0521284147).

Kander A. (2005). Baumol's disease and dematerialization of the economy. *Ecological Economics* **55**, 119–130. (DOI: 10.1016/j.ecolecon.2004.10.008). Available at: http://www.sciencedirect.com/science/article/pii/S0921800904004094.

Kanemoto K., M. Lenzen, G.P. Peters, D.D. Moran, and A. Geschke (2012). Frameworks for Comparing Emissions Associated with Production, Consumption, And International Trade. *Environmental Science & Technology* **46**, 172–179. (DOI: 10.1021/es202239t). Available at: http://dx.doi.org/10.1021/es202239t.

Karanfil F., and Y. Yeddir-Tamsamani (2010). Is technological change biased toward energy? A multi-sectoral analysis for the French economy. *Energy Policy* **38**, 1842–1850. Available at: http://ideas.repec.org/a/eee/enepol/v38y2010i4p1842-1850.html.

Kaufmann R.K. (2004). The Mechanisms for Autonomous Energy Efficiency Increases: A Cointegration Analysis of the US Energy/GDP Ratio. *The Energy Journal* **25**, 63–86.

Kaya Y. (1990). Impact of Carbon Dioxide Emission Control on GNP Growth: Interpretation of Proposed. Scenarios. Paris. 1990, .

Keller W. (2000). Do Trade Patterns and Technology Flows Affect Productivity Growth? *The World Bank Economic Review* **14**, 17–47.

Keller W., and S. Yeaple (2009). Multinational Enterprises, International Trade, and Productivity Growth: Firm Level Evidence from the United States. *Review of Economics and Statistics* **91**, 821–831.

Kennedy C., J. Steinberger, B. Gasson, Y. Hansen, T. Hillman, M. Havránek, D. Pataki, A. Phdungsilp, A. Ramaswami, and G.V. Mendez (2009). Greenhouse gas emissions from global cities. *Environmental Science and Technology* **43**, 7297–7302. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-70349617486&partnerID=40&md5=37442767d9f4778060f56bc8e97f98c2.

Kim E. (2000). Trade liberalization and productivity growth in Korean manufacturing industries: price protection, market power, and scale efficiency. *Journal of Development Economics* **62**, 55–83.

Kirschke S., P. Bousquet, P. Ciais, M. Saunois, J.G. Canadell, E.J. Dlugokencky, P. Bergamaschi, D. Bergmann, D.R. Blake, L. Bruhwiler, P. Cameron-Smith, S. Castaldi, F. Chevallier, L. Feng, A. Fraser, M. Heimann, E.L. Hodson, S. Houweling, B. Josse, P.J. Fraser, P.B. Krummel, J.-F. Lamarque, R.L. Langenfelds, C. Le Quéré, V. Naik, S. O'Doherty, P.I. Palmer, I. Pison, D. Plummer, B. Poulter, R.G. Prinn, M. Rigby, B. Ringeval, M. Santini, M. Schmidt, D.T. Shindell, I.J. Simpson, R. Spahni, L.P. Steele, S.A. Strode, K. Sudo, S. Szopa, G.R. van der Werf, A. Voulgarakis, M. van Weele, R.F. Weiss, J.E. Williams, and G. Zeng (2013). Three decades of global methane sources and sinks. *Nature Geoscience* **6**, 813–823. (DOI: 10.1038/ngeo1955).

Klimont Z., S.J. Smith, and J. Cofala (2013a). The last decade of global anthropogenic sulfur dioxide: 2000–2011 emissions. *Environmental Research Letters* **8**, 014003. (DOI: 10.1088/1748-9326/8/1/014003). Available at: http://iopscience.iop.org/1748-9326/8/1/014003.

Klimont Z., S.J. Smith, and J. Cofala (2013b). The last decade of global anthropogenic sulfur dioxide: 2000–2011 emissions. *Environmental Research Letters* **8**, 014003. (DOI: 10.1088/1748-9326/8/1/014003).

Kollmuss A., and J. Agyeman (2002). Mind the Gap: Why do people act environmentally and what are the barriers to pro-environmental behavior? *Environmental Education Research* **8**, 239–260. (DOI: 10.1080/13504620220145401). Available at: http://www.tandfonline.com/doi/abs/10.1080/13504620220145401.

Koopman R., Z. Wang, and S.-J. Wei (2008). How Much of Chinese Exports is Really Made In China? Assessing Domestic Value-Added When Processing Trade is Pervasive. Available at: http://www.nber.org/papers/w14109.

Koornneef J., A. Ramírez, W. Turkenburg, and A. Faaij (2012). The environmental impact and risk assessment of CO2 capture, transport and storage – An evaluation of the knowledge base. *Progress in Energy and Combustion Science* **38**, 62–86. (DOI: 10.1016/j.pecs.2011.05.002). Available at: http://www.sciencedirect.com/science/article/pii/S0360128511000402.

Krausmann F., H. Schandl, and R.P. Sieferle (2008). Socio-ecological regime transitions in Austria and the United Kingdom. *Ecological Economics* **65**, 187–201. (DOI: 10.1016/j.ecolecon.2007.06.009). Available at: http://www.sciencedirect.com/science/article/pii/S0921800907003503.

Kubiszewski I., R. Costanza, C. Franco, P. Lawn, J. Talberth, T. Jackson, and C. Aylmer (2013). Beyond GDP: Measuring and achieving global genuine progress. *Ecological Economics* **93**, 57–68. (DOI: 10.1016/j.ecolecon.2013.04.019).

Lamarque J.F., T.C. Bond, V. Eyring, C. Granier, A. Heil, Z. Klimont, D.S. Lee, C. Liousse, A. Mieville, B. Owen, M. Schultz, D. Shindell, S.J. Smith, E. Stehfest, J. van Aardenne, O. Cooper, M. Kainuma, N. Mahowald, J.R. McConnell, K. Riahi, and D. van Vuuren (2010). Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. *Atmospheric Chemistry and Physics* **10**, 7017–7039.

Lancaster K. (1965). The Theory of Qualitative Linear Systems. *Econometrica* **33**, 395–408. (DOI: 10.2307/1909797). Available at: http://www.jstor.org/stable/1909797.

Layton D., E. Jenkins, S. Macgill, and A. Davey (1993). *Inarticulate science?: perspectives on the public understanding of science and some implications for science education*. Studies in Education, (ISBN: 090548455X 9780905484556).

Lenzen M. (2011). AGGREGATION VERSUS DISAGGREGATION IN INPUT-OUTPUT ANALYSIS OF THE ENVIRONMENT. *Economic Systems Research* **23**, 73–89. Available at: http://econpapers.repec.org/article/tafecsysr/v_3a23_3ay_3a2011_3ai_3a1_3ap_3a73-89.htm.

Lenzen M., B. Gallego, and R. Wood (2009). Matrix Balancing Under Conflicting Information. *Economic Systems Research* **21**, 23–44. (DOI: 10.1080/09535310802688661). Available at: http://www.tandfonline.com/doi/abs/10.1080/09535310802688661.

Lenzen M., L.-L. Pade, and J. Munksgaard (2004). CO2 Multipliers in Multi-region Input-Output Models. *Economic Systems Research* **16**, 391–412. (DOI: 10.1080/0953531042000304272). Available at: http://www.tandfonline.com/doi/abs/10.1080/0953531042000304272.

Lenzen M., M. Wier, C. Cohen, H. Hayami, S. Pachauri, and R. Schaeffer (2006). A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan. *Energy* **31**, 181–207. (DOI: doi: 10.1016/j.energy.2005.01.009). Available at: http://www.sciencedirect.com/science/article/pii/S0360544205000113.

Lenzen M., R. Wood, and T. Wiedmann (2010). Uncertainty Analysis for Multi-Region Input–Output Models – a Case Study of the Uk's Carbon Footprint. *Economic Systems Research* **22**, 43–63. (DOI: 10.1080/09535311003661226). Available at: http://www.tandfonline.com/doi/abs/10.1080/09535311003661226.

Lescaroux F. (2011). Dynamics of final sectoral energy demand and aggregate energy intensity. *Energy Policy* **39**, 66–82. (DOI: 10.1016/j.enpol.2010.09.010). Available at: http://www.sciencedirect.com/science/article/pii/S0301421510006907.

Li Y., and C.N. Hewitt (2008). The effect of trade between China and the UK on national and global carbon dioxide emissions. *Energy Policy* **36**, 1907–1914. (DOI: 10.1016/j.enpol.2008.02.005). Available at: http://www.sciencedirect.com/science/article/pii/S0301421508000694.

Liao H., Y. Fan, and Y.-M. Wei (2007). What induced China's energy intensity to fluctuate: 1997–2006? *Energy Policy* **35**, 4640–4649. (DOI: 10.1016/j.enpol.2007.03.028). Available at: http://www.sciencedirect.com/science/article/pii/S0301421507001437.

Liddle B. (2011). Consumption-driven environmental impact and age structure change in OECD countries: A cointegration-STIRPAT analysis. *Demographic Research* **Volume 24**, 749–770. Available at: www.demographic-research.org/Volumes/Vol24/30/.

Liddle B., and S. Lung (2010). Age-structure, urbanization, and climate change in developed countries: Revisiting STIRPAT for disaggregated population and consumption-related environmental impacts. *Population and Environment* **31**, 317–343. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-77952429903&partnerID=40&md5=44342c066f5991af0d9456a5b996feac.

Lim H.-J., S.-H. Yoo, and S.-J. Kwak (2009). Industrial CO2 emissions from energy use in Korea: A structural decomposition analysis. *Energy Policy* **37**, 686–698. (DOI: 10.1016/j.enpol.2008.10.025). Available at: http://www.sciencedirect.com/science/article/pii/S0301421508005879.

Linares P., and X. Labandeira (2010). ENERGY EFFICIENCY: ECONOMICS AND POLICY. *Journal of Economic Surveys* **24**, 573–592. Available at: http://econpapers.repec.org/article/blajecsur/v_3a24_3ay_3a2010_3ai_3a3_3ap_3a573-592.htm.

Lindner S., J. Legault, and D. Guan (2012). Disaggregating Input–Output Models with Incomplete Information. *Economic Systems Research* **24**, 329–347. (DOI: 10.1080/09535314.2012.689954). Available at: http://www.tandfonline.com/doi/abs/10.1080/09535314.2012.689954.

Lindner S., J. Legault, and D. Guan (2013). Disaggregating the Electricity Sector of China's Input–Output Table for Improved Environmental Life-Cycle Assessment. *Economic Systems Research* **25**, 300–320. (DOI: 10.1080/09535314.2012.746646). Available at: http://www.tandfonline.com/doi/abs/10.1080/09535314.2012.746646.

Liu Z.. (2009). Thinking of economic transformation of coal resource-based cities in Shanxi. Available at: http://old.sxgov.cn/qj/nr/622963.shtml (in Chinese).

Liu L.-C., G. Wu, J.-N. Wang, and Y.-M. Wei (2011). China's carbon emissions from urban and rural households during 1992–2007. *Journal of Cleaner Production* **19**, 1754–1762. (DOI: doi: 10.1016/j.jclepro.2011.06.011). Available at: http://www.sciencedirect.com/science/article/pii/S0959652611002228.

Lovins A.B. (1988). Energy Saving from the Adoption of More Efficient Appliances: Another View. *The Energy Journal* **9**, 155–162. Available at: http://econpapers.repec.org/article/aenjournl/1988v09-02-a10.htm.

Lu Z., Q. Zhang, and D.G. Streets (2011). Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996–2010. *Atmospheric Chemistry and Physics* **11**, 9893–9864. (DOI: doi:10.5194/acp-11-9839-2011). Available at: http://www.atmos-chem-phys.net/11/9839/2011/acp-11-9839-2011.pdf.

Ma C., and D.I. Stern (2008). China's changing energy intensity trend: A decomposition analysis. *Energy Economics* **30**, 1037–1053. (DOI: 10.1016/j.eneco.2007.05.005). Available at: http://www.sciencedirect.com/science/article/pii/S0140988307000758.

Macknick J. (2011). Energy and CO2 emission data uncertainties. *Carbon Management* **2**, 189–205. (DOI: 10.4155/Cmt.11.10). Available at: http://www.future-science.com/doi/abs/10.4155/cmt.11.10.

Mäenpää I., and H. Siikavirta (2007). Greenhouse gases embodied in the international trade and final consumption of Finland: An input–output analysis. *Energy Policy* **35**, 128–143. (DOI: 10.1016/j.enpol.2005.10.006). Available at: http://www.sciencedirect.com/science/article/pii/S0301421505002739.

Malla S. (2009). CO2 emissions from electricity generation in seven Asia-Pacific and North American countries: A decomposition analysis. *Energy Policy* **37**, 1–9. (DOI: 10.1016/j.enpol.2008.08.010). Available at: http://www.sciencedirect.com/science/article/pii/S0301421508004096.

Mann W., L. Lipper, T. Tennigkeit, N. McCarthy, and G. Branca (2009). *Food Security and Agricultural Mitigation in Developing Countries: Options for Capturing Synergies*. Food and

Agriculture Organization (FAO) of the United Nations. Available at: http://www.fao.org/docrep/012/i1318e/i1318e00.pdf.

Marechal K. (2009). An evolutionary perspective on the economics of energy consumption: the crucial role of habits. *Journal of Economic Issues* **XLIII**.

Markandya A., B.G. Armstrong, S. Hales, A. Chiabai, P. Criqui, S. Mima, C. Tonne, and P. Wilkinson (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation. *The Lancet* **374**, 2006–2015. (DOI: 10.1016/S0140-6736(09)61715-3).

Marland G., R.J. Andres, T.A. Boden, C.A. Johnston, and A. Brenkert (1999). *Global, regional, and national CO2 emission estimates from fossil fuel burning, cement production, and gas flaring: 1751–1996.* In: trends online: a compendium of data on global change. Oak Ridge National Laboratory, Oak Ridge, TN. Available at: http://cdiac.esd.ornl.gov/ftp/ndp030.

Marland G., K. Hamal, and M. Jonas (2009). How Uncertain Are Estimates of CO2 Emissions ? *Journal of Industrial Ecology* **13**, 4–7. (DOI: 10.1111/J.1530-9290.2009.00108.X). Available at: http://onlinelibrary.wiley.com/doi/10.1111/j.1530-9290.2009.00108.x/abstract.

Martínez-Zarzoso I., and A. Maruotti (2011). The impact of urbanization on CO2 emissions: Evidence from developing countries. *Ecological Economics* **70**, 1344–1353. (DOI: doi: 10.1016/j.ecolecon.2011.02.009). Available at: http://www.sciencedirect.com/science/article/pii/S0921800911000814.

Matisoff D.C. (2008). The Adoption of State Climate Change Policies and Renewable Portfolio Standards: Regional Diffusion or Internal Determinants? *Review of Policy Research* **25**, 527–546. (DOI: 10.1111/j.1541-1338.2008.00360.x). Available at: http://onlinelibrary.wiley.com/doi/10.1111/j.1541-1338.2008.00360.x/abstract.

Meinshausen M., N. Meinshausen, W. Hare, S.C.B. Raper, K. Frieler, R. Knutti, D.J. Frame, and M.R. Allen (2009). Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* **458**, 1158–1162. (DOI: 10.1038/nature08017). Available at: http://www.nature.com/nature/journal/v458/n7242/full/nature08017.html.

Meschi E., and M. Vivarelli (2009). Trade and Income Inequality in Developing Countries. *World Development* **37**, 287–302.

Metcalf G.E. (2008). An Empirical Analysis of Energy Intensity and Its Determinants at the State Level. *The Energy Journal* **29**, 1–26.

Metz B. (2007). *Climate Change 2007 - Mitigation of Climate Change: Working Group III Contribution to the Fourth Assessment Report of the IPCC*. Cambridge University Press, 863 pp., (ISBN: 9781139468640).

Minx J.C., G. Baiocchi, G.P. Peters, C.L. Weber, D. Guan, and K. Hubacek (2011). A "Carbonizing Dragon": China's Fast Growing CO2 Emissions Revisited. *Environ. Sci. Technol.* **45**, 9144–9153. (DOI: 10.1021/es201497m). Available at: http://dx.doi.org/10.1021/es201497m.

Minx J.C., T. Wiedmann, R. Wood, G.P. Peters, M. Lenzen, A. Owen, K. Scott, J. Barrett, K. Hubacek, G. Baiocchi, A. Paul, E. Dawkins, J. Briggs, D. Guan, S. Suh, and F. Ackerman (2009). INPUT–OUTPUT ANALYSIS AND CARBON FOOTPRINTING: AN OVERVIEW OF APPLICATIONS. *Economic Systems Research* **21**, 187–216. (DOI: 10.1080/09535310903541298). Available at: http://www.tandfonline.com/doi/abs/10.1080/09535310903541298?journalCode=cesr20#preview.

Monni S., R. Pipatti, A. Lehtilla, I. Savolainen, and S. Syri (2006). *Global climate change mitigation scenarios for solid waste management*. Technical Research Centre of Finland VTT Publications, Espoo. Available at: http://www.vtt.fi/inf/pdf/publications/2006/P603.pdf.

Mont O., and A. Plepys (2008). Sustainable consumption progress: should we be proud or alarmed? *Journal of Cleaner Production* **16**, 531–537.

Morioka T., and N. Yoshida (1995). Comparison of carbon dioxide emission patterns due to consumers' expenditure in UK and Japan. *Journal of Global Environmental Engineering* **1**, 59–78.

Mulder P., and H. de Groot (2007). Sectoral Energy- and Labour-Productivity Convergence. In: *Sustainable Resource Use and Economic Dynamics*. Springer, pp.165–190, .

Munksgaard J., K.A. Pedersen, and M. Wier (2001). Changing consumption patterns and CO 2 reduction. *International Journal of Environment and Pollution* **15**, 146–158.

Muñoz P., and K.W. Steininger (2010). Austria's CO2 responsibility and the carbon content of its international trade. *Ecological Economics* **69**, 2003–2019. (DOI: 10.1016/j.ecolecon.2010.05.017). Available at: http://www.sciencedirect.com/science/article/pii/S0921800910002235.

Myhre G., D. Shindell, F.-M. Brèon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and Zhang (2014). Anthropogenic and Natural Radiative Forcing. In: *IPCC Working Group 1 Fifth Assessment Report*.

Nakicenovic N., P.V. Gilli, and R. Kurz (1996). Regional and global exergy and energy efficiencies. *Energy* **21**, 223–237. (DOI: 10.1016/0360-5442(96)00001-1). Available at: http://www.sciencedirect.com/science/article/pii/0360544296000011.

Nakicenovic N., A. Grübler, and A. McDonald (1998). *Global Energy Perspectives*. Cambridge University Press, 267 pp., (ISBN: 9780521645690).

Nakicenovic N., and R. Swart (2000). *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 612 pp., (ISBN: 0521804930).

Nansai K., S. Kagawa, Y. Kondo, S. Suh, R. Inaba, and K. Nakajima (2009a). Improving the completeness of product carbon footprints using a global link input-output model: the case of Japan. *Economic Systems Research* **21**, 267–290. (DOI: 10.1080/09535310903541587).

Nansai K., S. Kagawa, S. Suh, M. Fujii, R. Inaba, and S. Hashimoto (2009b). Material and Energy Dependence of Services and Its Implications for Climate Change. *Environ. Sci. Technol.* **43**, 4241–4246. (DOI: 10.1021/es8025775). Available at: http://dx.doi.org/10.1021/es8025775.

Nansai K., S. Kagawa, S. Suh, R. Inaba, and Y. Moriguchi (2007). Simple indicator to identify the environmental soundness of growth of consumption and technology: "eco-velocity of consumption." *Environmental science & technology* **41**, 1465–1472. Available at: http://www.ncbi.nlm.nih.gov/pubmed/17593758.

Nemet G.F., T. Holloway, and P. Meier (2010a). Implications of incorporating air-quality co-benefits into climate change policymaking. *Environmental Research Letters* **5**, 014007.

Nemet G.F., T. Holloway, and P. Meier (2010b). Implications of incorporating air-quality co-benefits into climate change policymaking. *Environmental Research Letters* **5**, 014007. (DOI: 10.1088/1748-9326/5/1/014007). Available at: http://iopscience.iop.org/1748-9326/5/1/014007.

Newell R.G., A.B. Jaffe, and R.N. Stavins (1999). The Induced Innovation Hypothesis and Energy-Saving Technological Change. *The Quarterly Journal of Economics* **114**, 941 –975. (DOI: 10.1162/003355399556188). Available at: http://qje.oxfordjournals.org/content/114/3/941.abstract.

NRC (2010). *Advancing the Science of Climate Change, Report in Brief*. 528 pp., (ISBN: 0-309-14588-0).

O'Donoghue T., and M. Rabin (2008). Procrastination on long-term projects. *Journal of Economic Behavior & Organization* **66**, 161–175. Available at: http://ideas.repec.org/a/eee/jeborg/v66y2008i2p161-175.html.

O'Neill B.C., M. Dalton, R. Fuchs, L. Jiang, S. Pachauri, and K. Zigova (2010). Global demographic trends and future carbon emissions. *Proceedings of the National Academy of Sciences of the United States of America* **107**, 17521–17526. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-78049252451&partnerID=40&md5=7da8389d593807dde90debe5f3704457.

O'Neill B.C., B. Liddle, L. Jiang, K.R. Smith, S. Pachauri, M. Dalton, and R. Fuchs (forthcoming). Demographic change and emissions of carbon dioxide, the main greenhouse gas. *Lancet*.

Okushima S., and M. Tamura (2010). What causes the change in energy demand in the economy?: The role of technological change. *Energy Economics* **32, Supplement 1**, S41–S46. (DOI: 10.1016/j.eneco.2009.03.011). Available at: http://www.sciencedirect.com/science/article/pii/S0140988309000565.

Olivier J.G.J., G. Janssens-Maenhout, M. Muntean, and J.A.H.W. Peters (2013). *Trends in global CO2 emissions: 2013 Report*. PBL Netherlands Environmental Assessment Agency, The Hague, Netherlands, (ISBN: 978-94-91506-51-2).

Olivier J.G.J., G. Janssens-Maenhout, J.A.H.W. Peters, and J. Wilson (2011). *Long -Term Trend in Global CO2 Emissions*. PBL Netherlands Environmental Assessment Agency; JRC European Commission.

Deb Pal B., S. Pohit, and J. Roy (2012). Social Accounting Matrix for India. *Economic Systems Research* **24**, 77–99. (DOI: 10.1080/09535314.2011.618824).

Pan J. (2012). From Industrial Toward Ecological in China. *Science* **336**, 1397–1397. (DOI: 10.1126/science.1224009). Available at: http://www.sciencemag.org/content/336/6087/1397.2.

Pan J. (2013). An urgent need for a low carbon approach to environmental pollution control. *Environmental Protection (in Chinese)* **No. 12**.

Pan J., H. Ma, Y. Zhang, L. Mastny, and Worldwatch Institute (2011). *Green economy and green jobs in China: current status and potentials for 2020*. Worldwatch Institute, Washington, DC, (ISBN: 9780983543701 0983543704).

Pao H.-T., and C.-M. Tsai (2010). CO2 emissions, energy consumption and economic growth in BRIC countries. *Energy Policy* **38**, 7850–7860. (DOI: doi: 10.1016/j.enpol.2010.08.045). Available at: http://www.sciencedirect.com/science/article/pii/S0301421510006609.

Parente S., and E. Prescott (2000). *Barriers to riches*. MIT Press, Cambridge Mass., (ISBN: 9780262161930).

Parikh J., and V. Shukla (1995). Urbanization, energy use and greenhouse effects in economic development: Results from a cross-national study of developing countries. *Global Environmental Change* **5**, 87–103. (DOI: 10.1016/0959-3780(95)00015-G). Available at: http://www.sciencedirect.com/science/article/pii/095937809500015G.

Pavcnik N. (2002). Trade Liberalization, Exit, and Productivity Improvements: Evidence from Chilean Plants. *Review of Economic Studies* **69**, 245–276.

Pellegrini L., and R. Gerlagh (2006). Corruption, Democracy, and Environmental Policy An Empirical Contribution to the Debate. *The Journal of Environment & Development* **15**, 332–354. (DOI: 10.1177/1070496506290960). Available at: http://jed.sagepub.com/content/15/3/332.

Le Pen Y., and B. Sévi (2010). On the non-convergence of energy intensities: Evidence from a pair-wise econometric approach. *Ecological Economics* **69**, 641–650. (DOI: 10.1016/j.ecolecon.2009.10.001). Available at: http://www.sciencedirect.com/science/article/pii/S0921800909004108.

Persson T., and G. Tabellini (1994). Is Inequality Harmful for Growth? *American Economic Review* **84**, 600–621.

Peters G.P. (2007). Efficient algorithms for Life Cycle Assessment, Input-Output Analysis, and Monte-Carlo Analysis. *The International Journal of Life Cycle Assessment* **12**, 373–380. (DOI: 10.1065/lca2006.06.254). Available at: http://link.springer.com/article/10.1065/lca2006.06.254.

Peters G.P. (2008). From production-based to consumption-based national emission inventories. *Ecological Economics* **65**, 13–23. (DOI: 10.1016/j.ecolecon.2007.10.014). Available at: http://www.sciencedirect.com/science/article/pii/S0921800907005162.

Peters G.P. (2010). Managing carbon leakage. *Carbon Management* **1**, 35–37.

Peters G.P., and E.G. Hertwich (2008). CO2 Embodied in International Trade with Implications for Global Climate Policy. *Environ. Sci. Technol.* **42**, 1401–1407. (DOI: 10.1021/es072023k). Available at: http://dx.doi.org/10.1021/es072023k.

Peters G.P., G. Marland, C. Le Quéré, T. Boden, J.G. Canadell, and M.R. Raupach (2012). Rapid growth in CO2 emissions after the 2008-2009 global financial crisis. *Nature Climate Change* **2**, 2–4. (DOI: 10.1038/nclimate1332).

Peters G.P., J.C. Minx, C.L. Weber, and O. Edenhofer (2011a). Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences*. (DOI: 10.1073/pnas.1006388108). Available at: http://www.pnas.org/content/early/2011/04/19/1006388108.abstract.

Peters G.P., J.C. Minx, C.L. Weber, and O. Edenhofer (2011b). Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences* **108**, 8903–8908. (DOI: 10.1073/pnas.1006388108). Available at: http://www.pnas.org/content/108/21/8903.

Peters G., and C. Solli (2010). *Global carbon footprints: methods and import/export corrected results from the Nordic countries in global carbon footprint studies*. Nordic Council of Ministers, Copenhagen, (ISBN: 9789289321594 9289321598).

Peters G.P., C.L. Weber, D. Guan, and K. Hubacek (2007). China's Growing CO2 EmissionsA Race between Increasing Consumption and Efficiency Gains. *Environ. Sci. Technol.* **41**, 5939–5944. (DOI: 10.1021/es070108f). Available at: http://dx.doi.org/10.1021/es070108f.

Platchkov L.M., and M.G. Pollitt (2011). The Economics of Energy (and Electricity) Demand. *Cambridge Working Papers in Economics*. Available at: http://econpapers.repec.org/paper/camcamdae/1137.htm.

Pligt J. van der (1985). Energy Conservation: Two Easy Ways Out1. *Journal of Applied Social Psychology* **15**, 3–15. (DOI: 10.1111/j.1559-1816.1985.tb00890.x). Available at: http://onlinelibrary.wiley.com/doi/10.1111/j.1559-1816.1985.tb00890.x/abstract.

Pomeranz K. (2000). *The great divergence : China, Europe, and the making of the modern world*. Princeton University Press, Princeton N.J., (ISBN: 9780691090108).

Pongratz J., C.H. Reick, T. Raddatz, and M. Claussen (2009). Effects of anthropogenic land cover change on the carbon cycle of the last millennium. *Global Biogeochemical Cycles* **23**, n/a–n/a. (DOI: 10.1029/2009GB003488). Available at: http://onlinelibrary.wiley.com/doi/10.1029/2009GB003488/abstract.

Popp D. (2011). International Technology Transfer, Climate Change, and the Clean Development Mechanism. *Review of Environmental Economics and Policy* **5**, 131–152.

Poumanyvong P., and S. Kaneko (2010). Does urbanization lead to less energy use and lower CO2 emissions? A cross-country analysis. *Ecological Economics* **70**, 434–444. (DOI: doi: 10.1016/j.ecolecon.2010.09.029). Available at: http://www.sciencedirect.com/science/article/pii/S0921800910003885.

Le Quéré C., R.J. Andres, T. Boden, T. Conway, R.A. Houghton, J.I. House, G. Marland, G.P. Peters, G. van der Werf, A. Ahlström, R.M. Andrew, L. Bopp, J.G. Canadell, P. Ciais, S.C. Doney, C. Enright, P. Friedlingstein, C. Huntingford, A.K. Jain, C. Jourdain, E. Kato, R.F. Keeling, K. Klein Goldewijk, S. Levis, P. Levy, M. Lomas, B. Poulter, M.R. Raupach, J. Schwinger, S. Sitch, B.D. Stocker, N. Viovy, S. Zaehle, and N. Zeng (2012). The global carbon budget 1959–2011. *Earth System Science Data Discussions* **5**, 1107–1157. (DOI: 10.5194/essdd-5-1107-2012). Available at: http://www.earth-syst-sci-data-discuss.net/5/1107/2012/essdd-5-1107-2012.html.

Le Quere C., M.R. Raupach, J.G. Canadell, and G. Marland et al. (2009). Trends in the sources and sinks of carbon dioxide. *Nature Geosci* **2**, 831–836. (DOI: 10.1038/ngeo689). Available at: http://dx.doi.org/10.1038/ngeo689.

Ramachandra T.V., Y. Loerincik, and B.V. Shruthi (2006). Intra and inter country energy intensity trends. *The Journal of Energy and Development* **31**, 43–84.

Rao S., S. Pachauri, F. Dentener, P. Kinney, Z. Klimont, K. Riahi, and W. Schoepp (2013). Better air for better health: Forging synergies in policies for energy access, climate change and air pollution. *Global Environmental Change* **23**, 1122–1130. (DOI: 10.1016/j.gloenvcha.2013.05.003). Available at: http://www.sciencedirect.com/science/article/pii/S0959378013000770.

Raupach M.R., G. Marland, P. Ciais, C. Le Quéré, J.G. Canadell, G. Klepper, and C.B. Field (2007). Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Sciences* **104**, 10288 –10293. (DOI: 10.1073/pnas.0700609104). Available at: http://www.pnas.org/content/104/24/10288.abstract.

Reddy A.K.N., and J. Goldemberg (1990). Energy for the Developing World. *Scientific American* **263**, 110–18. Available at: http://www.eric.ed.gov/ERICWebPortal/detail?accno=EJ415546.

Renssen S. van (2012). Stuck on shipping. *Nature Climate Change* **2**, 767–768. (DOI: 10.1038/nclimate1723). Available at: http://www.nature.com/nclimate/journal/v2/n11/full/nclimate1723.html.

Reppelin-Hill V. (1998). Trade and Environment: An Empirical Analysis of the Technology Effect in the Steel Industry. *Journal of Environmental Economics and Management* **38**, 283–301.

Rey S., G. West, and M. Janikas (2004). Uncertainty in Integrated Regional Models. *Economic Systems Research* **16**, 259–277. Available at: http://ideas.repec.org/a/taf/ecsysr/v16y2004i3p259-277.html.

Richardson-Klavehn A., and R.. Bjork (1988). Measures of memory. *Annual Review of Psychology*, 475–543.

Rigby M., J. Muhle, B.R. Miller, R.G. Prinn, P.B. Krummel, L.P. Steele, P.J. Fraser, P.K. Salameh, C.M. Harth, R.F. Weiss, B.R. Greally, S. O'Doherty, P.G. Simmonds, M.K. Vollmer, S. Reimann, J. Kim, K.R. Kim, H.J. Wang, J.G.J. Olivier, E.J. Dlugokencky, G.S. Dutton, B.D. Hall, and J.W. Elkins (2010). History of atmospheric SF6 from 1973 to 2008. *Atmospheric Chemistry and Physics* **10**, 10305–10320. (DOI: 10.5194/Acp-10-10305-2010). Available at: http://www.atmos-chem-phys.net/10/10305/2010/.

Rogner H.H., R.F. Aguilera, C.L. Archer, R. Bertani, S.C. Bahattacharya, M.B. Dusseault, L. Gagnon, H. Haberl, M. Hoogwijk, A. Johnson, M.L. Rogner, H. Wagner, and V. Yakushev (2012). Chapter 7 - Energy Resources and Potentials. In: *Global Energy Assessment - Toward a Sustainable Future*. IIASA and Cambridge University Press, Vienna, Austria and Cambridge, UK(ISBN: 9781107005198).

Rothman D.S. (1998). Environmental Kuznets curves--real progress or passing the buck?: A case for consumption-based approaches. *Ecological Economics* **25**, 177–194. Available at: http://ideas.repec.org/a/eee/ecolec/v25y1998i2p177-194.html.

Rothman D.S. (2000). Measuring Environmental Values and Environmental Impacts: Going from the Local to the Global. *Climatic Change* **44**, 351–376. (DOI: 10.1023/A:1005645301478). Available at: http://www.springerlink.com/content/h1n81665474t92k3/abstract/.

Roy J. (2000). The rebound effect: some empirical evidence from India. *Energy Policy* **28**, 433–438. Available at: http://ideas.repec.org/a/eee/enepol/v28y2000i6-7p433-438.html.

Roy J., and S. Pal (2009). Lifestyles and climate change: link awaiting activation. *Current Opinion in Environmental Sustainability* **1**, 192–200. (DOI: 10.1016/j.cosust.2009.10.009). Available at: http://www.sciencedirect.com/science/article/pii/S1877343509000396.

Rutherford T.F., and D.G. Tarr (2002). Trade liberalization, product variety and growth in a small open economy: a quantitative assessment. *Journal of International Economics* **56**, 247–272. (DOI: 10.1016/S0022-1996(01)00121-0).

Saikawa E., M. Rigby, R.G. Prinn, S.A. Montzka, B.R. Miller, L.J.M. Kuijpers, P.J.B. Fraser, M.K. Vollmer, T. Saito, Y. Yokouchi, C.M. Harth, J. Muhle, R.F. Weiss, P.K. Salameh, J. Kim, S. Li, S. Park, K.R. Kim, D. Young, S. O'Doherty, P.G. Simmonds, A. McCulloch, P.B. Krummel, L.P. Steele, C. Lunder, O. Hermansen, M. Maione, J. Arduini, B. Yao, L.X. Zhou, H.J. Wang, J.W. Elkins, and B. Hall (2012). Global and regional emission estimates for HCFC-22. *Atmospheric Chemistry and Physics* **12**, 10033–10050. (DOI: 10.5194/Acp-12-10033-2012). Available at: http://www.atmos-chem-phys.net/12/10033/2012/.

Salganik M.J., P.S. Dodds, and D.J. Watts (2006). Experimental Study of Inequality and Unpredictability in an Artificial Cultural Market. *Science* **311**, 854–856. (DOI: 10.1126/science.1121066). Available at: http://www.sciencemag.org/content/311/5762/854.

Sanstad A., M. Hanemann, and M. Auffhammer (2006). *End-use Energy Efficiency in a "Post-Carbon" California Economy: Policy Issues and Research Frontiers.*

Sathaye J., O. Lucon, A. Rahman, J.M. Christensen, F. Denton, J. Fujino, G. Heath, M. Mirza, H. Rudnick, A. Schlaepfer, A. Shmakin, G. Angerer, C. Bauer, M. Bazilian, R. Brecha, P. Burgherr, L. Clarke, F. Creutzig, J. Edmonds, C. Hagelüken, G. Hansen, N. Hultman, M. Jakob, S. Kadner, M. Lenzen, J. Macknick, E. Masanet, Y. Nagai, A. Olhoff, K.H. Olsen, M. Pahle, A. Rabl, R. Richels, J. Roy, C. von Stechow, J. Steckel, E. Warner, T. Wilbanks, Y. Zhang, J. Sathaye, O. Lucon, A. Rahman, J.M. Christensen, F. Denton, J. Fujino, G. Heath, M. Mirza, H. Rudnick, A. Schlaepfer, A. Shmakin, G. Angerer, C. Bauer, M. Bazilian, R. Brecha, P. Burgherr, L. Clarke, F. Creutzig, J. Edmonds, C. Hagelüken, G. Hansen, N. Hultman, M. Jakob, S. Kadner, M. Lenzen, J. Macknick, E. Masanet, Y. Nagai, A. Olhoff, K.H. Olsen, M. Pahle, A. Rabl, R. Richels, J. Roy, C. von Stechow, J. Steckel, E. Warner, T. Wilbanks, and Y. Zhang (2011). Renewable Energy in the Context of Sustainable Development. In: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. C. Von Stechow, C. Von Stechow, (eds.), Cambridge University Press, .Available at: http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch09.

Sathaye J., A. Najam, C. Cocklin, T. Heller, F. Lecocq, J. Llanes-Regueiro, J. Pan, G. Petschel-Held, S. Rayner, and J. Robinson (2007). Sustainable development and mitigation. *Climate Change 2007: Mitigation of Climate Change*, 691–743. Available at: http://eprints.jcu.edu.au/2967/.

Saunders H.D. (2013). Historical evidence for energy efficiency rebound in 30 US sectors and a toolkit for rebound analysts. *Technological Forecasting and Social Change* **80**, 1317–1330. (DOI: 10.1016/j.techfore.2012.12.007). Available at: http://www.sciencedirect.com/science/article/pii/S0040162512003228.

Schäfer A. (2005). Structural change in energy use. *Energy Policy* **33**, 429–437. (DOI: 10.1016/j.enpol.2003.09.002). Available at: http://www.sciencedirect.com/science/article/pii/S0301421503002799.

Schipper L., and M. Grubb (2000). On the rebound? Feedback between energy intensities and energy uses in IEA countries. *Energy Policy* **28**, 367–388. (DOI: 10.1016/S0301-4215(00)00018-5). Available at: http://www.sciencedirect.com/science/article/pii/S0301421500000185.

Schöpp W., Z. Klimont, R. Suutari, and J. Cofala (2005). Uncertainty analysis of emission estimates in the RAINS integrated assessment model. *Environmental Science and Policy* **8**, 601–613.

Shafik N. (1994). Economic Development and Environmental Quality: An Econometric Analysis. *Oxford Economic Papers* **46**, 757–73.

Sheinbaum C., B.J. Ruíz, and L. Ozawa (2011). Energy consumption and related CO2 emissions in five Latin American countries: Changes from 1990 to 2006 and perspectives. *Energy* **36**, 3629–3638. (DOI: doi: 10.1016/j.energy.2010.07.023). Available at: http://www.sciencedirect.com/science/article/pii/S0360544210003981.

Shindell D., J.C.I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S.C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes, J. Schwartz, G. Faluvegi, L. Pozzoli, K. Kupiainen, L. Höglund-Isaksson, L. Emberson, D. Streets, V. Ramanathan, K. Hicks, N.T.K. Oanh, G. Milly, M. Williams, V. Demkine, and D. Fowler (2012). Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science* **335**, 183–189. (DOI: 10.1126/science.1210026).

Shindell D.T., J.F. Lamarque, M. Schulz, M. Flanner, C. Jiao, M. Chin, P.J. Young, Y.H. Lee, L. Rotstayn, N. Mahowald, G. Milly, G. Faluvegi, Y. Balkanski, W.J. Collins, A.J. Conley, S. Dalsoren, R. Easter, S. Ghan, L. Horowitz, X. Liu, G. Myhre, T. Nagashima, V. Naik, S.T. Rumbold, R. Skeie, K. Sudo, S. Szopa, T. Takemura, A. Voulgarakis, J.H. Yoon, and F. Lo (2013). Radiative forcing in the ACCMIP historical and future climate simulations. *Atmospheric Chemistry and Physics* **13**, 2939–2974. (DOI: 10.5194/Acp-13-2939-2013).

Shukla P., and S. Dhar (2011). Climate agreements and India: aligning options and opportunities on a new track. *International Environmental Agreements: Politics, Law and Economics* **11**, 229–243.

Simon H.A. (1957). *Models of man: social and rational; mathematical essays on rational human behavior in society setting*. Wiley, 312 pp.

Sjöström M., and G. Östblom (2009). *Future Waste Scenarios for Sweden based on a CGE-model*. National Institute of Economic Research. Available at: http://ideas.repec.org/p/hhs/nierwp/0109.html.

Slovic P., M. Finucane, E. Peters, and D.G. MacGregor (2002). Rational actors or rational fools: implications of the affect heuristic for behavioral economics. *The Journal of Socio-Economics* **31**, 329–342. (DOI: 10.1016/S1053-5357(02)00174-9). Available at: http://www.sciencedirect.com/science/article/pii/S1053535702001749.

Smith S.J., J. van Aardenne, Z. Klimont, R. Andres, A.C. Volke, and S. Delgado Arias (2011). Anthropogenic Sulfur Dioxide Emissions: 1850-2005. *Journal Name: Atmospheric Chemistry and Physics, 11(3):1101-1116; Journal Volume: 10*, Medium: X.

Sora M.J., and I.P. Ventosa (2013). *Incineration overcapacity and waste shipping in Europe the end of the proximity principle?* Global Alliance for Incinerator Alternatives. Available at: http://www.no-burn.org/downloads/Incineration%20overcapacity%20and%20waste%20shipping%20in%20Europe%20the%20end%20of%20the%20proximity%20principle%20-January%202013-1.pdf.

Sorrell S. (2007). The rebound effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency. Available at: http://www.ukerc.ac.uk/support/tiki-index.php?page=ReboundEffect.

Sorrell S., J. Dimitropoulos, and M. Sommerville (2009). Empirical estimates of the direct rebound effect: A review. *Energy Policy* **37**, 1356–1371. Available at: http://ideas.repec.org/a/eee/enepol/v37y2009i4p1356-1371.html.

Sovacool B.K., and M.A. Brown (2010). Twelve metropolitan carbon footprints: A preliminary comparative global assessment. *Energy Policy* **38**, 4856–4869. (DOI: 10.1016/j.enpol.2009.10.001). Available at: http://www.sciencedirect.com/science/article/pii/S0301421509007277.

Steckel J.C., M. Jakob, R. Marschinski, and G. Luderer (2011). From carbonization to decarbonization?—Past trends and future scenarios for China's CO2 emissions. *Energy Policy* **39**, 3443–3455. (DOI: doi: 10.1016/j.enpol.2011.03.042). Available at: http://www.sciencedirect.com/science/article/pii/S0301421511002229.

Steg L., C. Vlek, and G. Slotegraaf (2001). Instrumental-reasoned and symbolic-affective motives for using a motor car. *Transportation Research Part F: Traffic Psychology and Behaviour* **4**, 151–169. (DOI: 10.1016/S1369-8478(01)00020-1). Available at: http://www.sciencedirect.com/science/article/pii/S1369847801000201.

Stern D.I. (2010). *The Role of Energy in Economic Growth*. Social Science Research Network, Rochester, NY. Available at: http://papers.ssrn.com/abstract=1715855.

Stern D.I. (2011). The role of energy in economic growth. *Annals of the New York Academy of Sciences* **1219**, 26–51. (DOI: 10.1111/j.1749-6632.2010.05921.x). Available at: http://onlinelibrary.wiley.com/doi/10.1111/j.1749-6632.2010.05921.x/abstract.

Stern D.I. (2012). Modeling international trends in energy efficiency. *Energy Economics* **34**, 2200–2208. (DOI: 10.1016/j.eneco.2012.03.009). Available at: http://www.sciencedirect.com/science/article/pii/S0140988312000539.

Stern D.I., M.S. Common, and E.B. Barbier (1996). Economic growth and environmental degradation: The environmental Kuznets curve and sustainable development. *World Development* **24**, 1151–1160. (DOI: 10.1016/0305-750X(96)00032-0). Available at: http://www.sciencedirect.com/science/article/pii/0305750X96000320.

Stern D.I., and F. Jotzo (2010). How ambitious are China and India's emissions intensity targets? *Energy Policy* **38**, 6776–6783. (DOI: 10.1016/j.enpol.2010.06.049). Available at: http://www.sciencedirect.com/science/article/pii/S0301421510005136.

Stern D.I., and A. Kander (2012). The role of energy in the industrial revolution and modern economic growth. *Energy Journal* **33**, 127–154. Available at: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1759705.

Stiglitz J.E. (1988). *Principal and Agent*. John M. Olin Program for the Study of Economic Organization and Public Policy, Department of Economics/Woodrow Wilson School of Public and International Affairs, Princeton University, 30 pp.

Strømman A.H., E.G. Hertwich, and F. Duchin (2009). Shifting Trade Patterns as a Means of Reducing Global Carbon Dioxide Emissions. *Journal of Industrial Ecology* **13**, 38–57. (DOI: 10.1111/j.1530-9290.2008.00084.x). Available at: http://onlinelibrary.wiley.com/doi/10.1111/j.1530-9290.2008.00084.x/abstract.

Sue Wing I. (2008). Explaining the declining energy intensity of the U.S. economy. *Resource and Energy Economics* **30**, 21–49. (DOI: 10.1016/j.reseneeco.2007.03.001). Available at: http://www.sciencedirect.com/science/article/pii/S0928765507000164.

Suh S. (2005). Developing a sectoral environmental database for input-output analysis: the comprehensive environmental data archive of the US. *Economic Systems Research* **17**, 449–469. Available at: http://econpapers.repec.org/article/tafecsysr/v_3a17_3ay_3a2005_3ai_3a4_3ap_3a449-469.htm.

Suh S. (2006). Are Services Better for Climate Change? *Environ. Sci. Technol.* **40**, 6555–6560. (DOI: 10.1021/es0609351). Available at: http://dx.doi.org/10.1021/es0609351.

Syrquin M., and H. Chenery (1989). Three Decades of Industrialization. *The World Bank Economic Review* **3**, 145 –181. (DOI: 10.1093/wber/3.2.145). Available at: http://wber.oxfordjournals.org/content/3/2/145.abstract.

Teng H., G. Branstator, and G.A. Meehl (2011). Predictability of the Atlantic overturning circulation and associated surface patterns in two CCSM3 climate change ensemble experiments. *Journal of Climate* **24**, 6054–6076. Available at: http://journals.ametsoc.org/doi/abs/10.1175/2011JCLI4207.1.

Thaler R.H. (1999). Mental accounting matters. *Journal of Behavioral Decision Making* **12**, 183–206. (DOI: 10.1002/(SICI)1099-0771(199909)12:3<183::AID-BDM318>3.0.CO;2-F). Available at: http://onlinelibrary.wiley.com/doi/10.1002/(SICI)1099-0771(199909)12:3<183::AID-BDM318>3.0.CO;2-F/abstract.

Thaler R.H., and C.R. Sunstein (2009). *Nudge: Improving Decisions About Health, Wealth, and Happiness*. Penguin Books, 320 pp., (ISBN: 014311526X).

Thomas B.A., and I.L. Azevedo (2013). Estimating direct and indirect rebound effects for U.S. households with input–output analysis Part 1: Theoretical framework. *Ecological Economics* **86**, 199–210. (DOI: 10.1016/j.ecolecon.2012.12.003). Available at: http://www.sciencedirect.com/science/article/pii/S0921800912004764.

Timilsina G.R., and A. Shrestha (2009). Transport sector CO2 emissions growth in Asia: Underlying factors and policy options. *Energy Policy* **37**, 4523–4539. (DOI: 10.1016/j.enpol.2009.06.009). Available at: http://www.sciencedirect.com/science/article/pii/S0301421509004236.

Tol R.S.J., S.W. Pacala, and R.H. Socolow (2009). Understanding Long-Term Energy Use and Carbon Dioxide Emissions in the USA. *Journal of Policy Modeling* **31**, 425–445. (DOI: 10.1016/j.jpolmod.2008.12.002). Available at: http://www.sciencedirect.com/science/article/pii/S0161893808001014.

Toman M.A., and B. Jemelkova (2003). Energy and economic development: An assessment of the state of knowledge. *The Energy Journal* **24**, 93–112.

De la Tour A., M. Glachant, and Y. Ménière (2011). Innovation and international technology transfer: The case of the Chinese photovoltaic industry. *Energy Policy* **39**, 761–770. (DOI: 10.1016/j.enpol.2010.10.050). Available at: http://www.sciencedirect.com/science/article/pii/S0301421510008013.

Train K. (1985). Discount rates in consumers' energy-related decisions: a review of the literature. *Energy* **10**, 1243–1253.

Tukker A., M.J. Cohen, K. Hubacek, and O. Mont (2010). The Impacts of Household Consumption and Options for Change. *Journal of Industrial Ecology* **14**, 13–30.

U.S. Energy Information Administration (2010). *Annual Energy Review 2009*. Washington DC. Available at: http://www.eia.gov/totalenergy/data/annual/.

Ubaidillah N.Z. (2011). The Relationship between Income and Environment in UK's Road Transport Sector. Is There an EKC? Available at: http://www.ipedr.com/vol4/20-F00040.pdf.

UN (1999). *The World at Six Billion*. Available at: http://www.un.org/esa/population/publications/sixbillion/sixbillion.htm.

UN WPP (2012). *World Population Prospects, the 2012 Revision*. United Nations Department of Economic and Social Affairs. Available at: http://esa.un.org/wpp/.

UNEP (2009). *UNEP 2008 Annual Report*. United Nations Environment Programme. Available at: http://www.unep.org/PDF/AnnualReport/2008/AnnualReport2008_en_web.pdf.

UNEP (2012). The Emissions Gap Report 2012: A UNEP Synthesis Report. United Nations Environment Programme. Available at: http://www.unep.org/pdf/2012gapreport.pdf.

Unruh G.C. (2000). Understanding carbon lock-in. *Energy Policy* **28**, 817–830. (DOI: 10.1016/S0301-4215(00)00070-7). Available at: http://www.sciencedirect.com/science/article/pii/S0301421500000707.

Unruh G.C. (2002). Escaping carbon lock-in. *Energy Policy* **30**, 317–325. (DOI: 10.1016/S0301-4215(01)00098-2). Available at: http://www.sciencedirect.com/science/article/pii/S0301421501000982.

US DOE (2008). *Energy Efficiency Trends in Residential and Commercial Buildings*. US Department of Energy. Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/bt_stateindustry.pdf.

US EIA (2011). *International Energy Outlook*. U.S. Energy Information Administration, 300 pp., (ISBN: 9780160894459).

US EPA (2012). *Inventory of U.S. Greenhouse Gas Emissions And Sinks: 1990-2010*. US EPA. Available at: http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2012-Main-Text.pdf.

Verdolini E., and M. Galeotti (2011a). At home and abroad: An empirical analysis of innovation and diffusion in energy technologies. *Journal of Economics and Management* **61**, 119–134.

Verdolini E., and M. Galeotti (2011b). At home and abroad: An empirical analysis of innovation and diffusion in energy technologies. *Journal of Environmental Economics and Management* **61**, 119–134. Available at: http://ideas.repec.org/a/eee/jeeman/v61y2011i2p119-134.html.

Van Vuuren D.P., J. Cofala, H.E. Eerens, R. Oostenrijk, C. Heyes, Z. Klimont, M.G.J. den Elzen, and M. Amann (2006). Exploring the ancillary benefits of the Kyoto Protocol for air pollution in Europe. *Energy Policy* **34**, 444–460. (DOI: 10.1016/j.enpol.2004.06.012).

Wagner M. (2008). The carbon Kuznets curve: A cloudy picture emitted by bad econometrics? *Resource and Energy Economics* **30**, 388–408. (DOI: 10.1016/j.reseneeco.2007.11.001). Available at: http://www.sciencedirect.com/science/article/pii/S0928765507000504.

Wang C. (2011). Sources of energy productivity growth and its distribution dynamics in China. *Resource and Energy Economics* **33**, 279–292. (DOI: 10.1016/j.reseneeco.2010.06.005). Available at: http://www.sciencedirect.com/science/article/pii/S0928765510000552.

Wang H., L. Dwyer-Lindgren, K.T. Lofgren, J.K. Rajaratnam, J.R. Marcus, A. Levin-Rector, C.E. Levitz, A.D. Lopez, and C.J. Murray (2012a). Age-specific and sex-specific mortality in 187 countries, 1970–2010: a systematic analysis for the Global Burden of Disease Study 2010. *The Lancet* **380**, 2071–2094. (DOI: 10.1016/S0140-6736(12)61719-X). Available at: http://www.sciencedirect.com/science/article/pii/S014067361261719X.

Wang W.W., M. Zhang, and M. Zhou (2011). Using LMDI method to analyze transport sector CO2 emissions in China. *Energy* **36**, 5909–5915. (DOI: 10.1016/j.energy.2011.08.031). Available at: http://www.sciencedirect.com/science/article/pii/S0360544211005718.

Wang H., P. Zhou, and D.Q. Zhou (2012b). An empirical study of direct rebound effect for passenger transport in urban China. *Energy Economics* **34**, 452–460. (DOI: 10.1016/j.eneco.2011.09.010). Available at: http://www.sciencedirect.com/science/article/pii/S014098831100226X.

Warr B., R. Ayres, N. Eisenmenger, F. Krausmann, and H. Schandl (2010). Energy use and economic development: A comparative analysis of useful work supply in Austria, Japan, the United Kingdom and the US during 100 years of economic growth. *Ecological Economics* **69**, 1904–1917. (DOI: 10.1016/j.ecolecon.2010.03.021). Available at: http://www.sciencedirect.com/science/article/pii/S0921800910001175.

Weber C.L. (2009). Measuring structural change and energy use: Decomposition of the US economy from 1997 to 2002. *Energy Policy* **37**, 1561–1570. (DOI: 10.1016/j.enpol.2008.12.027). Available at: http://www.sciencedirect.com/science/article/pii/S0301421508007659.

Weber C., and S. Matthews (2007). Embodied Environmental Emissions in U.S. International Trade, 1997−2004. *Environ. Sci. Technol.* **41**, 4875–4881. (DOI: 10.1021/es0629110). Available at: http://dx.doi.org/10.1021/es0629110.

Weber C.L., and H.S. Matthews (2008). Quantifying the global and distributional aspects of American household carbon footprint. *Ecological Economics* **66**, 379–391. (DOI: 10.1016/j.ecolecon.2007.09.021). Available at: http://www.sciencedirect.com/science/article/pii/S0921800907004934.

Weber C.L., and G.P. Peters (2009). Climate change policy and international trade: Policy considerations in the US. *Energy Policy* **37**, 432–440. (DOI: 10.1016/j.enpol.2008.09.073). Available at: http://www.sciencedirect.com/science/article/pii/S0301421508005223.

Weber C.L., G.P. Peters, D. Guan, and K. Hubacek (2008). The contribution of Chinese exports to climate change. *Energy Policy* **36**, 3572–3577. (DOI: 10.1016/j.enpol.2008.06.009). Available at: http://www.sciencedirect.com/science/article/pii/S0301421508002905.

Wei C., J. Ni, and M. Shen (2009). Empirical Analysis of Provincial Energy Efficiency in China. *China & World Economy* **17**, 88–103. (DOI: 10.1111/j.1749-124X.2009.01168.x). Available at: http://onlinelibrary.wiley.com/doi/10.1111/j.1749-124X.2009.01168.x/abstract.

Welsch H., and C. Ochsen (2005). The determinants of aggregate energy use in West Germany: factor substitution, technological change, and trade. *Energy Economics* **27**, 93–111. Available at: http://ideas.repec.org/a/eee/eneeco/v27y2005i1p93-111.html.

West J.J., S.J. Smith, R.A. Silva, V. Naik, Y. Zhang, Z. Adelman, M.M. Fry, S. Anenberg, L.W. Horowitz, and J.-F. Lamarque (2013). Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change* **3**, 885–889. (DOI: 10.1038/nclimate2009).

Whitmarsh L. (2009). Behavioural responses to climate change: Asymmetry of intentions and impacts. *Journal of Environmental Psychology* **29**, 13–23.

Wiedmann T. (2009). A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecological Economics* **69**, 211–222. (DOI:

10.1016/j.ecolecon.2009.08.026). Available at: http://www.sciencedirect.com/science/article/pii/S0921800909003577.

Wiedmann T., M. Lenzen, K. Turner, and J. Barrett (2007). Examining the global environmental impact of regional consumption activities -- Part 2: Review of input-output models for the assessment of environmental impacts embodied in trade. *Ecological Economics* **61**, 15–26. Available at: http://ideas.repec.org/a/eee/ecolec/v61y2007i1p15-26.html.

Wiedmann T., R. Wood, J. Minx, M. Lenzen, D. Guan, and R. Harris (2010). A Carbon Footprint Time Series of the UK - Results from a Multi-Region Input-Output Model. *Economic Systems Research* **22**, 19–42. Available at: http://dx.doi.org/10.1080/09535311003612591.

Wier M. (1998). Sources of changes in emissions from energy: a structural decomposition analysis. *Economic Systems Research* **10**, 99–112.

Wier M., M. Lenzen, J. Munksgaard, and S. Smed (2001). Effects of household consumption patterns on CO2 requirements. *Economic Systems Research* **13**, 259–274.

Wilbanks T.J. (2011). Inducing transformational energy technological change. *Energy Economics* **33**, 699–708. Available at: http://ideas.repec.org/a/eee/eneeco/v33y2011i4p699-708.html.

Wood R. (2009). Structural decomposition analysis of Australia's greenhouse gas emissions. *Energy Policy* **37**, 4943–4948. (DOI: 10.1016/j.enpol.2009.06.060). Available at: http://www.sciencedirect.com/science/article/pii/S0301421509004704.

World Bank (2011). *World Development Indicators*. World Bank, Washington DC. Available at: http://data.worldbank.org/data-catalog/world-development-indicators.

World Bank (2012). World Development Indicators | Data. Available at: http://data.worldbank.org/data-catalog/world-development-indicators.

World Trade Organisation (2011). *International Trade Statistics, 2011*. Available at: http://www.wto.org/english/res_e/statis_e/its2011_e/its11_toc_e.htm.

Wrigley E. (2010). *Energy and the English Industrial Revolution*. Cambridge University Press, Cambridge ;;New York, (ISBN: 9780521766937).

Wu F., L.W. Fan, P. Zhou, and D.Q. Zhou (2012). Industrial energy efficiency with CO2 emissions in China: A non-parametric analysis. *Energy Policy* **49**, 164–172.

York R. (2007). Demographic trends and energy consumption in European Union Nations, 1960–2025. *Social Science Research* **36**, 855–872. (DOI: 10.1016/j.ssresearch.2006.06.007). Available at: http://www.sciencedirect.com/science/article/pii/S0049089X06000524.

Yunfeng Y., and Y. Laike (2010). China's foreign trade and climate change: A case study of CO2 emissions. *Energy Policy* **38**, 350–356. (DOI: 10.1016/j.enpol.2009.09.025). Available at: http://www.sciencedirect.com/science/article/pii/S0301421509007083.

Zhu S.C., and D. Trefler (2005). Trade and inequality in developing countries: a general equilibrium analysis. *Journal of International Economics* **65**, 21–48.