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		
(Sub)Section:	All		
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Remarks:	Second Order Draft (SOD)		
Version:	1		
File name:	WGIII_AR5_Draft2_Ch05		
Date:	22 February 2013	Template Version:	8

Chapter 5: Drivers, Trends and Mitigation

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Executive Summary

CO2 continues to be the most important anthropogenic greenhouse gas; its increase is due primarily to the combustion of fossil fuels and, to a lesser extent, to land use change. Between 1970 and 2010, global anthropogenic GHG emissions increased from 27.9 to 50.1 GtCO2e/yr (using GWP100). CO2 emissions increased by about 80% while CH4 and N2O increased by about 45% and 40%, respectively. Fluorinated gases represent a minuscule amount over the entire time span.

At sectoral level, global emissions trends can be summarized as follows. Emissions from the energy sector increased by 290%, from 6.1 to 17.5 GtCO2e/yr, between 1970 and 2010 (high confidence). Transport-related emissions increased by 230%, from 2.9 GtCO2e/yr in 1970 to 6.7 GtCO2 e/yr in 2010 (high confidence). Industry GHG emissions have grown from 6.3 GtCO2eq/yr in 1970 to 10.5 GtCO2eq /yr in 2010, with an increased growth rate after 2002 attributed to a 66% growth in China's industry (high confidence). Emissions from the building sector have increased by 27%, from 2.6 GtCO2eq/yr in 1970 to 3.3 GtCO2eq/yr in 2010 (medium confidence). Emissions from agriculture, forestry and other land uses (FOLU) increased by 25%, from 10 to 12 GtCO2eq/yr over the same period. Waste GHG emissions increased substantially but remained below 3 % of global GHG emissions (medium agreement, robust evidence).

In order to identify the main factors and drivers for the GHG emissions trends, a decomposition analysis based on IPAT and Kaya identities is used. The decomposition attributes changes in global emissions to changes of population size, per capita production or expenditures, and the emission-intensity of production and consumption. For energy-related emissions, the decomposition further divides the emission-intensity into energy-intensity of production and the carbon-intensity of energy.

Global population has increased by 87%, from 3.7 in 1970 to 6.9 billion in 2010 (high confidence). The direct effect of population on emissions is a proportional increase. The population has been increasing mainly in Asia, Latin America and Africa (high agreement, robust evidence). But the emissions increase for an additional person varies widely, depending on geographical location, income, lifestyle, and the available energy resources and technologies, among other factors. The gap between the top and bottom countries in terms of per capita emissions exceeds a factor of 50, though individual countries have changed their position in the ranking considerably (high agreement, robust evidence). The indirect effects of demographic changes on emissions are diverse (high agreement, robust evidence). Urbanization, ageing and household size have subtle effects on emissions; their overall effects are considered small compared to the direct effect of changes in population size (medium agreement, medium evidence).

As a measure of economic growth, per capita income in PPP has increased by 165%, from 3.7 in 1970 to 9.8 thousand USD2000/yr in 2010 (medium confidence) with much variation over time and regions (very high confidence). Innovation and investments are among the key long-term drivers of economic growth (medium agreement and evidence). Economic growth was strong in Asia, the OECD also showed considerable growth levels, while Latin America showed lower economic growth over the entire period. Africa and the formerly centrally planned economies have seen setbacks in economic growth. Growth in per capita productivity in OECD countries has been balanced by a proportional decrease in emission-intensity while per capita productivity growth in developing countries has been correlated with higher per capita emissions (high confidence) although the average per capita emissions in OECD countries of approximately 14 tCO2eq/yr are still more than twice the global average. Sector shifts, from agriculture to industry and services, is probably less important for the development of emissions than improved energy efficiency within sectors (low agreement, medium evidence).

The territorial-based emissions share of the OECD countries has decreased considerably as did their per capita emissions associated with production (high agreement, robust evidence). However, over the last 10 years, per capita emissions associated with consumption increased. Generally, consumption-based emissions are higher than territorial-based emissions for developed countries and lower for emerging economies (high agreement, medium evidence).

International trade has grown by about 10% annually between 1970 and 2010; emissions embedded in trade result in significant variation between the territorial-based and consumption-based GHG emissions of countries. Trade is not a significant driver of global emissions per se, but it is an important driver for the regional distribution (medium agreement, medium evidence). Trade also implies transport, and in this respect it contributes increasingly to greenhouse gas emissions with a robust upward trend.

Emission-intensity of production and consumption has declined by 64%, from 2.0 in 1970 to 0.72 kgCO2e/USD2000 in 2010. In particular, in relation to energy-related emissions, long-term statistical records since 1880 show improvements in energy intensities of economic outputs (measured by GDP) by an average decline of about 1% per year (high confidence). Most regions show declining trends in energy intensity over the period 1970-2010 (high confidence) including most developed countries and major developing countries such as India and China. Fast economic growth leads to a higher turnover of the capital stock, offering opportunities to switch to more energy-efficient technologies (low to medium confidence). Regarding carbon intensity since 1880, the fossil fuels mix has moved from mainly coal to increasing shares of oil and gas, with lower carbon per unit of energy released when burned (very high confidence). The global rate of energy decarbonization has been on average about 0.3% annually from 1970 to 2010, not sufficient to offset the increase in global energy use of about 2% annually. The last decade shows a significant slowdown of the decarbonization rate, particularly due to rising carbon intensities in some developing regions, and to the lingering turnover of the energy system in developed countries (high confidence).

From the analysis of the factors in the decomposition of GHG emissions over the past 40 years, the improvements in energy intensity at a global level and the slight reduction in the carbon content of energy resources have not been sufficient to overcome the increasing per capita income and population trends leading to a substantial increase in GHG emissions.

When looking at the underlying drivers of these trends, technological, infrastructure and behavioural choices and changes appear to be key.

Technological change drives overall economic growth as well as the energy intensity of growth and the carbon-intensity of energy. Some new technologies lead to lower greenhouse gas emissions, but other innovations improve labour productivity and increase emissions. Moreover, technological innovations that potentially decrease emissions (e.g. energy-saving technologies) are sometimes offset by the “rebound effect”, a phenomenon where efficiency improvements induce an increase in demand reducing the innovations original emissions benefits.

Infrastructural choices before the 1970s have had long-lasting effects on emissions after 1970s, as they determined, for example, the fuel of choice. Infrastructure also guides the choices in technological innovation. The mechanism is reasonably understood, but data are insufficient to quantify its role in facilitating or impeding reductions in GHG emissions.

Behavioural choices are important agents for change in emissions trends; the literature mainly considers behaviour through changes in the demand for goods and services towards those that entail lower emissions (medium agreement and confidence). There is not much quantitative evidence on the effects of specific behavioural changes on past emissions trends, but there is evidence on large variations in emissions implied by different consumption patterns and lifestyles (low agreement, limited evidence). Across countries various policies and strategies have been used to change individual choices, sometimes through changing the context in which decisions are made, at varying degrees of success.

In addition to technological and behavioural related drivers, co-benefits derived from the implementation of non-environmental policies may also affect emissions trends, although their quantitative influence on past emissions is not clear.

The analysis of factors and drivers is not straightforward, they are interconnected and influence each other; the effects of an individual driver on past GHG emissions are difficult to isolate and quantify. Policies and measures, in turn, can be designed and implemented to affect drivers but at the same time other drivers influence policy makers and affect the type of policies and measures that are finally adopted.

To bring about a major shift in GHG emissions trends, as stabilization pathways require, behaviour, infrastructure and technological choices need to be address and act upon as early as possible, as these choices will affect future emissions for several decades. Technological change contributes to the decrease in energy intensity across regions although the rebound effect may diminish its final effect on emissions; resource availability, in particular fossil fuels, influences the development pathways of many countries; behavioural change, as an overarching driver, affects other drivers such as consumption patterns and food and technological choices. Past policies have not changed drivers and trends in a way that has stopped the upward GHG emissions trends. If future policies aim to change the trends and bring emissions down, they will have to be different from past policies.

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 GHG emissions from fossil fuel combustion followed by emissions from land use, land use change and forestry (LULUCF) were the main causes of the rising GHG levels in the atmosphere (IPCC, 2007). Chapter 5 analyzes the factors and drivers associated with anthropogenic GHG emissions in the past as a reference for assessing the potential future emissions and mitigation measures in subsequent chapters beginning with Chapter 6.

For a systematic assessment of the main factors and drivers of the observed patterns of GHG emission trends, this and subsequent chapters employ a decomposition analysis based on the IPAT and Kaya identities. Chapter 5 first considers the *factors* in the decomposition that affect total emissions such as population, GDP and GNE per capita, energy intensity and GHG emissions intensity of energy. Secondly, it considers the underlying *drivers* defined as the processes, mechanisms and properties of society that influence emissions through the factors, such as ease of use and prices of fossil fuels, consumption patterns, structural and technological changes and behavioural choices. Where policies and measures can be applied, these drivers may induce changes in GHG emissions trends.

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 *5.3.3 Energy demand and supply* and *5.3.4 Other key sectors*.

The decomposition framework and its main results at both global and regional levels are presented in section *5.3 Key drivers of global change*. Due to data availability, section 5.3 as well as the subsequent sections uses a 40-year timeframe, from 1970 to 2010. The trends of the different factors in the decomposition identity are discussed in subsections *5.3.2 Population and demographic structure*, *5.3.3 Energy demand and supply*, and *5.3.4 Other key sectors*, including transport, buildings, industry, forestry, agriculture, and waste sectors. The drivers directly related to these factors and their trends are identified and analyzed.

At a more profound level, drivers underlying past emissions trends are identified and discussed in sections *5.4 Production and trade patterns*, *5.5 Consumption and behavioural change*, and *5.6*

Contribution of technological change to mitigation. In these sections, the influence of individual and societal choices as well as the impact of technological changes on the GHG emissions factors is thoroughly discussed.

Section *5.7 Co-benefits and trade-offs of mitigation actions*, in turn, identifies the effects of GHGH mitigation policies, measures or actions on other aspects such as energy security and public health.

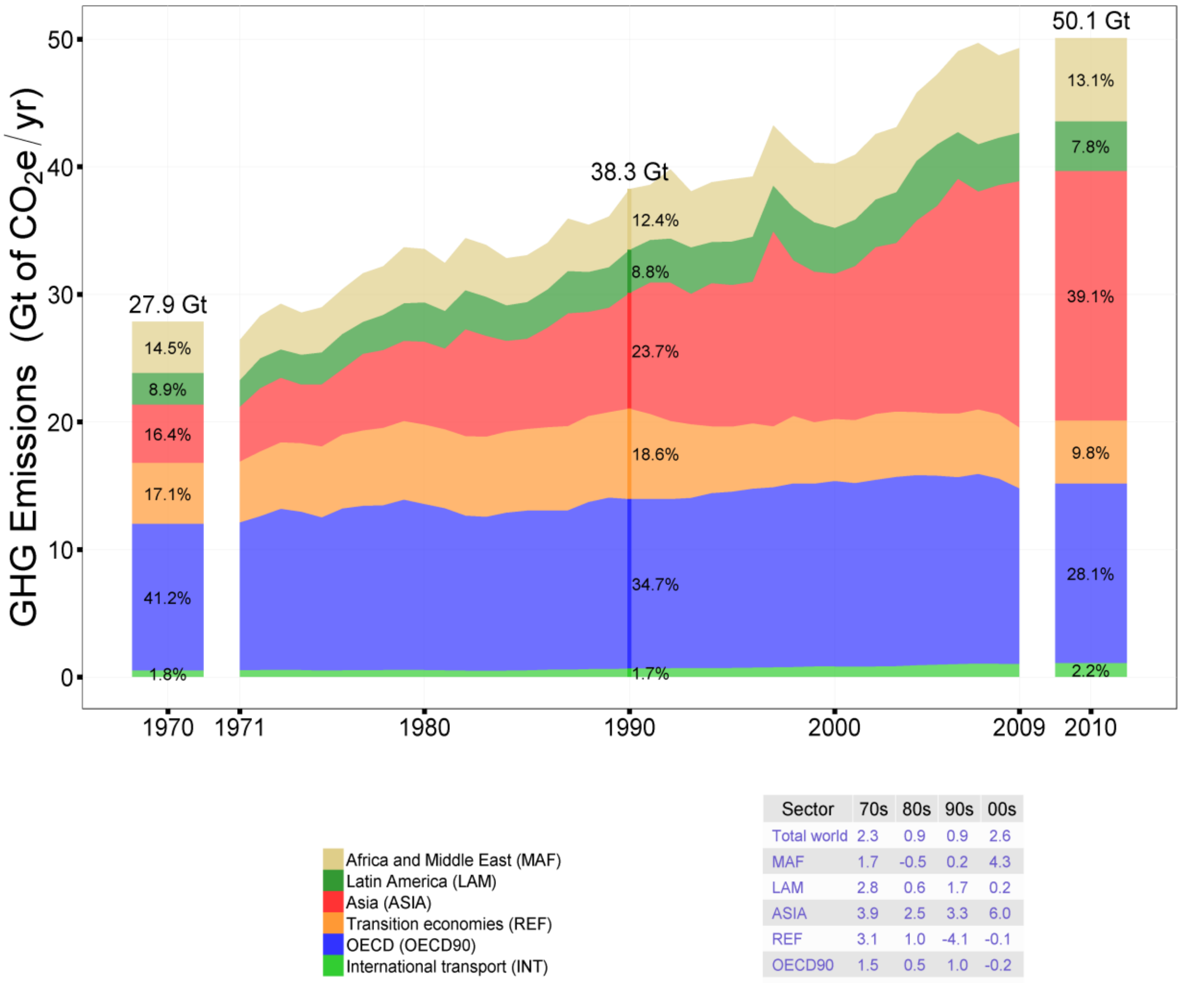
Section *5.8 The System Perspective: Linking Sectors, Technologies and Consumption Patterns* syntheses the main findings of the chapter and highlights the relevant linkages among drivers and between drivers and factors that may be key for the design of mitigation policies and measures.

Finally, section *5.9 Gaps in knowledge and data* addresses shortages in the dataset that prevent a more thorough analysis of certain variables and factors or limit their time span. The section also discussed the gaps in the knowledge on the linkages among factors and 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, greenhouse gas emissions increased from 27.9 to 50.1 GtCO2eq (Fig 5.2.1). As we see in Figure 5.2.3a, carbon dioxide (CO2) is the most important anthropogenic greenhouse gas (GHG). Its increase is due primarily to the combustion of fossil fuels and land use change. In 2010, CO2 emissions exceeded 75% of GWP weighted anthropogenic greenhouse gas emissions. Between 1970-2010, global anthropogenic CO2 emissions increased by about 80%, while CH4 and N2O by about 45% and 40% respectively. Fluorinated gases, which represented about 0.1% in 1970, increased to comprise between 1 and 2% of GHG emissions in 2010.



Sector	70s	80s	90s	00s
Total world	2.3	0.9	0.9	2.6
MAF	1.7	-0.5	0.2	4.3
LAM	2.8	0.6	1.7	0.2
ASIA	3.9	2.5	3.3	6.0
REF	3.1	1.0	-4.1	-0.1
OECD90	1.5	0.5	1.0	-0.2
INT	0.4	2.0	2.4	3.2

Figure 5.2.1. GHG emissions per region (territorial) over 1970-2010 (JRC, 2012). Following general practice (e.g. UNFCCC), 100-year GWPs are used for comparing GHG emissions in this section. There is, however, no unique method of comparing trends for different climate forcing agents. The section on Metrics in Chapter 3 discusses the implications of using different metrics or time horizons.

Figure 5.2.2 shows the growth in CO2 emissions, the main GHG, since 1850. In developing countries emissions of carbon dioxide have increased rapidly between 2000 and 2010. This sharp increase results from developing countries experiencing 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 clear 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.

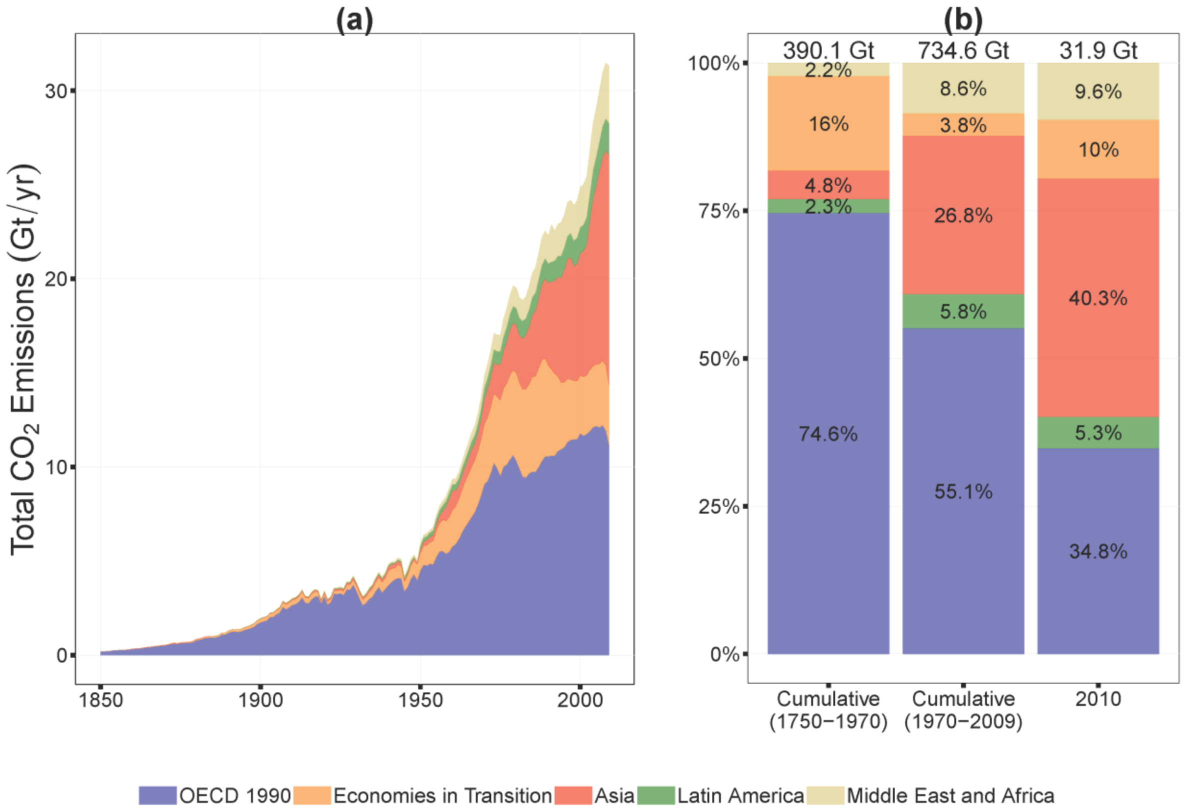
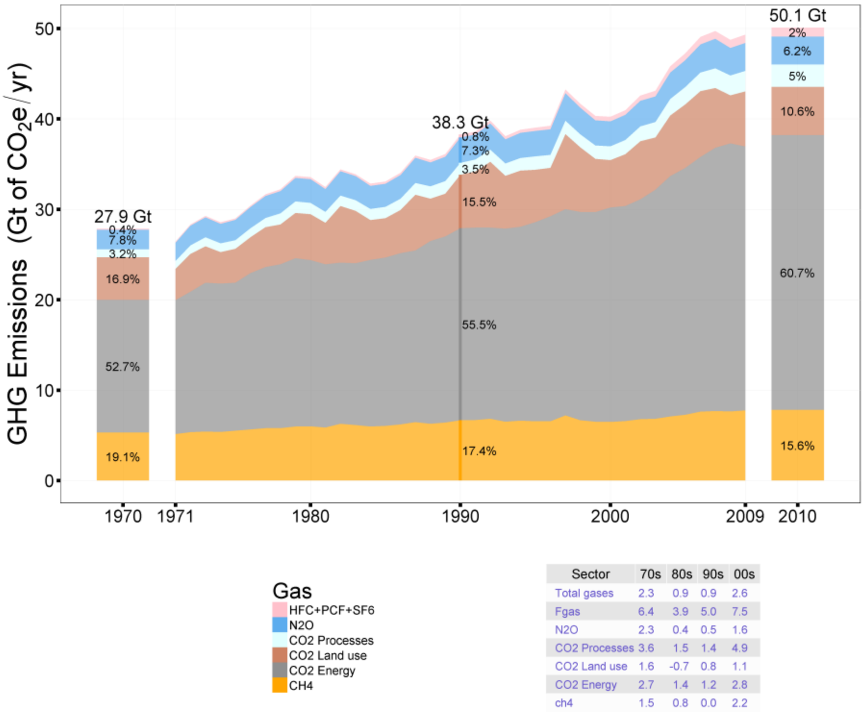


Figure 5.2.2. Historic fossil-fuel CO2 emissions per region (territorial). The figure shows that as regions industrialize their CO2 emissions increase reflecting an increase in energy intensity (Boden et al., 2012).

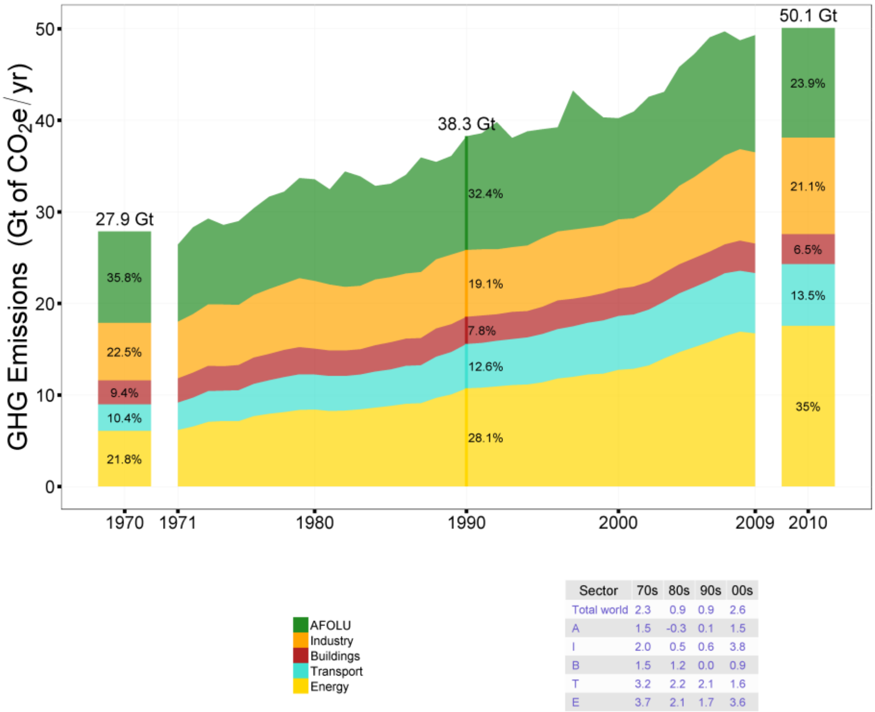
Figure 5.2.3a shows the trends for major greenhouse gases, over 1970 through 2010, the period where comprehensive data is available. Total GWP-weighted greenhouse gas emissions increased by about 75% between 1970 and 2010 (IEA, 2011). By comparison, radiative forcing (see below) for the same substances increased by 100% over the same period (Meinshausen et al., 2011).

(a)



Sector	70s	80s	90s	00s
Total gases	2.3	0.9	0.9	2.6
Fgas	6.4	3.9	5.0	7.5
N2O	2.3	0.4	0.5	1.6
CO2 Processes	3.6	1.5	1.4	4.9
CO2 Land use	1.6	-0.7	0.8	1.1
CO2 Energy	2.7	1.4	1.2	2.8
ch4	1.5	0.8	0.0	2.2

(b)



Sector	70s	80s	90s	00s
Total world	2.3	0.9	0.9	2.6
A	1.5	-0.3	0.1	1.5
I	2.0	0.5	0.6	3.8
B	1.5	1.2	0.0	0.9
T	3.2	2.2	2.1	1.6
E	3.7	2.1	1.7	3.6

Figure 5.2.3. *The principal greenhouse gases and sources*. that enter the atmosphere because of human activities (JRC, 2012). *Panel (a)*: CO2 continues to be the major anthropogenic greenhouse gas accounting for more than 75% of GWP-weighted emissions. Non CO2 greenhouse gases are converted to CO2 equivalents using 100-year global warming potentials. *Panel (b)*. Contribution is more diversified over sectors. Emissions related to transport and energy increased most.

CO2 is the largest contributor to anthropogenic emissions. CO2 is released during the combustion of fossil fuels such as coal, oil and gas in power plants, industrial operations and transportation as well as the the production of cement. CO2 emissions from land use change are due primarily to deforestation. Fossil carbon dioxide emissions over 2002-2011 were estimated at 8.3 ± 0.7 GtC/yr and emissions associated with land use estimated to be 1.6 ± 1 GtC/yr (Ciais et al., 2014).

Methane (CH4) 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. Approximately half of global methane emissions are related to human activities, although these emissions and their attribution to source sectors are uncertain (Myhre et al., 2014). The largest natural source of methane is wetlands, with a variety of additional sources including freshwater bodies, geological sources, and other animals (Ciais et al., 2014).

The third most important anthropogenic greenhouse gas is nitrous oxide (N2O), which is emitted during agricultural and industrial activities, as well as during combustion and human waste disposal. Current estimates are that about 40% of total N20 emissions are anthropogenic. While uncertainty for CH4 and N2O will, in general, be larger than those for fossil CO2, global uncertainty ranges by source for these emissions have not been quantified (Ciais et al., 2014).

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 are typically emitted in smaller quantities, but because they are potent greenhouse gases, they are sometimes referred to as High Global Warming Potential gases (“High GWP gases”). These gases are emitted 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.

GHGs are emitted from many societal activities (Figure 5.2.3b), and the next sections of this chapter describe the main trends associated with these activities and prospects for future mitigation options.

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 in the future. The exact rate of increase cannot be known but a 75% increase in emissions occurred between 1970 and 2008, from just over 25 gigatons of GHG to over 45 gigatons. A business-as-usual view would assume that rate would continue into the future. The human population will increase at approximately the rate of recent decades, and on global scales economies will continue to grow, as well as energy consumption per person. The latter two factors already vary greatly among countries, and national policies can affect their future trajectories as well as how much economic growth and energy consumption contribute to GHG emissions. 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 give no indication that the aggregate effects of population and economic growth plus personal energy consumption rates will result in a reduced rate of growth in GHG emissions.

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. These changes are discussed in terms of radiative forcing, which is the change in the radiative energy budget of the Earth (Myhre et al., 2014). A positive forcing, such as that due to increases in GHGs, tends to warm the system while a negative forcing tends to cool it. Trends for the relevant emissions are shown in the Figure 5.2.4

Aerosols contribute a net negative, but uncertain, radiative forcing (IPCC, 2007; Myhre et al., 2014). 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).

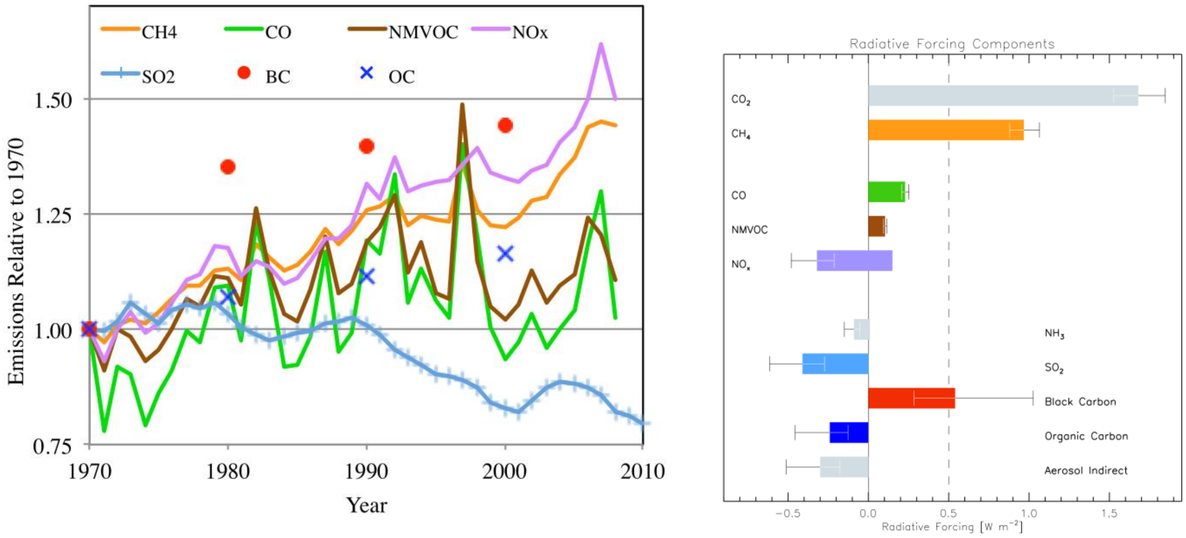


Figure 5.2.4. Left panel presents *global trends for air pollutant and methane emissions from anthropogenic and open burning, normalized to 1970 values*. Short-timescale variability, in CO and NMVOC in particular, is due to grassland and forest burning. Data from EDGAR 4.2 (JRC, 2012), except for SO2 (Smith et al., 2011)(Klimont et al., 2013). Right panel presents 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 shown in grey.

A recent update of carbonaceous 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), although recent assessments indicate that these emissions may be underestimated overall (Bond et al., 2013). These emissions are highly sensitive to combustion conditions, which results in a large uncertainty (Bond et al., 2004). 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.

Tropospheric ozone contributes a positive forcing and Is formed by chemical reactions in the atmosphere. Concentrations are impacted by a variety of emissions, including nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic hydrocarbons (VOC), and methane (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). Methane emissions also impact background tropospheric ozone levels (IPCC, 2001).

5.3 Key drivers of global change

5.3.1 Drivers of global emissions

Drivers of the global trends in GHG emissions discussed in the section 5.2 are analyzed in this section. In general, drivers are the elements that directly or indirectly contribute 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.

Nevertheless, neither there is 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), 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 (Suh, 2006; Nansai et al., 2009), 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. 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. The next subsection will discuss the framework for analyzing major drivers of GHG emissions.

5.3.1.1 Framework of analysis

Overall change in GHG emissions can be decomposed into contributing factors. We start here with the well-known Kaya identity. 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 overall GHG emissions at a global level (see Section 5.2). The Kaya can be written as

(1) $$F^{(p)} = P\frac{G}{P}\frac{E}{G}\frac{F^{(p)}}{E} = Pgef \quad \mathbf{F^{(p)} = P\frac{G}{P}\frac{E}{G}\frac{F^{(p)}}{E} = Pgef}$$

$F^{(p)}$ is global GHG emission from productive activities, P is world population, G is global producing activities generally measured in Gross World Product per capita, and E is energy use. G can be measured either in market exchange rate or in PPP. G/P, E/G, and $F^{(p)}/E$ are noted as g, e and f, respectively following (Raupach et al., 2007). In this chapter, those initial elements to which overall CO_2 emissions from fossil fuel combustion is decomposed are referred to as "factors". Equation (1) is referred to as a four factor decomposition as it uses four initial factors. The E term in the Kaya identity can be cancelled out further simplifying it to (Raupach et al., 2007):

(2) $$F^{(p)} = P\frac{G}{P}\frac{F^{(p)}}{G} = Pg\boldsymbol{h}$$

$F^{(p)}/G$ is noted as h following (Raupach et al., 2007). This type of decomposition is referred to as three factor decomposition. Using equation (2) total global GHG emission is decomposed to three root level factors. Taking a natural log for proportional growth rate of $F^{(p)}$:

$$\ln\left(1+\frac{\Delta F^{(p)}}{F^{(p)}}\right)=\ln\left(1+\frac{\Delta P}{P}\right)+\ln\left(1+\frac{\Delta g}{g}\right)+\ln\left(1+\frac{\Delta h}{h}\right) \quad (3)$$

Each right-hand-side term in equation (3) can be used as a basis to identify key drivers to overall change in global GHG emission.

Complementary to the traditional decomposition methods shown in eqs 1 and 2, which are based on territorial emission and production-based GHG accounting, is a consumption-based or life-cycle-based decomposition. The consumption-based GHG accounting approach takes a life-cycle perspective, and allocates GHG emissions throughout the supply chain to final consumption expenditure. At the global level, the total GHG emissions can be decomposed into zero order drivers such that:

$$F^{(c)}=P\frac{Y}{P}\frac{F^{(c)}}{Y}=Pym \quad (4)$$

$F^{(c)}$ is the life-cycle GHG emission by global final consumption expenditure, P is the world population, Y is the global final consumption expenditure, y is the global consumption expenditure per capita, and m is the life-cycle GHG intensity per dollar. Proportional rate of growth in logarithmic form is given by:

$$\ln\left(1+\frac{\Delta F^{(c)}}{F^{(c)}}\right)=\ln\left(1+\frac{\Delta P}{P}\right)+\ln\left(1+\frac{\Delta y}{y}\right)+\ln\left(1+\frac{\Delta m}{m}\right) \quad (5)$$

The extended I=PAT equation in (3) can be calculated for each consuming region n or for each commodity consumed k:

Another frequently applied approach in an input-output framework is the Structural Decomposition Analysis (SDA) (Greening et al., 1997; Ang, 2006; Wood, 2009a). The approach enables quantifying the contributions of multiple factors to overall GHG emissions. For example, SDA can be designed to allocate the overall changes in GHG emissions to e.g., changes in carbon intensity of a fuel type, fuel mix, overall volume of fuel consumption, economic structure, final demand composition and final demand volume. Studies often identified the changes in volume and composition of final demand and economic growth as the major contributors to overall changes in GHG emissions (Wier, 1998; De Haan, 2001; Kagawa and Inamura, 2001; Peters et al., 2007; Nansai et al., 2007; Lim et al., 2009; Wood, 2009a; Dong et al., 2010; Minx et al., 2011).

In the next section, major factors of historic GHG emissions will be analyzed using both production and consumption-based GHG account approaches.

5.3.1.2 Key drivers

Figure 5.3.1. shows a traditional, four factor Kaya decomposition results from 1970-2010 at 5-region aggregation based on territorial emissions. The small inset in each panel shows the absolute magnitude of CO2 emission from fossil energy combustion in black, which is decomposed into four factors in the larger panel, together with the magnitude of LULUCF and the rest of GHG emissions.

Figure 5.3.1 shows that, globally LULUCF emissions have been relatively stable over the last four decades with -9% to +32% of average decadal changes during the period and +44% change over the 4 decades. On the other hand, major increases in GHG emission have been associated with CO_2 emissions from fossil fuel combustion (+11% to +28% decadal changes, +103% over 4 decades) and other GHG emissions mainly from industrial processes (+12% to +35% decadal changes, +125% over 4 decades). The largest contributor to overall increase in global GHG emission is CO_2 emission from fossil fuel combustion, which increased 103% from 14.4 Gt to 29.5 Gt CO_2 since 1970. The increase can be explained by a combination of 12% decrease in CO_2 intensity in energy, 36% decrease in energy intensity in GDP, 100% increase in GDP per capita, and 82% increase in population. The improvements in CO_2 intensity in energy and energy intensity of GDP that the world has achieved over the last four dates have been almost exactly cancelled out by the continuous growth of global population resulting in an unusual synchronous behaviour between GDP per capita and CO_2 emission from energy trends during the period.

At a regional scale, all regions achieved modest reduction in CO_2 intensity in energy (2% to 34%) with an exception of Asia, where CO_2 intensity of energy increased by 44% during the period. Energy intensity in GDP has been reduced in all regions (10% to 54%) but in the Middle East and Africa (MAF), where energy intensity in GDP increased by 57%. In all regions, population growth has been a persistent trend. The Economies in Transition (REF) showed the lowest population growth rate over the last four decades (18%), whereas MAF marked 175% 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 GPD also grew in all regions ranging from 28% (REF) to remarkable 573% increase (Asia) over the last four decades. In summary, the improvements in energy intensity in GDP and CO2 intensity of energy 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 largest contributor to the increase in GHG emissions.

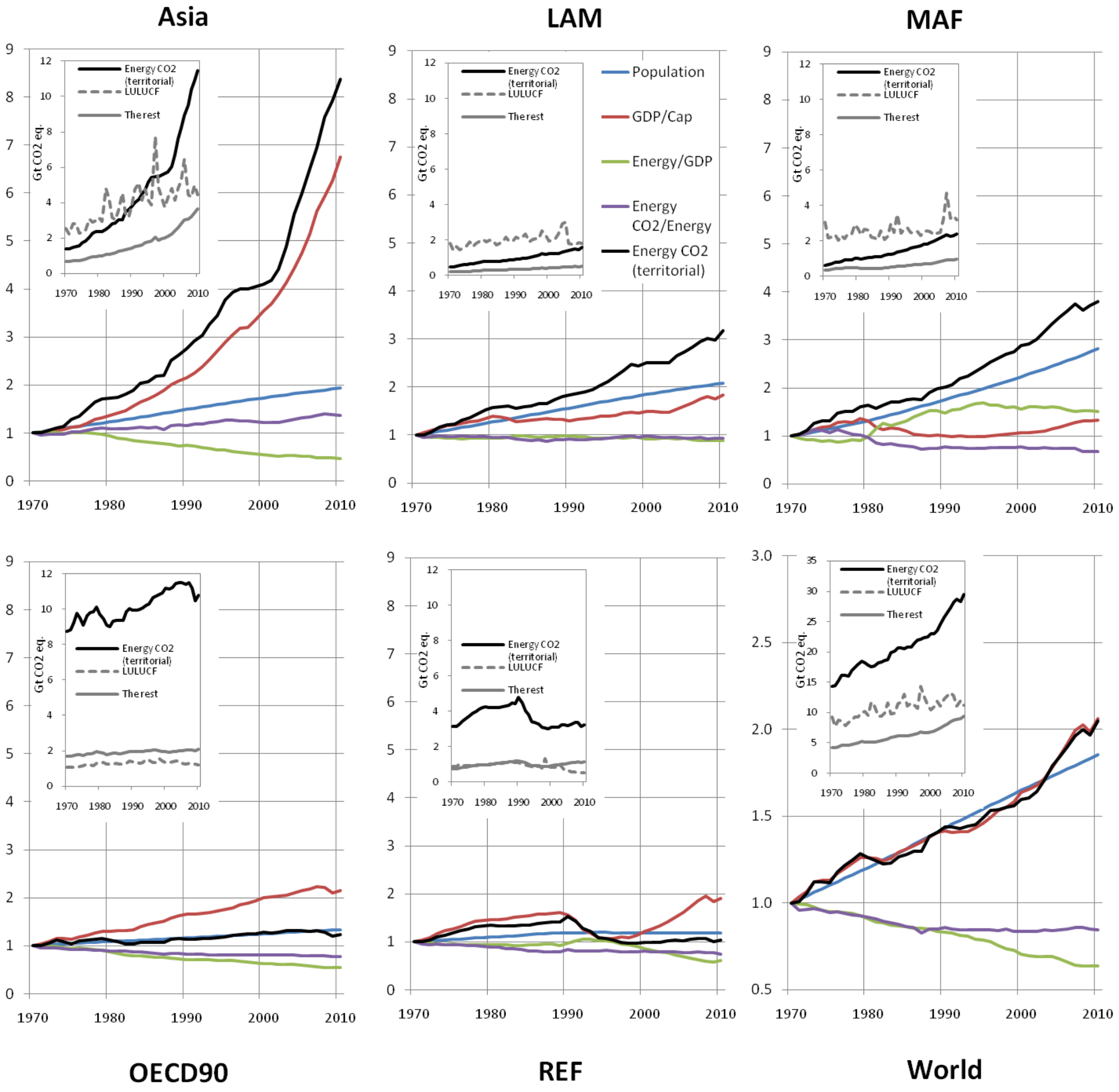


Figure 5.3.1. Four factor decomposition of territorial fossil energy CO_2 emission at regional level (1970 – 2010); note that only the bottom-right panel for the World has a different scale for its vertical axis (created using IEA (2011) and JRC/PBL (2012); based on PPP adjusted GDP).

Using production (territorial) and consumption (life-cycle) accounts, global CO_2 emissions from fossil energy can be decomposed into three factors. Figure 5.3.2 highlights the case of Asia and OECD90. According to the territorial account, OECD90 increased its CO_2 emissions from fossil energy only by 6% from 1990 to 2010. Increase in CO_2 emission from fossil energy embodied in consumption by OECD90, however, is more pronounced (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 206% during the period. The decomposition results show that Asia achieved a deeper reduction in embodied CO_2 emission intensity in consumption than in direct, territorial CO_2 emission in production, while OECD90 achieved less reduction in embodied CO_2 emission intensity in consumption than in territorial emission in production. Obviously increasing international trade played an important role in this result, which will be elaborated in Section 5.4.

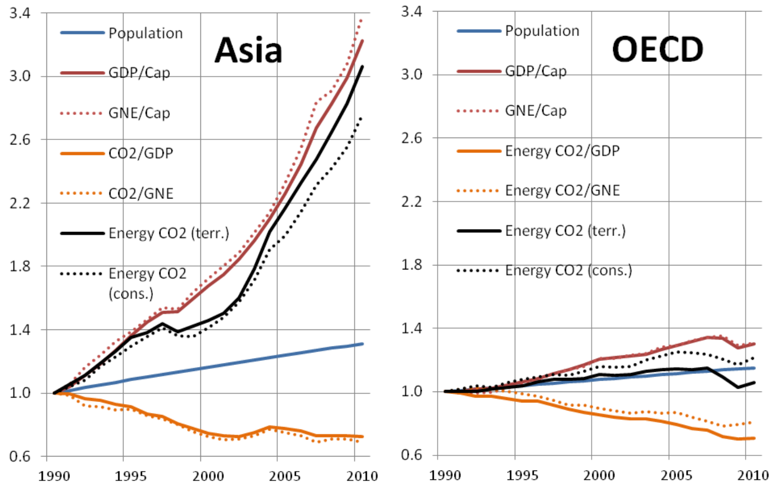


Figure 5.3.2. Three factor decomposition of territorial and life-cycle fossil energy CO2 emission based on production (left) and consumption (right) accounts (1990 – 2010) (JRC, 2012).

The strong correlation between production, consumption and CO_2 emissions can be identified from the historical trajectories of CO_2 emissions and GDP/GNE (Figure 5.3.3). Although there are notable exceptions (REF), regional CO_2 emission trajectories are closely aligned with the growth in GDP and GNE. On average, 1% of GDP or GNE increase has been accompanied with 0.54% increase in CO_2 emission from fossil energy between 1990 and 2010. Except for REF, all regions increased 0.12% (OECD90) to 0.95% (MAF) CO_2 emission from energy per each 1% of GDP increase. The relationship becomes more homogenous across the regions when consumption and life-cycle emission is concerned; all regions but REF showed 0.43% (The 1990 OECD countries, OECD90) to 0.99% (Latin America, LAM) increase in life-cycle CO_2 emission per 1% increase in GNE during the period (see also (Hertwich and Peters, 2009). In other words, 1 USD increase in GDP has been accompanied with 0.06 – 0.7kg increase in CO_2, and 1 USD of GNE increase has been accompanied with 0.2 – 0.6kg increase in CO_2 from energy at regional level between 1990 and 2010 (world average for both is 0.4kg/USD).

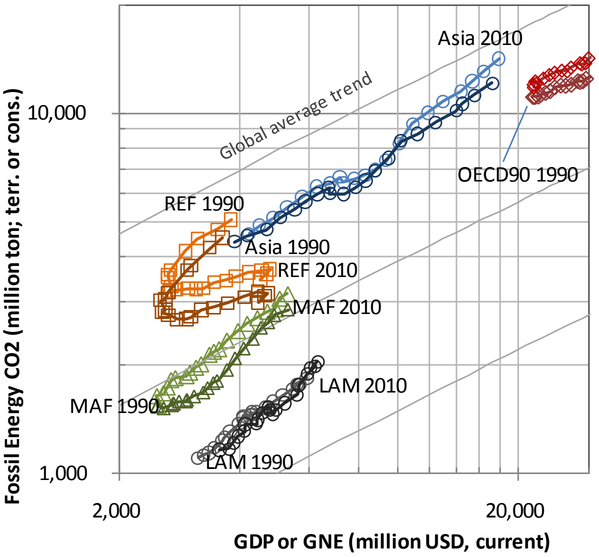


Figure 5.3.3. Historical regional trajectories of territorial fossil energy CO2 emission v.s. GDP and life-cycle fossil energy CO2 emission v.s. GNE (1990 – 2010): lighter colour of the same pattern for territorial, darker colour for consumption-based accounting (Drawn using data from JRC/PBL (2012)).

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.

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

It is hard to attribute causation to the factors influencing GHG emissions because there are so many of them, they interact with each other directly and indirectly, and each factor can have several aspects. The large majority of things people produce, consume, or do for recreation may result in GHG emissions. A single basic activity like eating has involved land use, infrastructure, transportation, energy production systems, and other considerations to go from producing the food to the food being available for consumption. All along the way, there are influences of technologies available to and personal choices of the farmers and fishers, all the intermediaries in the path of trade, and the consumers. These don’t function independently: available technologies affect prices, prices affect consumer preferences, and consumer preferences can influence development and distribution of technologies. Policies, culture and traditions, and external economic factors can intervene in every link. Because these factors cannot be disentangled in the real world, it is not possible to disentangle their individual roles in the growth of carbon emissions either. This is a key reason why policies to address GHG emissions need to be coherent and robust It is also a cause for optimism, because it means there are many pathways to a desired outcome of lower emissions, and taking a good opportunity to act anywhere along the interacting pathway may provide cobenefit to connected factors as well.

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. 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. 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 5.3.4 presents the main outcomes.

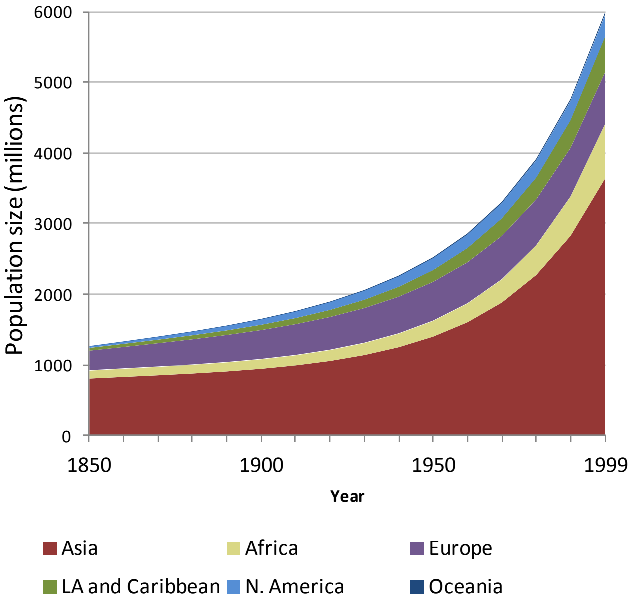


Figure 5.3.4. Trends in regional and global population growth 1850-1999 (UN, 1999).

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), see also Figure 5.3.5. 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, Figure 5.3.5 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 OECD90 and Economies in Transition (REF). The evolution of total population and per capita GHG emissions in the same period is shown in Figure 5.3.5. 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 growth in ASIA (JRC, 2012).

(a) **(b)**

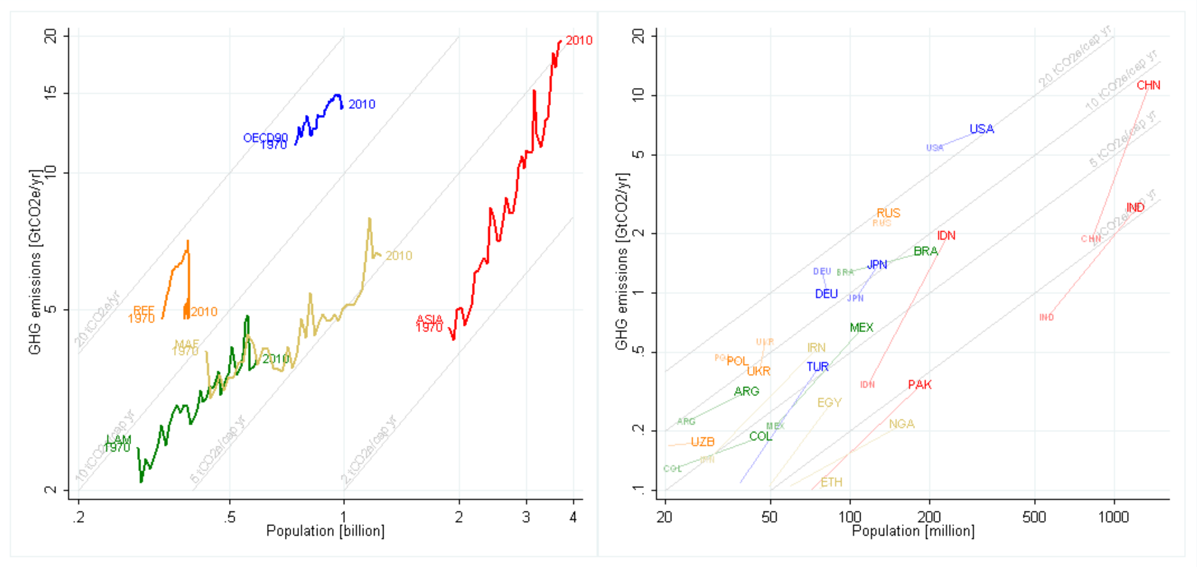


Figure 5.3.5. Trends in population and GHG emissions in the five IPCC RCP regions (panel a) and for each region the four most populous countries in 2010 (panel b). Gray diagonals connect points with constant emission intensity. Major GHG emitting regions or countries are in the upper half. A shift to 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).

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 2.35 (Liddle, 2011) (although the latter studied CO2 emissions from domestic transport activities, not total CO2 emissions). 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. Yet most recent studies find more than proportional increase of emissions triggered by the increase in population. Yet the literature presents contradicting results concerning whether an additional rich or poor person contributes more to increasing GHG emissions: Poumanyvong and Kaneko (2010) estimate an elasticity 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. Over the period from 1970 to 2008 the global rate of urbanization has increased from 36% to 50% but the linkages between urbanization and GHG emissions trends are complex and involve other determinants such as the level of development, rate of economic growth, availability of energy resources and technologies and others. Regional differences between changes in urbanization rates and GHG emissions show that emissions were increasing much faster than the rate of urbanization in Asia while a virtually constant urbanization rate was accompanied by declining emissions since 1990 in the Economies in Transition.

Direct measures of the effect of urbanization on emissions remain difficult due to the system boundary problems. 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. 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.

Many studies observe that GHG emissions from urban regions differ extensively 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) 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 include the extent of public transport system within the city. 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 assesses the second-order effect of urbanization and finds that, all other things equal, in the early phase of urbanization emissions increase while further urbanization is associated with decreasing emissions (Martínez-Zarzoso and Maruotti, 2011). 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 renewable and nuclear electricity could mitigate the fast increasing CO2 emissions associated with the combination of fast urbanization and the related energy transition in these countries. 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).

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, 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 Energy demand and supply

5.3.3.1 Energy demand

Globally, per capita energy consumption rose by a fairly moderate 29% from 1970 to 2010 but there was great regional variation. In both the OECD and transition economies (REF) energy use rose by 13%, but in Latin America it rose by 117%, in the Middle East and Africa by 154%, and in Asia by

442%. The figure shows trends in global and regional per capita primary energy consumption over the last four decades.

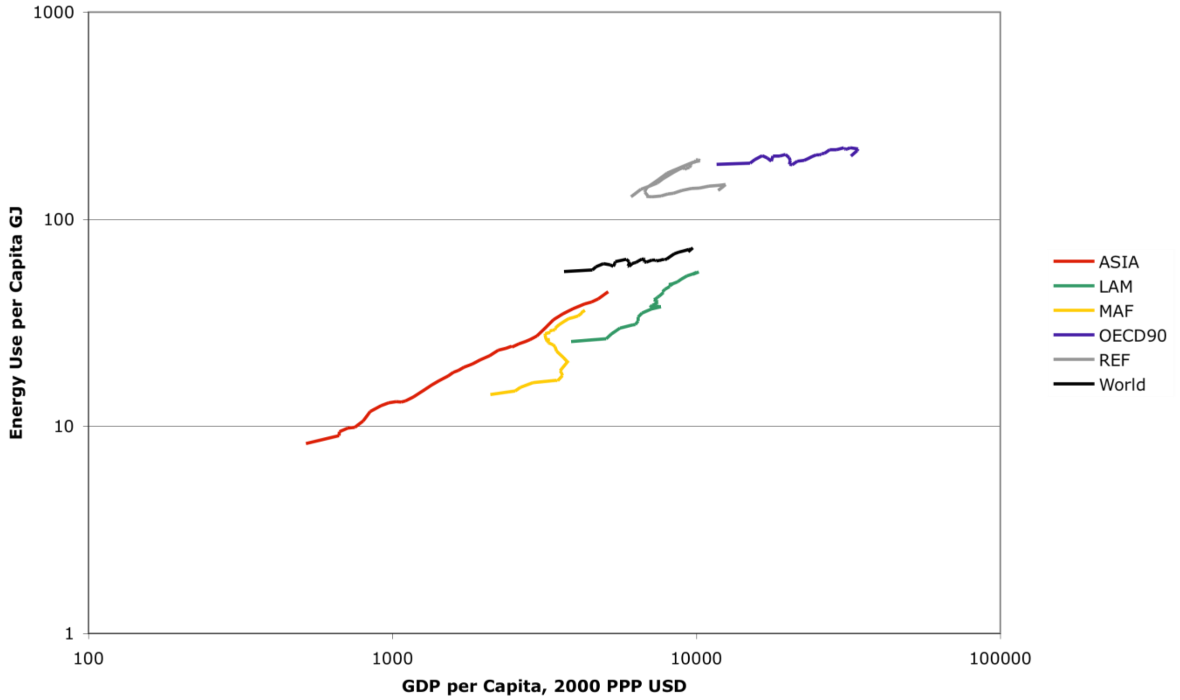


Figure 5.3.6. Per Capita Energy Use and Income per Capita by Region (World Bank, 2011; "BP Statistical Review of World Energy," 2011).

The impact of the recent economic recession and the two oil price shocks in the 1970s are very pronounced in the OECD data and less evident in the other regions. The collapse of the Soviet Union and other centrally planned economies in Eastern Europe in the early 1990s is the most prominent feature of the Reforming Economies data. Of course, due to population growth total energy use has increased much more, 142% between 1970 and 2010 globally (see Section 7.3 in Chapter 7 for further details about total energy use). There have also been important changes in the mix of energy carriers with a trend to lower carbon energy sources over time as discussed below (Section 5.3.3.3). These lower carbon energy sources also tend to be higher quality energy sources generally with lower quantities of other pollutants, increased flexibility – liquids, gases, and electrons replacing solid fuels – and higher economic marginal productivity (Burke, in press; Cleveland et al., 2000).

As the Figure shows, regions (and countries) with higher income per capita tend to have higher energy use per capita – at any point in time this relation is almost linearly proportional, when income is measured in purchasing power parity (PPP) terms (Stern, 2012). The Figure also shows that income per capita has increased over time in each region as income has increased though the rate of growth is lower in the more developed countries than in the less developed countries so that energy use per capita has converged to some degree over time. Per capita energy use in the developing regions is still, however, only about a quarter of that in the developed economies. Declines in income in the OECD90 and reforming economies have been associated with reduced energy use but this does not seem to be the case in the developing countries.

Increases in energy prices tend to reduce per capita energy use, at least in the short-run. The effects of the oil price shocks in 1973 and 1979 and perhaps 2008 (Hamilton, 2009) are particularly visible in the OECD data. These price shocks do not appear, however, to have had a long-term impact on the trend in per capita energy use in this region. In the longer 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 (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. Improvements in energy intensity have slowed the growth in energy use but have been insufficient to offset the growth in the scale of the economy (Stern, 2012).

Numerous studies have tested for the direction of causality between energy and economic output and also between these variables and emissions of greenhouse gases using the time series econometric techniques of Granger causality testing (Granger, 1969) and cointegration analysis (Engle and Granger, 1987). There are both studies that examine these relations in individual countries and in panels of time series data for varying numbers of countries together. Studies of causality between energy and growth have been carried out for more than three decades (Ozturk, 2010) but have been generally inconclusive. Stern (2011) suggests that the inconclusive nature of the literature on causality between energy and economic growth is due to the omission of non-energy inputs – capital and human capital - in most studies and that studies that include non-energy inputs find that energy use causes economic growth (and sometimes vice versa as well) such as the recent panel data studies by Lee and Chang (2008) for Asian countries and Lee *et al*. (2008) for OECD countries.

5.3.3.2 Energy efficiency and Intensity

Energy efficiency can be defined as the ratio of the desired (usable) energy output to the energy input for any energy conversion process. 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). Economic studies (including those based on the Kaya identity) 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. However, energy intensity depends on many factors other than technical efficiencies, as discussed below, and is a poor indicator of actual energy (conversion) efficiency (Ang, 2006), (Filippini and Hunt, 2011), (Stern, 2012).

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 (such as light) is lower, with an estimated global average of 51% (i.e. 169 EJ over 330 EJ). Thus, about one half of global primary energy use does not end up as useful energy input for providing energy services but 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).

Energy intensity metrics yield valuable insights into potentials for efficiency improvements related to various activities, and are applied widely in the literature (Fisher and Nakicenovic, 2008)(Grübler et al., 2012). Furthermore, energy intensity measured at the economy-wide level is a parsimonious indicator that is appealing because of its relative simplicity and seeming ease of comparability across time and different systems (e.g. national economies, regions, cities, etc.). However, the indicator is affected by a number of important measurement and definitional issues (Ang, 2006), (Filippini and Hunt, 2011) with many factors besides technical efficiency driving 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[1] is included (see Figure 5.3.7).

The thin green curve in Figure 5.3.7 shows the commercial energy intensity for the U.S. 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 proceeds to decline. This phenomenon is sometimes called the "hill of energy intensity." It has been observed that the successive peaks in the procession of countries achieving this transition are ever lower, indicating a possible catch-up effect and promising further energy intensity reductions in developing countries that still have to reach the peak (Gales et al., 2007), (Lescaroux, 2011), (Reddy and Goldemberg, 1990). 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. 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.

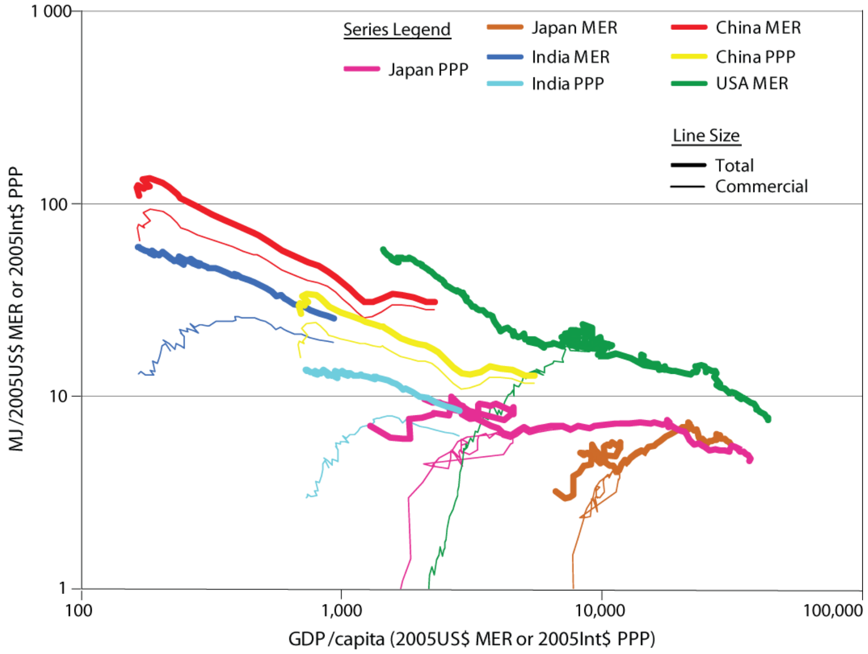


Figure 5.3.7. Energy intensity improvements and per capita income - US (1800–2008), Japan (1885–2008), India (1950–2008), and China (1970–2008). Source: (2012). Note: Energy intensities (in MJ per $) are always shown for total primary energy (bold lines) and commercial primary energy only (thin lines) and per unit of GDP expressed at market exchange rates (MER in 2005US$) and for China, India, and Japan also at purchasing power parities (PPP in 2005 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

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[1] 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 5.3.7) In the cases of India and China, MER energy intensities are very high, resembling 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 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).

Data for countries with long-term statistical records show improvements in total energy intensities by more than a factor of five since 1800, corresponding to an average decline of total energy intensities of about 0.75-1% per year ((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 in samples of both developed and developing countries (Le Pen and Sévi, 2010).

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 minor role in determining trends in energy use and CO_2 emissions, though they can be important in individual countries. More generally, energy intensity can also be affected by the substitution of capital and other inputs for energy (Stern, 2012). The causes for energy intensity trends in 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.

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, 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), nor is there a 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 the former 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 of between -0.2 and -0.45 for the OECD countries (Filippini and Hunt, 2011).

5.3.3.3 Carbon-intensity, the energy mix and resource availability

Carbon intensity is the ratio of emissions of CO2 per unit of primary or final energy, whereas decarbonization refers to the rate at which the carbon intensity of energy is reduced. Throughout the 20th century, our 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). Hydrogen-rich fuels release more energy for every carbon atom that is oxidized to CO_2 during combustion. 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[2], as well as the introduction of near-zero carbon energy sources, such as renewables and nuclear, and consequently further decarbonization of energy systems (Grübler and Nakićenović, 1996), (Grubler, 2008). Figure 5.3.8 shows the historical dynamics of primary energy substitution. It indicates that it took more than half a century to replace the dominant source of energy.

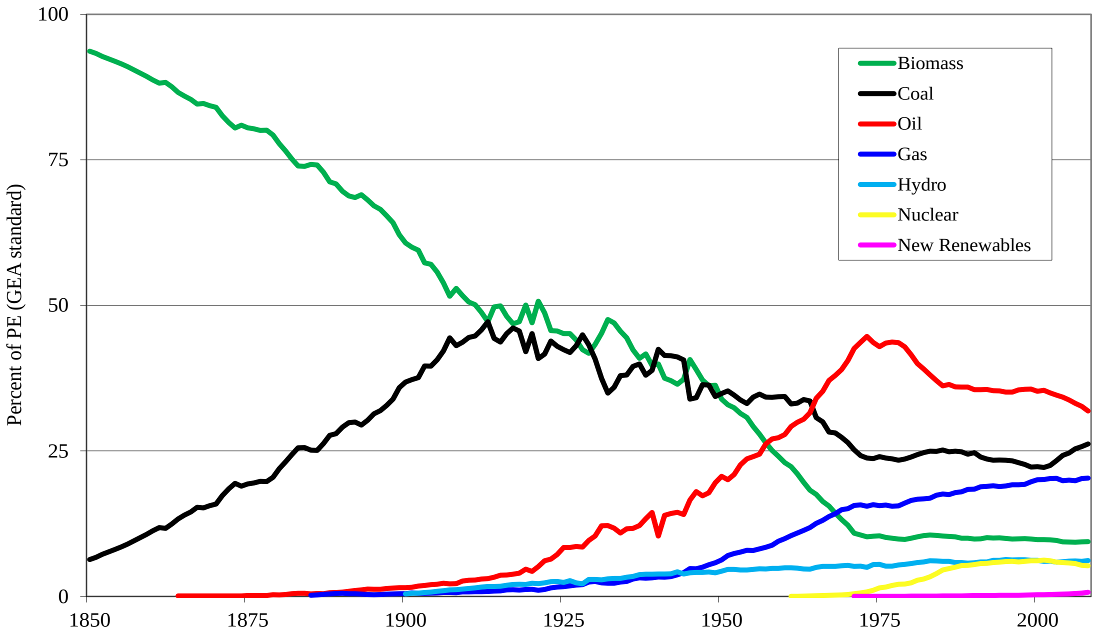

Figure 5.3.8. Structural change in world primary energy (in percent) illustrating the substitution of traditional biomass (mostly non-commercial) by coal and later by oil and gas. The emergence of hydro, nuclear and new renewables is also shown. Source: Nakicenovic et al. (1998) and Grübler (2008).

Figure 5.3.9 illustrates the historical trend of global decarbonization 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, biomass emissions related to land-use changes (deforestation) 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).

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

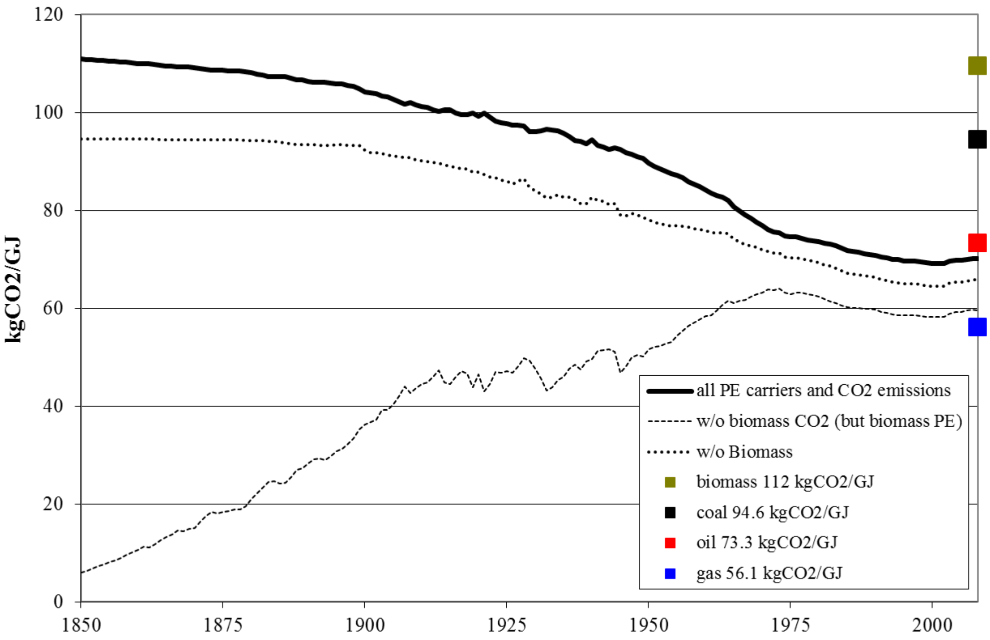

Figure 5.3.9. Decarbonization of primary energy (PE) use worldwide since 1850 (kg of CO2 emitted per GJ). The solid line shows carbon intensities of all primary energy sources, dashed line of commercial energy sources without biomass CO_2 emissions, assuming they have all been taken up by the biosphere 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).

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 some 2% annually. 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).

Some future scenarios foresee continuing decarbonization over the next several decades as natural gas and non-fossil energy sources increase their share in total primary energy use. Other scenarios anticipate a reversal of decarbonization in the long term as more easily accessible sources of conventional oil and gas are replaced by more carbon-intensive alternatives such as coal and unconventional oil and gas (Fisher and Nakicenovic, 2008). Nonetheless, virtually all scenarios foresee 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, in order to reduce GHG emissions energy efficiency improvements alone will not suffice and it is 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, sociopolitical decisions and other salient driving forces.

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. Reserve additions have shifted to inherently more challenging and potentially costlier locations, with technological progress outbalancing potentially diminishing returns (Nakicenovic et al., 1998).

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, often concentrated in some regions and not others (U.S. Energy Information Administration, 2010). These upper estimates of the 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 exceed the carbon of the atmosphere. Chapter 7 of this report discusses in detail the current and future availability of global energy resources (see also Table 7.2).

5.3.4 Other key sectors

This section presents the past trends and drivers of greenhouse gas emissions for the key sectors of transport; buildings; industry; agriculture, forestry, other land use, fisheries and aquaculture (AFOLUFA) and waste for the five regions of OECD, REF, LAM, ASIA and MAF. The analysis of the sector emissions endeavours to take into consideration a factor decomposition to assess how population, GDP per capita, energy intensity and GHG emissions intensity of energy and related underlying drivers and past policy frameworks have influenced the greenhouse gas emissions in these key sectors in the past. The subsector performance and required mitigation options to reduce emissions from these sectors are dealt with in the sector chapters 8-11.

5.3.4.1 Transport Sector

The global transport GHG emissions[3] grew from 2.9 GtCO_2eq in 1970 to 4.8 Gt CO_2eq and 6.7 Gt CO_2eq in 1990 and 2010 respectively[4]. The OECD countries contributed the largest share of the emissions (i.e. 60% in 1970, 56% in 1990 and 46% in 2010) though growth rate tapered off after 2000 in this region. The highest growth rate in transport emissions was in the Asia region, where emissions registered more than 7-fold growth between 1970 and 2010, increasing the share from 5% to 16% during the same period. The other developing regions of MAF and LAM also registered more than 5-fold and 3-fold growth in GHG emissions respectively, although the share remained relatively low (3% in 1970 to 7% in 2010 for MAF and 5% in 1970 to 8% in 2010 for LAM). The REF region shows a near 2-fold growth in 1990 but a reduction in emissions growth to 2000 coinciding with the period after the collapse of the Soviet Union. REF emissions are starting to take a positive growth to 2010 (Figure 5.3.10).

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[3] Consisting of CO2, CH4 and N2O. Although F-gases are about 5-10% of transport emissions, ttransition from CFCs to HFCs, consumption of gases but contribution to GHG emissions continues to reduce (Freight Vision, 2009).

[4] (JRC, 2012)

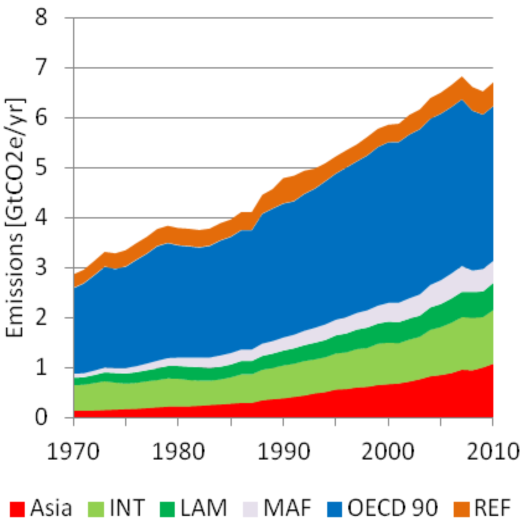


Figure 5.3.10. Regional distribution of transport CO2eq trends (JRC, 2012)

The key factors that determined energy demand in the transportation sector and hence greenhouse gas emissions were growth in economic activity and population. The demand for personal transportation increases as standards of living rise and increased economic activity leads to growing income per capita (International Energy Outlook 2011, 2011). A primary driver in the increase of energy demand for transportation is steadily increasing demand for personal travel in both the developing and developed economies. In the developing economies, with gains in urbanization and personal incomes, demand for air travel and motorized personal vehicles increases. In addition, strong GDP growth in the non-OECD economies leads to modal shifts in the transport of goods, and freight transportation by trucks leads to the growth in non-OECD demand for transportation fuels.

Population has grown much more rapidly in non-OECD countries than in OECD countries (Zachariadis, 2012) leading to increased population densities by urbanization in cities and, in turn, increased number of private or passengers' vehicles (Ubaidillah, 2011). Population density however has been observed to having a significant positive contribution to reduce GHG emissions (Lua et al., 2006; Kenworthy, 2011; Newman, 2012).

Transport emissions have also been affected by rising international trade particularly following the liberalization measures when GATT was introduced and as the volume of international trade grew, fuel use for freight transportation by air and marine vessels also increased. The growth rate of international transport emissions after 2002 reflects the growth in Chinese exporting industries showing the influence of trade policies and agreements on the 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 percent in 2008 and an estimated 6.3 percent in 2009. The greenhouse gas emissions in non- OECD emissions were not affected and even caused a 2.2% increase in total world emissions and an estimated 0.3 percent in 2009 (*International Energy Outlook 2011*, 2011).

Urbanization and urban planning, infrastructure, behavioural choices, motor vehicles growth travel demand, modal share, fuel prices and share of fossil fuels are generally found to be the principal drivers of the transport sector CO2 emission growth (Jolley, 2004; Davies et al., 2007; IPCC, 2007; Timilsina and Shrestha, 2009; Ubaidillah, 2011; Wang et al., 2011)(Newman, 2012).

Policy wise, the enforcement of the use of cleaner fuels and technologies has led to strong reductions of emissions in the developed world e.g. EU and Japan that use high gasoline taxes, although the motivation is said to be revenue rather than carbon emissions reductions (Proost and Van Dender, 2012).

The overall picture shows that transport emissions have steadily increased but show a marked decrease around 2008/2009, coinciding with the huge fuel prices and global recession. The marked effect is shown on OECD and REF countries and to some extent MAF. Both Asia and International transport do not reflect such changes, but steady increases.

5.3.4.2 Buildings Sector

The building sector emissions grew from 2.6 Gt CO_2eq in 1970 to 3.0 Gt CO_2eq in 2010 hence remained flat over the entire period despite the global growth in the buildings stock. The rising CO2 emissions from developing countries were nullified in the 1970s and 1990s by decreases in the USA and in the 1990s by the economic decline of the EIT countries (Olivier et al., 2011) (Figure 5.3.11).

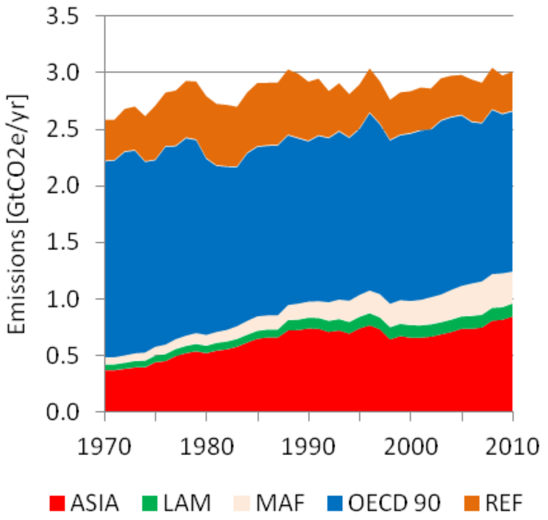


Figure 5.3.11. Regional distribution of buildings CO2eq trends (JRC, 2012).

The global share has been dominated by OECD countries with 67% in 1970and 47% in 2010. The largest increases have been registered in Asia which doubled from 14% in 1970 to 28% in 2010. The share of REF emissions increased modestly from 14% in 1970 to 18% in 1990 declining to 11% in 2010. MAF has registered the largest growth rate in emissions but its share increased from 3% in 1970, to 9% in 2010 and was higher than LAM shares from 2% in 1970 to 4% in 2010.

CO_2 emission from households shows considerable annual fluctuations, due to the variations in climatic conditions, in particular annual temperature fluctuations (*Greenhouse gas emission trends and projections in Europe 2009*, 2009). The shift from coal to oil or gas for electricity and district heating and the final energy efficiency per household resulted in significant lowering of emissions.

Emissions from developing countries doubled over the four decades, while industrialised countries managed to reduce the direct CO2 emissions from the buildings sector by 18% since 1970, despite large increases in production of goods, the service sector and population (Olivier et al., 2011).

A strong relationship exists between GDP per capita and final energy use in residential (R^2=0.77) and commercial buildings (R^2 = 0.78) based on data for 25 industrialized countries, China, and the regions of Asia, Africa, Latin America, and Middle East. A correlation of GDP with floor space for commercial buildings was also observed (Price et al., 1999).

In many low-income countries, especially in rural areas, a large proportion of operational energy is derived from burning wood and other biomass, such as dung and crop residues. The number of people (2.4 billion) using biomass for cooking and heating is likely to increase in the future (International Energy Agency, 2002, 2006) (leach, 1988). Emissions from biomass is exacerbated by the inefficient combustion devices (Tonooka et al., 2003; *International Energy Outlook 2011*, 2011).

On average, most residential energy in developed countries is consumed for space heating, particularly in cold climates. Share of space heating in commercial building was 12% and 45% while in Residential building shares were 29% and 32% in the US and China respectively. Trends in demand for energy 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).

Considering life cycle analysis starting with manufacturing of building materials to demolition over 80 percent of greenhouse gas emissions take place during operation phase (*UNEP 2008 Annual Report*, 2009). Much of the emissions being attributed to use of electricity for heating, ventilation, and air conditioning (HVAC), water heating, lighting, entertainment and telecommunications (*UNEP 2008 Annual Report*, 2009). In primary energy terms electricity is the largest buildings energy and emission source in developed countries (US DOE, 2008).

Population growth is directly proportional to households and hence residential building floor space increases. As populations become more urbanized and areas become electrified, the demand for energy services such as refrigeration, lighting, heating, and cooling increases. In the residential buildings sector, the level of energy demand is further influenced by population age distribution, household income, number of households, size of households, and the number of people per household. Similarly population level of people desiring commercial services and the size of the labour force influence commercial building emissions (Price et al., 1999), see also Section 5.3.2.

In summary, key drivers of emissions in buildings are: Population, which drives the number of homes, schools, and other community buildings; economic growth (real GDP), which is a major driver of new floor space in offices and retail buildings; carbon intensity of electricity and other energy sources used in buildings (US DOE, 2008).

The building sector emissions have increased at a slower pace than those for transport, but the perturbations shown with the OECD countries are mirrored in the REF regions. The significant dip is shown in all the regions around 1996/7 to about 2000 before another increase in emissions is shown.

5.3.4.3 Industry Sector

The industry emissions grew from 4.8Gt CO_2 eq in 1970 to 8.7 Gt CO_2 eq in 2010 and OECD emissions dominated at the start of the period with over 61% of the emissions declining to 26% in 2010. Asia has become the region with the largest emissions with a share of 53% in 2010 from 14% in 1970.

The REF share of industry emissions that was about 20% between 1970 and 1990 declined from 2000 to 9% in 2010 coinciding with the economic slowdown in EIT economies. The MAF, with Africa as the least industrialized region, had a share below 3% in 1970 rising to 9% in 2010 while the share of LAM fluctuated between 3% and 5% in the same period. The highest rate of emissions growth was in Asia, then MAF and LAM. OECD emissions have peaked while that of REF declined and is now increasing.

Industrial emissions had a relatively modest long term growth rate until 2002, when the annual growth rate increased due to the accelerating industrialisation of China. The acceleration started after China joined the World Trade Organization (WTO) in 2001, when its export-oriented growth increased rapidly. Until 2002 direct global CO_2 emissions from industrial activities increased moderately by about 16%, with increasing emissions by developing countries mostly compensated for by decreases in the 1980s by the OECD countries and in the 1990s by the EIT countries (Olivier et al., 2011).

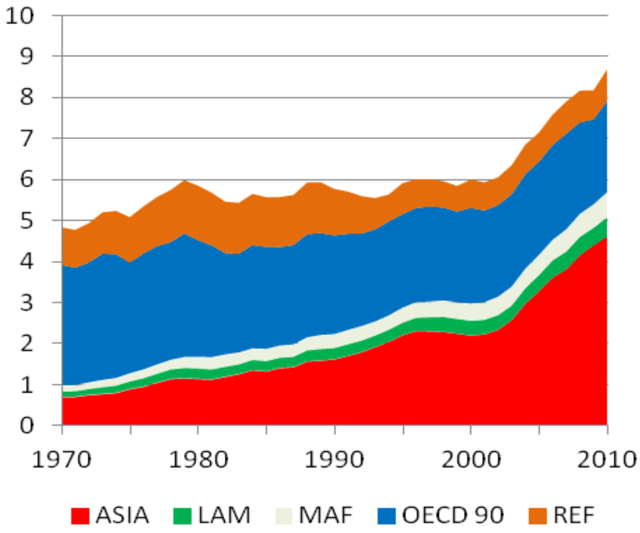


Figure 5.3.12. Regional distribution of *Industry CO2eq trends* (JRC, 2012).

In general, CO2 emissions from direct use of fuels in the industrial sector have increased between 1990 and 2000 in the OECD Pacific region, decreased slightly in North America and Europe, and decreased significantly in countries with economies in transition (EIT). Electricity use in industry has grown in both absolute and relative terms in all OECD regions and in relative terms in EIT countries. These trends are caused by such factors as changes in GDP, level of industrial output, fuel switching and structural changes (International Energy Agency, 2003).

Decreases in emissions as a result of improvements in final energy efficiency and to a lesser extent the fuel-switching from coal to gas have been realized with final energy efficiency constantly improving since 1990, whereas most of the shift from coal to gas was achieved before 2000 (*Greenhouse gas emission trends and projections in Europe 2009*, 2009).

The production of energy-intensive industrial goods has grown dramatically and is expected to continue driven by population and per capita income increase and hence demand for infrastructure, goods and services. Since 1970, global annual production of cement increased 271%; aluminium, 223%; steel, 84% ammonia, 200% and paper, 180%; with energy-intensive industries being located in developing nations, China alone was the world's largest producer of steel, aluminium and cement prior to 2010. China now makes about half of the world's flat glass and cement, and about one-third of its steel and aluminium. Developing countries still maintain higher shares in these production industries (IPCC, 2007).

Rapid growth in export industries (primarily lighter goods such as DVD players, toys, and clothes) has also driven emissions growth. According to a study conducted in 2009, roughly half of China's new greenhouse gas emissions between 2002 and 2005 were produced by light industrial facilities producing goods for export.

There was reduction industrial emissions over the 1990s were due to technology development, e.g. the ability to cost-effectively reduce N_2O emissions from adipic acid production, reductions in GDP, e.g. in EIT countries, or from demand growth, e.g. for HFCs.

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).

The major increase in industry emissions has been realized from about 2002 coinciding with marked increase in emissions for Asia being attributed to the large industrialization in Asian countries particularly in China. The increase in Asia emissions is being compensated to some extent by decreases in emissions in OECD and REF particularly after 2002.

5.3.4.4 Agriculture, Forestry, Other Land Use (AFOLU)

Agricultural lands occupy about 4889 Mha km^2 (38%) whereas forests cover 4038 Mha (31%) of the Earth's total land area (FAOSTAT). About 70% of the agricultural lands are used for pasture and 30% are devoted to crops. This section analyses the trends and identifies the main drivers in GHGs emission in the AFOLU sectors.

Agriculture contributed about 5.7 Gt CO_2 eq. yr^{-1} (11%) of the global GHGs emission in 2010. Asia contributed the largest (43%) amount of the emission (2.4 Gt CO_2 eq. yr^{-1}) followed by the OECD countries and Middle East and Africa (MAF) countries contributing 1.00 Gt CO_2 eq. yr^{-1} each (18%), Latin America (LAM) 0.97 Gt CO_2 eq. yr^{-1} (17%) and Economies and Transition (REF) 0.30 Gt CO_2 eq. yr^{-1} (5%) (Figure 5.3.13) (See also Figure 11.1 in Chapter 11). Compared to 1970, emissions in agriculture increased by 35% in 2010. The largest relative growth occurred in Latin America (87%), followed by Asia and Middle East and Africa (50%) and the OECD (6%). Agriculture related emission decreased in the Economies in Transition (38%).

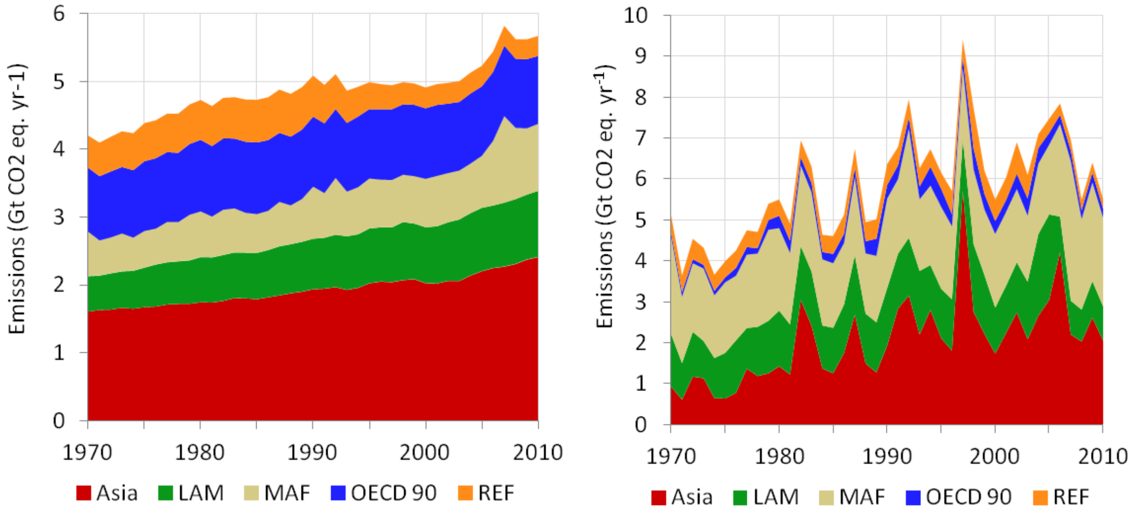


Figure 5.3.13. Regional emissions trends for the agriculture sector (left panel) and from forestry and other land use sectors (right panel) (JRC, 2012).

In 2010, enteric fermentation contributed 2.1 Gt CO_2 eq. yr^{-1} (38%), followed by direct soil emission (1.9 Gt CO_2 eq. yr^{-1}, 35%), rice cultivation (0.79 Gt CO_2 eq. yr^{-1}, 14%), savannah burning (0.43 Gt CO_2 eq. yr^{-1}, 8%), manure management (0.35 Gt CO_2 eq. yr^{-1}, 6%) and agricultural waste burning (0.05 Gt CO_2 eq. yr^{-1}, 1%). Compared to 1970, direct soil emission increased by 90% in 2010, and enteric fermentation by 43%.

In agriculture, methane is the main greenhouse gas (3.4 Gt CO_2 eq. yr^{-1} in 2010, 60%), followed by nitrous oxide (38%) and carbon dioxide (2%). Between 1970 and 2010, emissions of nitrous oxide increased by 73% whereas emissions of methane increased by 18%.

Deforestation, with periodic pulses from wildfires, is a main cause of GHG emissions in the forest and other land use sectors (FOLU), contributing 5.5 Gt CO_2 eq. yr^{-1} to global emissions (11%) in 2010. Forest fires contributed 1.7 Gt CO_2 eq. yr^{-1} (31%), but they are followed by post-burn decay (2.6 Gt CO_2 eq. yr^{-1}, 46%), and peat fires and decay of drained peat lands (1.3 Gt CO_2 eq. yr^{-1}, 23%). In 2010, the Middle-East and African countries contributed 40%, followed by Asia (37%), Latin America (15%), the Economies in Transition (4%) and the OECD1990 countries (4%) (Figure 5.3.13).

Emissions in the FOLU sectors increased by 8% from 1970 to 2010 though emissions through grassland fires and forest fires decreased by 71% and 41%, respectively. There was large increase of indirect emissions through peat fires and decay of drained peat lands and post burn forest decay. There are large variations in annual emission of GHGs from the FOLU sector mostly because of variations in climate conditions although Asia saw a robust upward trend.

The AFOLU sector has drivers on all spatial levels: global (e.g., prices of energy and agricultural products, international trade), regional (e.g., water scarcity, urbanization, public policy, income growth) and local (e.g., population pressure and demographic structure, infrastructure and market access, non-farm opportunities and labour scarcity, capacity of natural resources, poverty) (Hazell and Wood, 2008). Global population increased by 87% from 3.71 to 6.94 billion between 1970 and 2010 but the cropped area increased only by 14%, from 1350 Mha to 1550 Mha (FAOSTAT). As a result per capita land availability declined by 39%, from 0.364 ha to 0.223 ha, but the productivity increased considerably. For example, cereal production has doubled from 1.76 billion ton to 3.57 billion ton during the period. To enable this increase, use of nitrogenous fertilizer increased by 230% from 31.8 Mton in 1970 to 106 Mton in 2010, which has been a major driver for increased N_2O emissions (FAOSTAT). During the past 40 years, there has been 70% increase in irrigated cropland area (Foley et al., 2005). Forest area decreased from 4168 Mha in 1990 to 4038 Mha in 2009, a decrease of 3% in the last 20 years (FAOSTAT). Deforestation and other land-use change for production of crop, biofuel and livestock are key drivers influencing GHGs emission by altering organic carbon content of soil through tillage and use of agricultural inputs such as fertilizers and manure (See Chapter 11 for details).

The continued world population growth causes greater demand for food and energy, with reduced per capita land availability. This will necessitate the intensification of agriculture, and perhaps more land for biofuel production, which based on past trends is expected to increase GHGs emissions. The details of GHGs mitigation options in AFOLU sector are discussed in Chapter 11.

5.3.4.5 Waste

Total global waste emissions almost double from 1970 to 2010 (Figure 5.3.14). 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, 2012). Main sources of emissions were solid wastes on land and wastewater handling (Figure 5.3.14).

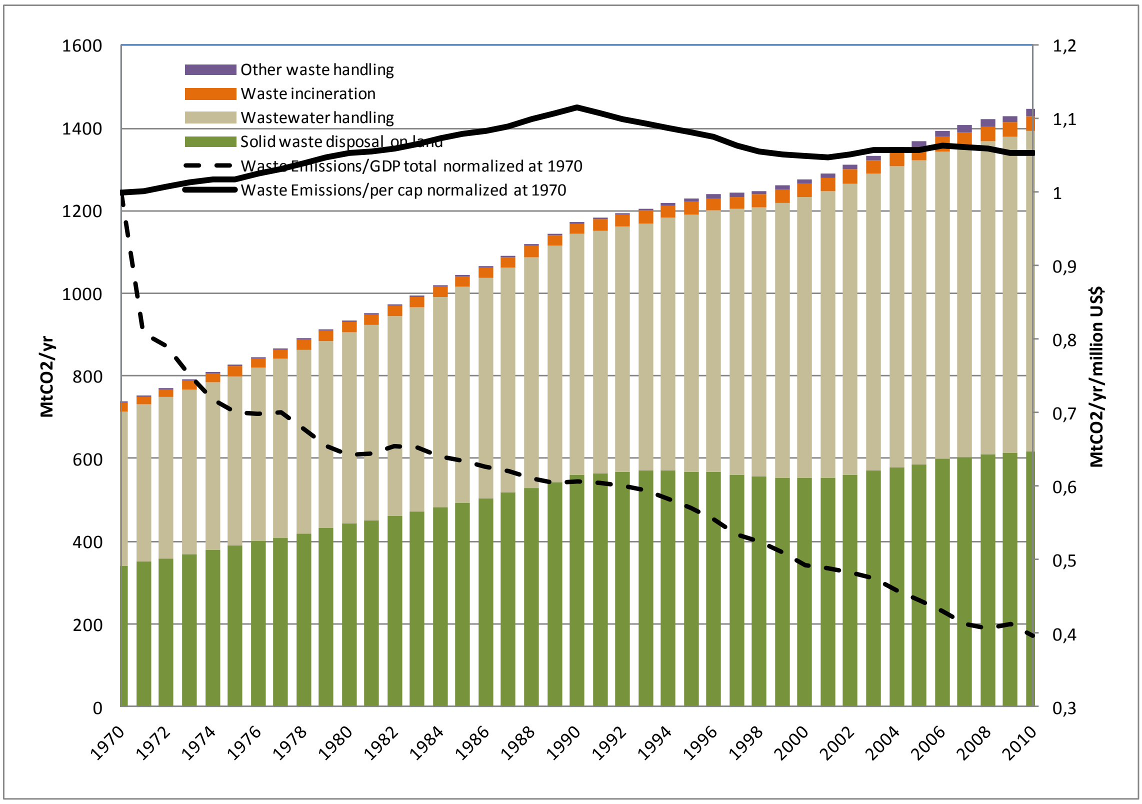


Figure 5.3.14. Global waste emissions MtCO2eq / Year, and global waste emissions per GDP and global waste emissions per capita referred to 1970 values. Based on (JRC, 2012).

From 1998 and forward waste GHG emissions in Asia are larger than in OECD countries; while in 1970 OECD's emissions represented 50% of emissions (364 MtCO2eq) and Asia 27% (199 MtCO2eq), in 2010 Asia represented 41% of waste GHG emissions (596 MtCO2eq) and OECD 27% (391 MtCO2eq) (Figure 5.3.15). The main GHG from waste is CH4 (methane) representing 91% in 1970 and 90% in 2010.

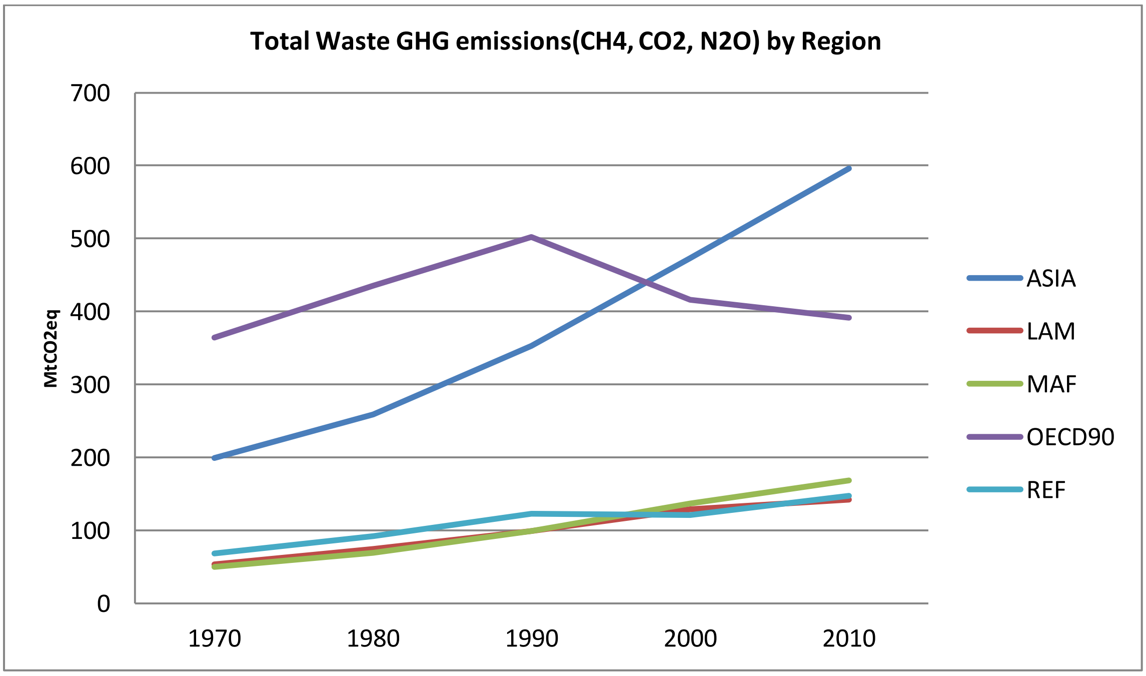


Figure 5.3.15 Total Waste GHG emissions (CH4, CO2, N2O) by Region, in MtCO2eq. Based on (JRC, 2012).

Global waste emissions per unit of GDP decreased 65% from 1970 to 1990 and also 34% from 1990 to 2010, with a total decrease of 60% for the entire period (1970-2010). Global waste emissions per capita increased 10% between 1970 and 1990, decreased 5.6% from 1990 to 2010, with a total increase of 5.4% for the entire period 1970-2010 (Figure 5.3.14).

Several reasons may explain the behavior of these trends: GHG emissions from waste in EU, mainly from solid waste disposal on land and wastewater handling decreased by 19.4% in the decade 2000-2009; the decline is notable when compared to total EU-27 emissions over the same period, which decreased by 9.3 % ("Eurostat: Climate change - driving forces," 2011). The energy production from waste in the EU in 2009 is more than double that generated a decade ago in 2000, while biogas has experienced 270% increase in the same period. With the introduction of the Landfill Directive 1999/31/EC, the EU has established a powerful tool to reduce the amount of biodegradable municipal waste disposed in landfills (Blodgett and Parker, 2010). Moreover, methane emissions from landfills in USA decreased by approximately 27% from 1990 to 2010. This net emissions decrease can be attributed to many factors, including changes in waste composition, an increase in the amount of landfill gas collected and combusted, a higher frequency of composting, and increased rates of recovery of degradable materials for recycling, e.g. paper and paperboard (US EPA, 2012).

In recent years, with rapid economic growth and urbanization in China, waste generation and its GHG emissions have been growing fast. The result indicates that China's GHG emissions in the waste sector has been rapidly increasing in the 1981 to 2009 period, along with the growing scale of waste generation by industries as well as households in the urban and rural areas (Qu and Yang, 2011). A 79% increase in landfill emissions (CH4) was estimated between 1990 (2.43 Tg) and 2000 (4.35 Tg) due to changes in both the amount and composition of municipal waste generated (Streets et al., 2001)and a pick value of carbon emission of China´s waste sector will reach 33.236 million tons at 2024 (Qu and Yang, 2011).

According to Garg et al. (2011), methane emissions from urban solid waste in India are steadily rising over the past two decades; their share in aggregate methane emissions has reached 8%, municipal solid waste collection and disposal has been increasing resulting in a higher growth rate of emissions.

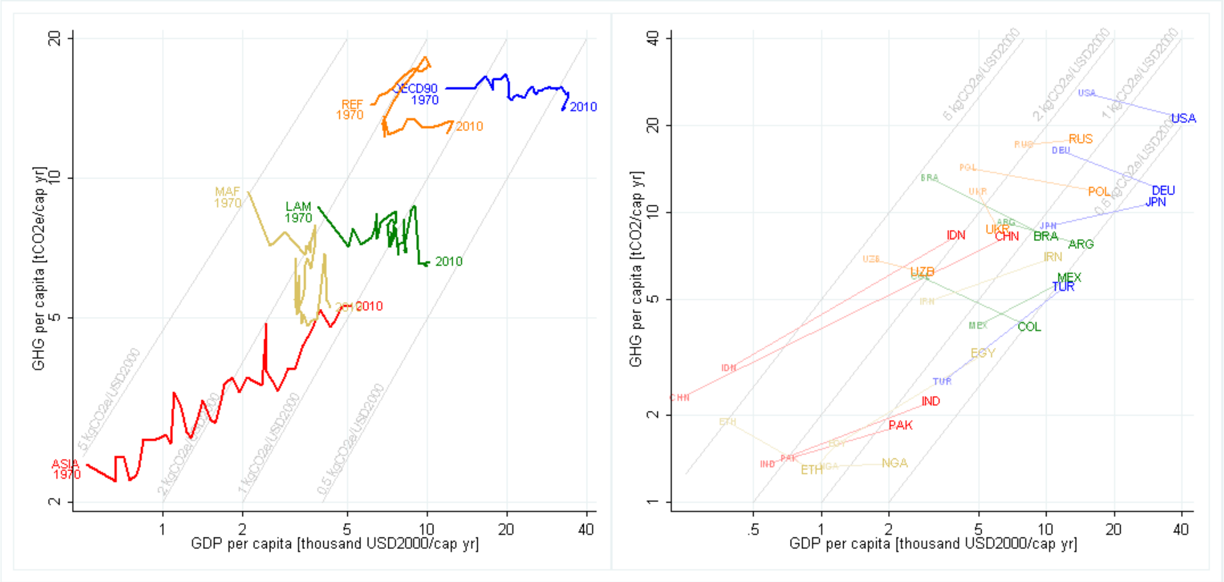
In summary, the decrease of GHG emissions in the waste sector in the EU and USA from 1990 to 2009 may have not been enough to compensate for the increase of emissions in other regions, notably China and India, resulting in an increasing trend of total waste-related GHG emissions in that period. However, these total emissions seem to be enough to keep the trend of emissions per capita stable over the same period and to create a declining trend in emissions per GDP.

5.4 Production and trade patterns

5.4.1 Economic growth & development

Global trends in GDP and GHG emissions vary dramatically by region as shown in Figure 5.4.1. Economic growth was strong in Asia averaging 5.3% per annum and to some degree the OECD (2.1%) over the entire 1970-2010 period and below the world average of 2.0% in the other 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, OECD90 and REF as well as globally and declined in MAF. Results would look different for energy related CO2 emissions alone as these have increased in per capita terms globally over this period.

The levels of the GDP and emissions per capita also vary tremendously globally as shown in Figure 5.4.1.:



(a) (b)

Figure 5.4.1. 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, 2012). Gray 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 though 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. Panel B shows there is wide variation in energy use and 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). These will be discussed in the following sections.

The true 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). 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 points to technological change and increases in human capital per worker as the key driver of per capita economic output growth in the long-run (Aghion and Howitt, 2009). 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.

Countries vary in their distance from the frontier of innovation and, therefore, in their levels of productivity (Caselli, 2005). Productivity is lower in developing countries than developed countries (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. 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, Taiwan, 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.

Research on the role of resources and energy as drivers for economic growth has been more limited (Toman and Jemelkova, 2003). Resource economists have developed models that incorporate the role of resources including energy in the growth process but these ideas generally remain isolated in the resource economics field. By contrast, heterodox 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 by an organic energy production system, 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).

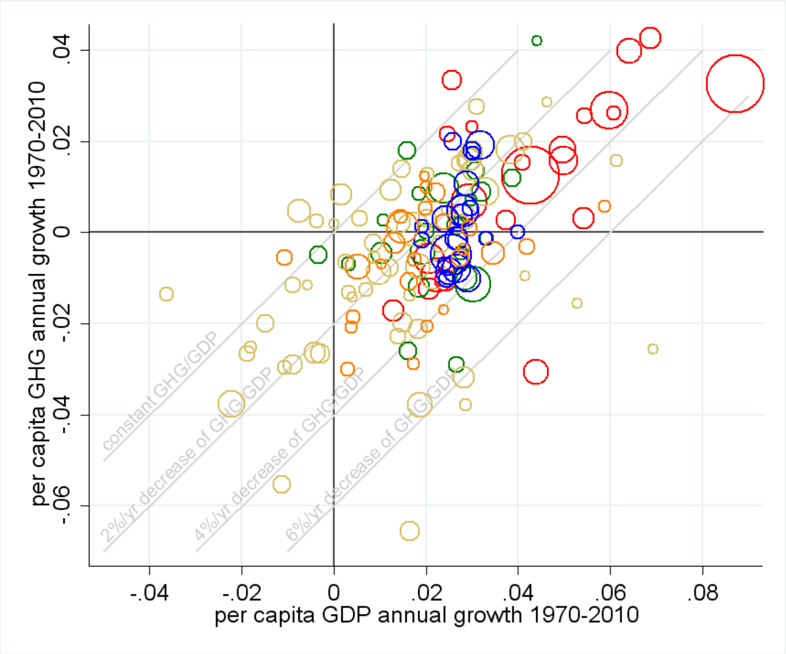


Figure 5.4.2. Growth rates of per capita income and emissions (JRC, 2012). The figure shows the correlation between the average annual growth rate of per capita income and per capita emissions from 1970 to 2010, for all countries with more than 1 million people by 2010. Points along the grey lines have either constant emissions intensity or emissions intensity declining at 2% or 5% per annum. The size of the circles is proportional to countries' populations. 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, in particular China (upper right hand red circle).

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 has been very popular among economists but the econometric evidence has been found to be not very robust (Wagner, 2008; Gallagher, 2009). 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 5.4.2. 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).

5.4.2 Production Trends

This section examines the effect of structural change in the economy on emissions. Structural change is usually measured in terms of the shares of each economic or industry sector in the output of the economy. This separates the effect overall economic scale, dealt with in the previous section from structural change. 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 appear to 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). 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 Development Indicators).

But the sectoral shift away 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 been falling relative to the price of services for most of the time. 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 in 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 the long-run 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 using a much finer disaggregation of industries finds that structural change between industries explained most of the decline in energy intensity in the United States (1958-2000), especially before 1980.

The reform of previously centrally planned economies has been an important factor in the development of greenhouse gas emissions. Emissions and energy intensity was 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. Like most other centrally planned economies, its energy intensity was very high compared to similar but market oriented countries before 1980, and it decreased sharply between 1980 and 2000, as China opened its economy through market-based reforms and shifted away from the focus on heavy industry growth (Ma and Stern, 2008). Energy and emissions intensity rose again from 2000 to 2005, mainly due to the exhaustion of easy catch-up opportunities in energy efficiency (Stern, 2012) and weakening of energy efficiency policy institutions over time (Zhou et al., 2010). On the other hand, China¹s carbon intensity of energy supply has increased steadily over time (Stern and Jotzo, 2010). Since 2005, the emission intensity (emissions/GDP) has declined as the central government has adopted more ambitious energy and emissions intensity reduction policies, which have been quite successful. Structural change has played a small role only in these large movements of the past three decades (Ma and Stern, 2008)(Steckel et al., 2011).

5.4.3 Trade

Between 1971 and 2010, world trade has grown by 10% a year on average, meaning it doubled nearly every 7 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. 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 5.1. Definition of Carbon Leakage

Phenomena whereby the reduction in emissions (relative to a benchmark) are offset by an increase outside the jurisdiction. 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 and international trade 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 being the unintentional consequence of an increase in consumption of one country resulting in emission **increases** in another country.

CAs presented in Section 5.2, 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, by 62% over 18 years (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 23 and 24% of total global emissions in 2004 (Davis and Caldeira, 2010; Peters et al., 2011b).

Trade plays a crucial role, enabling a rise in consumption in main OECD countries that has been met by an increase in trade as opposed to an increase in domestic production. The associated increase in emissions in exporting countries (mostly non Annex B) is defined in the literature as "weak leakage" (Davis and Caldeira, 2010), (Rothman, 1998, 2000; Change and Development, 2000; Peters and Hertwich, 2008; Weber and Peters, 2009; Strømman et al., 2009; Peters, 2010; Yunfeng and Laike, 2010). Other global studies (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. Due to the sparse data available for empirical work, estimates of how greenhouse gas emissions could react to regional regulatory changes have so far mostly relied on numerical modelling. These studies find a wide variety of rates of leakage (i.e. which fraction of unilateral emission reductions are set off 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 for most industries energy accounts for only a small fraction of total costs and that therefore leakage should not be expected to render unilateral climate policies grossly ineffective (Hourcade et al., 2008), and a 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%.

5.4.4 Trade and productivity

Trade does not only affect emissions through its effect on consumption patterns and the relocation of production, it also affects emissions through its effect on innovation and the exchange of technologies between trading partners. The theoretical literature emphasizes several channels through which trade (broadly defined as trade in goods and foreign direct investment) affects productivity.

At the aggregate level, trade can improve productivity through increased allocative efficiency. Trade allows each country to specialize in sectors in which it has a comparative technology or labour advantage, ensuring that other factors of production can be utilized in the sectors in which they are most productive. 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 also increases the international flow of intermediate goods, allowing for the production of higher-quality final products. In this way, trade liberalizations increase the productivity of final-good sectors, and it spurs the invention of additional and/or improved varieties of intermediate goods, that can now be sold in a larger number of markets (Keller, 2000).

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). Through this mechanism, trade liberalization directly increases productivity, but it also has a dynamic effect on innovation. Increasing trade increases (decreases) R&D incentives and raises productivity in export-oriented (import-competing) sectors.

Aside allocation and competition effects, trade can increase productivity growth through knowledge spillovers. Multinationals do more R&D than purely domestic firms, thus FDI can increase the knowledge stock of the recipient country. Moreover, domestic firms may improve their technology after entry by a foreign multinational by reverse-engineering their products or hiring 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 (Javorcik, 2004).

There are many studies that estimate the effect of trade on sector overall productivity, and other studies estimate the effect of trade on the international diffusion of specific technologies. Yet there are no studies that quantify the effect of trade, through productivity, on emissions. Empirical work suggests that trade openness indeed enhances productivity. Most studies focus on labour productivity or total factor productivity (TFP), although a few concern themselves with energy- and environmental applications. (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. 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 TFP growth by 2 percentage points in Korea between 1985-1988. Keller and Yeaple (2009) document that FDI spillovers accounted for 14% of productivity growth in US firms between 1987-1996, particularly in high-tech sectors and in low-productivity firms. Pavcnik (2002) find that the Chilean trade liberalizations in the late 70’s and early 80’s lead to an extra productivity growth in import-competing sectors by 3-10% vis-a-vis the non-traded sectors. The plants that collapsed after the reforms were on the average 8% less productive than plants that continued to produce.

With regards to 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. Lanjouw and Mody (1996) provide evidence that developing countries typically obtain environmentally friendly technologies because it is embodied in imported abatement equipment, rather than through domestic disembodied production through FDI. 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

5.5.1 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 associated with consumption in Annex B increased by 5% (Peters et al., 2011a); (Wiedmann et al., 2010). In a similar vein, as Figure 5.5.1 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 capital 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 associated with consumption in OECD countries.

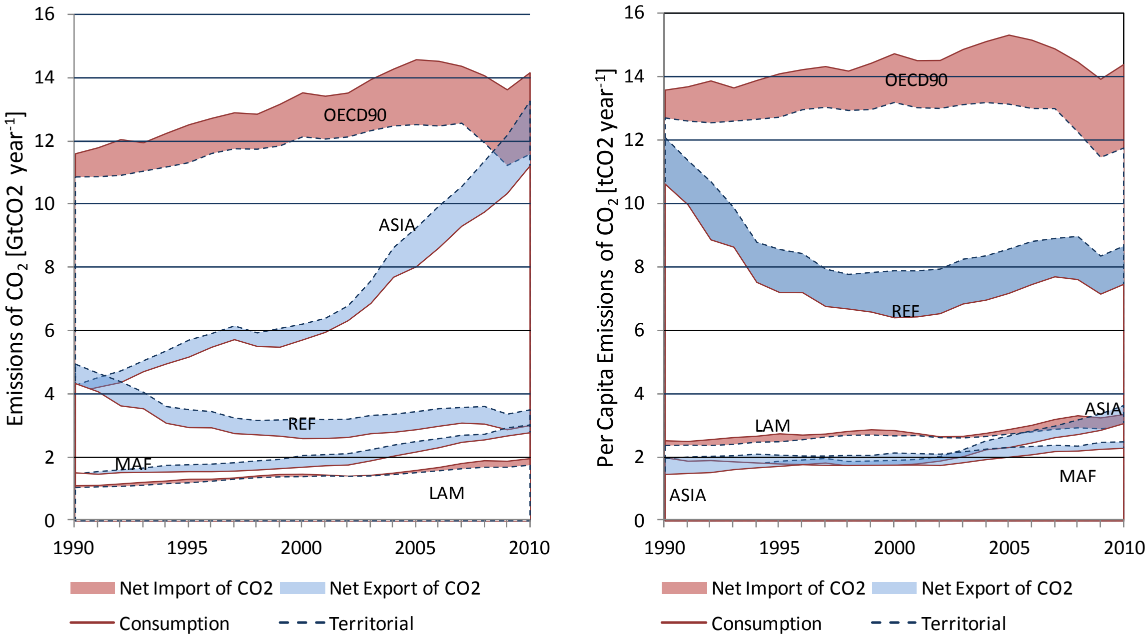


Figure 5.5.1. Territorial (blue lines) versus consumption-based (red dotted lines) emissions in five world regions, from 1990 to 2010. The left panel presents total emissions, while the right panel presents per capita emissions. The red areas indicate that a region is a net importer of embedded GHG emissions. The blue area indicates a region is a net exporter of embedded GHG. 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, 2009b), (Weber, 2009). The analysis has been used to separate factors such as the intensity per value added, shifts in production structure, as well as changes in the composition and the level of consumption. In most 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 less than 100% offset by structural change and efficiency improvements, leading to increasing 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 annual National Emission Inventories. These inventories are used to assess the progress made by individual countries in reducing GHG emissions. The UNFCCC follows the Intergovernmental Panel on Climate Change's guidelines in term of the allocation of GHG emissions which is, "emissions and removals taking place within national (including administered) territories and offshore areas over which the country has jurisdiction" (IPCC, 1996, pp.5). According to this definition, however, GHG emissions emitted in international territory, international aviation and shipping, are only reported as a memo and not allocated to individual countries. We call these "**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). Conceptually, consumption-based inventories can be thought of as consumption equals production minus exports plus imports. We call these "consumption-based emission inventories". Consumption-based emissions are currently not reported officially by any country, but they are increasingly estimated by researchers (see reviews by (Wiedmann et al., 2007; Wiedmann, 2009; Barrett et al., 2013).

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.

5.5.2 Behavioural change

Behaviour is one of the drivers affecting the factors that influence anthropogenic GHG emissions. Though it is difficult to delineate and attribute the effects clearly, there is empirical evidence of variation in behaviour and consumption patterns across regions and over time affecting energy intensity and emissions.

This section reviews the evidence of how behaviour relates to 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.

5.5.2.1 Impact of behaviour on consumption and emissions

Consumption patterns are shaped not only by economic forces, but also by technological, political, cultural, psychological and environmental factors. There is strong evidence to indicate that non–economic factors such as behaviour affect direct household energy consumption patterns and transport and housing related energy expenditure. For example, domestic energy use and travel choices have been found to be 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). Literature also indicates that the cultural context in which an individual lives and the inherent values imbibed by people in society are also responsible for shaping intrinsic motivation (Fuhrer et al., 1995; Chawla, 1998, 1999). Traditional values that are deep rooted in societies on account of cultural and religious values may also influence consumption patterns and lifestyles, affecting emissions. For example, emissions per unit of food are much lower in regions with a large proportion of vegetarian people. Poor people in developing countries such as India, who are inherently frugal in consumption behaviour, also have very low levels of waste generation coupled with high levels of waste recycling and re-use (Ghosh, 2006), leading to low energy use.

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 is not the sole explanatory factor (see figures 5.3.2 and 5.5.1). Disparities in consumption and related emissions between regions have been increasing (Mont and Plepys, 2008). 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), and have a bearing on resultant emissions. Time series data at the global level indicate that key consumption activities of households that contribute to emissions such as personal travel by car, amount of meat and fossil fuel consumed have intensified during the past three decades (Mont and Plepys, 2008), having implications on the level of GHG emissions. While literature comparing household energy requirements across countries ascribes differences to behaviour apart from resource endowments and market conditions present in the region, some studies also show that differences in household CO_2 emissions vary more than energy requirements due to considerable variation in carbon intensity of energy supply between countries (Hertwich, 2005).

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. The decomposition analysis therefore clearly places behaviour not only as an implicit and relevant driver of emissions, but also equally 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, and businesses, policy makers, as well as non-governmental consumer organizations need to be involved. Studies show that environmental values are important determinants of willingness to accept climate change policy measuresi , and that there is a need for combining values and norms to account for climate policy support within public and private organizations (Biel and Lundqvist, 2012).

5.5.2.2 What drives change in behaviour?

A theory of behavior is needed in order to explain what causes changes in behavior. In economics, it has been observed for several decades that the conventional theory of a fully informed, constantly optimizing consumer fails to explain consumer behavior regarding energy-savings appliances. However, over the last decade, there has been some significant innovation in economics with the growing prominence of behavioral economics, which modifies conventional economic models to incorporate findings from psychology. Behavioral economics has recently been used not only to explain anomalies in consumer's energy choices but also to design approaches aimed at influencing and modifying those behaviors.

A common finding in economics concerns the "energy efficiency gap" – the empirical observation 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. Other explanations draw on some newer ideas in economics, including bounded rationality and the notion that consumers “satisfice” rather than “optimize” (Simon, 1957), the importance of non-price product attributes and consumers’ perceptions thereof (Lancaster, 1965), and asymmetric information and the principal-agent problem (Akerlof, 1970; Stiglitz, 1988). From psychology and behavioral economics comes 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[5] and the role of salience[6] (Fiske and Morling, 1996), priming (Richardson-Klavehn and Bjork, 1988), affect (Slovic et al., 2002), norms[7] (Axelrod, 2006), a present-bias in inter-temporal decision making (O’Donoghue and Rabin, 2008; DellaVigna, 2009), mental accounts (separate decision making for subsets of commodities, (Thaler, 1999)). Recently, the literature has moved from documenting that these phenomena are present and affect actual consumer decisions to identifying strategies which consciously take advantage of them to influence the outcome of decisions. These strategies, under the rubric Nudge (Thaler and Sunstein, 2009) or MINDSPACE (Dolan et al., 2012), are actively being tested by government agencies and the private sector, including some electric and water utilities, in the US and UK.

5.5.2.3 Interventions in behaviour

Behavioural interventions may 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, for instance, through financial rewards, laws or provision of energy efficient equipment, among others measures (Abrahamse et al., 2005). Various policies and strategies have been used across countries with varying degrees of success to bring about behaviour change in the consumption choices and patterns. These may be antecedent strategies (involving commitment, goal setting, information or modelling) or consequence strategies (feedback or rewards) (Abrahamse et al., 2005).

Non-price interventions have been shown to reduce energy use, including working with consumers to set energy use goals, provide commitment devices or drawing attention to energy use (Stern, 1992; Abrahamse et al., 2005), and providing feedback on historical energy consumption (Fischer, 2008). The Nudge programs being used to promote energy efficiency involve several elements such as seeking to increase the salience of financial incentives, invoking norms, providing information that makes social comparisons, and modifying the choice architecture (the structure of the choice) including the default alternative.[8] Ayres et al. (2009) estimate that non-price, peer comparison intervention induce a consumption response equivalent to a 17-29% price increase.[9] Newell et al. (1999) also provide some information on the degree to which energy price increases induce improvements in the energy efficiency of consumer products; as an example, for room air conditioners in the USA, only about one quarter of the gain in energy efficiency since 1973 was induced by higher energy prices, another quarter was found to be due to raised government standards and labeling.

Some recent innovative financing mechanisms have been designed to address behaviour barriers. For 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

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

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

[7] 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)

[8] UK Cabinet Office (2012).

[9] 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.

buildings through providing local governments financing for retrofits of buildings repayable through a supplement to property taxes (Ameli and Kammen, 2012).

Although voluntary reduction in energy consumption by individuals depends on their state of awareness and concern about climate change, their willingness to act, and their ability to change, 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). Rewards are seen to have effectively encouraged energy conservation, though with rather 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, it is difficult to delineate which strategy actually contributed to the effectiveness of interventions (Abrahamse et al., 2005).

Further, while non-action may be due to lack of motivation, it is also due to lack of opportunities, even when individuals have a positive attitude and intention to act. Such factors influencing behaviour or constraining behaviour change may relate to institutional and physical structures. Moreover, 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).

Literature also differentiates between (1) efficiency behaviours, that manifest themselves as one-shot behaviours and entail the purchase of energy efficient equipment such as 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 of efficiency behaviours is greater than that of curtailment behaviours. However, energy-efficient appliances do not necessarily result in a reduction of overall energy consumption due to increased use of these appliances, i.e. the “rebound effect”. The rebound effect is discussed more extensively in section 5.6.2.

Many consumption oriented environmental studies suggest that technological solutions directed at improving resource productivity may not be sufficient for curbing the environmental effects of consumption, and that solutions need to be based not only on changing consumption patterns, but also on reducing the levels of consumption. The vision of sustainable consumption requires individual action in changing consumption habits and adjusting lifestyles in line with the principles of sustainable development (Mont and Plepys, 2008). For developed countries this implies not only buying more environmentally sound products and services, but also finding happiness in less material ways of living. Sustainable development strategies that propagate eco-efficiency in production as well as sufficiency in consumption are currently missing and are required in order to conceive of ways of shifting from current culture of limitless consumerism to a society with less materialistic aspirations (Mont and Plepys, 2008).

FAQ 5.3. If society does wish to change the trajectory of GHG emissions, what options are available for doing so?

Fundamentally, the options are to have individuals consume less, have the things consumed require less energy, use energy sources that have lower carbon content, or have fewer people. Although inhabitants of the most developed countries have options to simply consume less, most of the human population and most population growth occurs in less developed countries and economies in transition, where achieving a “middle-class lifestyle” will involve consuming more, not less. Accepting that the human population will continue to grow, choices will involve changes in technology and human behaviour, so products and services can be provided with lower rates of GHG emission in their production and use (technology), and consumers choose products and services, and prefer activities with lower GHG emissions per unit (behaviour).

5.6 Technological change

This section will provide an update of the AR4 on technological change as a driver of GHG emissions from a historical perspective. Distinguishing the “fingerprint” of technological change among other drivers of emissions is not straightforward; often, several drivers affect a factor, and drivers affect each other. Similarly, it is not easy to single out what causes technological change. Therefore, this section will discuss case studies where such attribution could be made, and system aspects that, jointly with technological change, can be said to have caused changes in factors or emissions, with a focus on the literature since the AR4.

The multiple-driver nature of technological change is exemplified by an emerging literature on system aspects of technological change. Building on earlier literature on national innovation systems (Lundvall, 1992), many authors emphasize the enabling conditions of technological change, such as the role of learning, institutional and organizational factors, interaction between actors, dynamic aspects and social capital in technological change (Pinske and Kolk, 2010; Soete et al., 2010), and in developing countries innovation capabilities and institutional factors (Ockwell et al., 2010); (Altenberg, 2008).

After presenting an overall trend, this section will discuss two particular topics in technological change’s contribution to mitigation; the “rebound effect”, and infrastructure and lock-in. How technological change is covered in scenario studies is discussed in Chapter 6.

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, points at a question of whether technological change might also lead to rising emissions – in developed and developing countries. According to some studies, due to a combination of rebound effects (see section 5.6.2) and an observed bias in R&D investments towards more cost-effective energy savings, which is the mitigation option that contributes to the rebound effect, the result of technological change could be an increase in emissions (Fisher-Vanden and Ho, 2010). In addition, technological change may 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). How do macro-economic factors affect differences in energy efficiency between countries and changes over time? Using a bottom-up 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 also 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). Differences in the adoption of energy efficiency technologies across countries and states, over time, and among individuals might be suboptimal due to differences in endowments, preferences, or the state of technology. But the rate of adoption may also be inefficient due to market failures and behavioural factors. Market failures include environmental externalities, information problems, liquidity constraints in capital markets, failures of innovation markets, and principal-agent problems such as between landlords and tenants (Gillingham et al., 2009); (Linares and Labandeira, 2010). Behavioural factors are discussed in section 5.5.2.

5.6.1.2 Historical pattens 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 declining in China energy intensity (Ma and Stern, 2008).

Technological change in the energy sector is best studied. Koh and Magee (2008) analyze functional performance metrics for energy transformation, storage and transport. They arrive at the conclusion that energy technology has annual progress rates of a diversity of functional performance metrics of 3-13%, which is lower than the more extensively studied information technologies (19-37%). Other studies found that technological change in energy was particularly pronounced in periods with a great political sense of urgency, such as the oil crisis period or high energy prices (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. 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 investments in R&D and patenting, although they did not evaluate the impact of that on emissions. In a study specifically on France, Karanfil and Yeddir-Tamsamani’s (2010) results indicate that in energy, policy choices to some extent influence the direction of technical change in the economy. 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).

5.6.2 The Rebound Effect

If energy saving innovations induce an increase in energy use that offsets the technology derived energy saving there is said to be a rebound effect (Berkhout et al., 2000). Rebound effects include “direct rebounds” and “indirect rebounds”. Direct rebounds appear when, for example, an energy efficient car has lower operating costs encouraging the owner to drive further (Sorrell, 2007). Additionally, 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 increases demand for all goods in the economy and, therefore, for the energy required to produce them (Berkhout et al., 2000). For example, savings in fuel due to a more efficient car provides more disposal income that could be spent on an additional holiday. Economy-wide changes include 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. 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 empirical studies relying predominately on econometric techniques to evaluate rebounds. A comprehensive review of 500 studies suggests that direct rebounds are likely to always be over 10% and could be considerably higher (i.e. 10% less savings that the projected saving from engineering principles). For household efficiency measures the majority of studies show rebounds in the region of 30-35%, meaning that efficiency measures achieve 65-70% 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). Roy (2000) argues that because high quality energy use is still small in households in India, demand is very elastic, and thus rebound effects in the household sector in India and other developing countries can be expected to be larger than in developed economies see also (Van den Bergh, 2010).

However, there are further projected losses in addition to direct rebounds through economy-wide effects. These indirect rebound effects are likely to be larger due to long-run growth effects and in some cases could be larger than the initial saving resulting are higher resulting in “backfire” also known as Jevons’ paradox (Brookes, 1990; Sorrell, 2009). While less evidence is available for indirect than direct rebounds, several studies suggest indirect rebounds between 11% and 40% (Barker et al., 2007; Sorrell, 2009; Saunders, 2011).

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 raises 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. 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 review in this part focuses on the narrower physical part. Among physical infrastructure are roads and bridges, ports, airlines, railway, power, telecom, water supply and waste water treatment, and irrigation systems. 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. The choices in industrial countries at that time have been set as examples followed by many new emerging economies in their process of urbanization and industrialization (IPCC, 2007), including two main emerging economies, China and India, which have shown accelerating physical infrastructure construction since 2000 (Pan, 2010). Davis et al. (2010) estimate the commitment to future emissions and warming by existing carbon dioxide–emitting devices, totalling to 496 (282 to 701) GtCO2 between 2010 and 2060, and an associated warming of 1.3°C (1.1° to 1.4°C). CO2-emitting infrastructure will expand unless extraordinary efforts are undertaken to develop alternatives.

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 have 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 (WEA, 2012). 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 high population growth and relatively low levels of infrastructure supply, so that these emerging megacities become future major emitters of greenhouse gases.

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 trade-offs of mitigation actions

5.7.1 Co-benefits

Many strategies for reducing greenhouse gas emissions also decrease emissions of health-damaging air pollutants and precursor species, including particulate matter, nitrogen oxides. Reductions in greenhouse gas emissions provide significant “co-benefits” by helping achieve these other goals. Mitigation strategies directly or indirectly affect health by acting upon health exposures and risks related to ambient air pollution from electricity production, indoor air pollution in homes reliant on coal and biomass fuels, transport related air pollution, and the spread of sedentary lifestyles. Health effects have been at the centre of co-benefit considerations (Van vuuren, 2006; Bell and Dominici, 2008).

The reduction of short-lived climate forcing agents often generates health cobenefits (Shindell et al., 2012). As an example, West et al. (2006) show that methane emissions abatement also has ozone air quality and health co-benefits, as methane is an ozone precursor.

Box 5.3. Co-benefits estimates

A light-rail transit line in Charlotte NC with 15 stations covering 9.6 miles averaged 14,000 daily riders in its first year (2007) (Charlotte Area Transit System, 2007). Estimates suggest this transit line will save $12.6 million dollars in total healthcare costs over 9 years (Stokes et al., 2008).

Implementation of measures to mitigate black carbon and tropospheric ozone can help avoid 0.6–4.4 and 0.04–0.52 million annual premature deaths globally in 2030; more than 80% of the health benefits are estimated to occur in Asia (Anenberg et al., 2012).

Wilkinson et al. (2009) find that in India around two million premature deaths, particularly in women and children, can be averted by introducing 150 million improved efficiency cook stoves over a decade.

Two principal paths for reducing greenhouse gas emissions are via improvements in energy efficiency and through reduced use of coal. Energy efficiency improvements reduces the amount of energy needed and consequently reduces air emissions if energy is carbon based (Van Vliet et al., 2012). Reducing coal use provides immediate improvements in local and regional air quality.

Numerous studies have provided quantitative estimates of these potential co-benefits (Nemet et al., 2010). Some studies calculate reduced mortality, increased person-life-years or other physical measures. Others – by assuming monetary values for morbidity and premature mortality – provide monetary estimates which are compared to the cost of climate policy (Rao et al., 2012).

To the extent that climate policies stimulate commercial fuels for cooking and heating in developing countries, they have substantial health benefits. Although commercial cooking fuels, such as liquid propane, have negative environmental impacts, the move away from biomass generates large net health benefits (Haines and Dora, 2012). The benefit-cost ratio has been estimated at 4:1 (“WHO | Outdoor air pollution,” 2012). The resulting change in radiative forcing though is uncertain because biomass combustion emits significantly more organic carbon, which produces a cooling effect on the atmosphere, compared to black carbon, which is a warming agent. The improved stoves often reduce emissions of organic carbon more than those of black carbon (*UNEP/WMO*, 2011).

Energy security is a primary goal of many countries even though it is not clearly or consistently defined. Several climate mitigation actions improve energy security. Efficiency measures, increased deployment of renewable energy, and electrification of transportation reduces the dependence on imported fuels in many countries. On the other hand, reductions in coal use can lead to additional fuel imports dependent on the substitute. Economic co-benefits are also reported for both of the cement plant owner and local government to treat municipality wastes in the cement kiln, while it also reduces GHG emissions (Sano et al., 2005).

Implementation of selected measures to mitigate black carbon and tropospheric ozone increases annual crop yields of wheat, rice, maize, and soy (Shindell et al., 2012). Other important co-benefits of climate change mitigation include water savings (Abeysuriya et al., 2009), biodiversity increase from investing in reafforestation and habitat restoration for carbon biosequestration (Dickson, 2009), and improvement in soil productivity (Bahor et al., 2009).

Co-benefits from mitigation in the transport sector include the reduction of air pollution, noise, congestion and road surface damage. Motorised transport contributes to urban air pollution, responsible for around 1.3 million deaths a year (“WHO | Outdoor air pollution,” 2012). Increasing active travel modes reduces greenhouse gas emissions and diseases such as ischaemic heart disease, cerebrovascular disease, depression, Alzheimers disease, diabetes, and breast and colon cancer (Woodcock et al., 2009). A systematic review of the economic benefits of cycling interventions, including economic benefits of health impacts from more physical activity, results in a median benefit-cost ratio of 5:1, with a range of -0.4 to 32.5 (Cavill et al., 2008).

Energy efficiency also results in quality improvements; better insulated houses are more comfortable, increasing quality of life and productivity (GEA, 2012).

5.7.2 Risk Tradeoffs

Climate policy also produces a range of new technical and social challenges. Stenborg and Honkatukia (2008) report adverse side effects of emission reductions on employment, indicating a risk tradeoff between the long-run employment effects and abatement of greenhouse gases while other studies report increased employment as a result of climate policy (Berndes and Hansson, 2007). Carbon capture and sequestration reduces SO_2 emissions, but increases NOx and NH_3 emissions (Koornneef et al., 2012), and increases the costs and water use (Zhai et al., 2011).

Wind power is sometimes rejected by local communities, mostly for aesthetics reasons. Hydropower dams can cause negative local environmental impacts. Bio-fuels increases land scarcity leading to higher food prices and loss of biodiversity if fuel plantations displace diverse ecosystems. The increased demand for grains for both livestock feed and bio-fuels have contributed to increases in commodity prices, threatening the nutrition of the world's poorest populations (Lee et al., 2008; IEA/OECD, 2009).

5.7.3 Complex issues in using co-benefits and risk tradeoffs to inform policy

Costs of mitigation policies are over- or underestimated when co-benefits and risk tradeoffs are not included. 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 (IPCC, 2007),(Henriksen et al., 2011).

The Stern review estimates the value of co-benefits as 'up to 1% of GDP' (Stern, 2006). Östblom and Samakovlis (2007) find substantial co-benefits for Sweden. Bollen et al. (2009) find that global air quality co-benefits are twice as large as climatic benefits. The co-benefits of GHG mitigation on air pollution impacts have been found to be larger in developing countries, where air pollutants are often emitted without stringent emission regulations (IPCC, 2007). The co-benefits from climate change mitigation in terms of reduced outdoor local air pollution cover a significant part of the cost of action. Nonetheless, they do not provide sufficient participation incentives to large developing countries. This is partly because direct local air pollution control policies appear to be typically cheaper than indirect action via greenhouse gases emissions mitigation (Bollen et al., 2009).

A critical step in estimating co-benefits of climate mitigation policy requires the assessment of policies already in-place and to evaluate the likely evolution of future non-climate policies. The air pollution co-benefits of climate policy are dominated by countries where there are few air pollution controls in-place (Van Asselt and Brewer, 2010). In the United States, large reductions in air pollutant emissions have already occurred in the absence of climate policy and further tightening of air regulations is underway. Rapidly developing countries such as China may follow the pattern of developed countries and adopt regulations to improve local air quality before focusing upon climate policy. Such a scenario reduces the co-benefits of climate policy, though benefits remain substantial.

The scale of deployment also affects the co-benefit or trade-off. Small scale biomass for fuels reduces greenhouse gas emissions and provides energy security (local energy supply) and local jobs. At a large scale, biofuels compete with food and forests. Also, benefits of policies are distributed unequally.

In summary, good estimates of co-benefits are important to the policy process. There is a rich literature on calculated co-benefits and trade-offs, but a limited literature on the role these played in past policies. Many co-benefits of mitigation are short-term, while climate change mitigation policies need a long-term perspective.

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

Between 1970 and 2010 global greenhouse gas emissions have increased by approximately 80%, from 28 to 50 GtCO2e/yr. The use of fossil fuels for energy has been the major contributor to GHG emissions, and its share increased consistently over the last 40 years; their contribution doubled from about 15 to 30 GtCO2/yr, now making up 60% of GHG emissions. The second contributors over the same period were agriculture, deforestation and other land use changes whose emissions rose from 9.3 to 11 GtCO2e/yr. Two factors stand out as the main drivers for these trends: First, global population that grew by 87%, from 3.7 to 6.9 billion, and second, global average per capita income as measured through GDP that rose by 165%, from 3,700 to 9,800 USD2000/yr. The strong correlation between income and GHG emissions is clear from a cross-country comparison, despite the reduction in the average emission-intensity of production, from 2.0 to 0.72 kgCO2e/USD2000 over the same 40-year period. Efficiency improvements have been strongest for non-fossil fuels emissions.

Regions vary greatly with respect to these trends. The OECD90 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 Middle East, Africa, and the Economies in Transition showed a decrease in income around 1990, which together with decreasing emissions per output led to robust decreasing per capita emissions. In the Middle East and Africa, a high population growth led to a robust increase in overall emissions, nonetheless, while the Economies in Transition showed a very low population growth, and declining overall emissions. Emerging economies in Asia showed very high economic growth rates, and booming industries; associated emissions expanded rapidly. In 2010, Asia emitted more than half of worldwide industrial emissions. Even though Asia showed the highest economy-wide efficiency improvements measured as output per emissions, it also showed the largest growth in per capita emissions. The emerging economies progress through an industrial transformation that is similar to the process that current OECD countries went through before 1970. Yet, the scale of the current transition is vastly larger. If the world continues the 2010 emission levels for another 12 years, it will emit as much CO2 from fossil fuels as in the period between 1850 and 1970.

Though income and emissions are correlated, there are substantial variations among regions, among countries within regions, and among countries with the same per capita income level. As a case in point, in 2010, various large Asian countries have per capita emissions comparable to OECD countries, even when their income levels are still substantially lower. The OECD90 countries on average have lower per capita emissions for given income level compared to countries with similar income levels in other regions. There are two qualifications to be made: First, the average per capita GHG emissions by 2010 in OECD90 countries of 14.2 ktCO2e/yr is still about twice the worldwide average of about 7.2 ktCO2e/yr; second, there is an emerging gap between territorial emissions and consumption-related emissions; the latter includes CO_2 embedded in trade flows. OECD90 countries have higher consumption-related emissions vis-a-vis territorial emissions, while the reverse holds for Asia. The gap shows that the increase in the volume of consumption in the OECD90 countries is not compensated by an equal decrease in the emissions intensity of production; because of trade, what matters is the emission intensity in the countries where goods are produced, rather than the domestic emission intensity. The increase in consumption-related emissions also relates to consumption patterns and life styles in rich, developed countries (see Chapter 14). From an accounting perspective, the gap between consumption and production emission can be explained by unbalanced trade flows, differences in energy efficiency and carbon intensity, and the structure of trade, but there is no literature yet that analyzes the drivers of these factors.

Various non-economic drivers that affect the factors in the decomposition identity were identified. Urbanization tends to increase energy intensity, but it also favours more efficient energy choices. Ageing tends to increase the demand for heat, but at the same time decreases labour supply and thus GDP. Smaller household sizes also increase demand for energy and thus emissions. Overall, demographic changes tend to have increased emissions in the past. International trade increases overall production and consumption, but also enables a more efficient allocation of resources. The overall effect is unclear. Efficiency improvements through innovation and technological change have contributed to the downwards pressure on emissions, while the shift from industries to services has been less important as typically perceived. The growth in fossil fuel emissions has been supported by the availability and accessibility to fossil fuel energy sources. Accessibility to renewable energy has the opposite effect but has been limited so far. Chapter 7 will provide more details and future policies options to change these past trends on energy resources. As expected, economic growth and population have been identified as key GHG emissions drivers in the transport, buildings, industry and waste sectors. For industry and buildings carbon intensity of electricity and other energy sources are also critical. Key drivers for emissions from agriculture, forestry and other land use are population growth and the need for food and, to some extent, the need for energy through biofuels (see Chapters 8, 9, 10, and 11).

At a more general level, technological and behavioural changes appear to be key drivers of GHG emissions. For high-income countries, innovations stand out as the main driver for increasing labour productivity and output, while innovations also determine the energy-intensity of production. For middle and lower income countries, the literature is less clear on the main drivers of economic growth and energy intensity. In general, innovation increased income but also resource use, as past technological change has favoured labour productivity increase over resource efficiency. At the same time, there is empirical evidence that for example energy prices affect the direction of innovations, and thus become a driver of long-run energy use through the state of technology. On the other hand, there is also evidence that innovations that are not supported by the right prices policies can produce rebound effects reducing the overall benefit.

Behavioural change, as a key and overarching driver of emissions, affects the factors that determine life-styles and consumption patterns, including, among others, transportation modes, housing related energy expenditure, and food and technological choices.

Behavioural interventions may be aimed at voluntary behaviour change and/or by changing the context in which decisions are made. A combination of strategies is generally found to be more effective than applying any one strategy, although the evidence shows that the success in applying strategies to change behaviour varies across countries. More recently, behavioural economics has been used to design approaches aimed at influencing and modifying consumer’s product and energy choices. Behaviour of companies and organizations also contribute to emissions. The development of environmental values seems to be important determinants of willingness to accept climate change policy measures in the private sector.

In addition, co-benefits derived from the implementation of policies and measures to reduce GHG emissions, such as those related to public health improvements or energy security, are important drivers for GHG mitigation actions.

The analysis of factors and drivers is not straightforward. As described across the different section 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; Figure 5.8.1 shows these interconnections. Policies and measures, in turn, can be designed and implemented to affect drivers but at the same time drivers may influence policy makers and the type of policies and measures finally adopted.

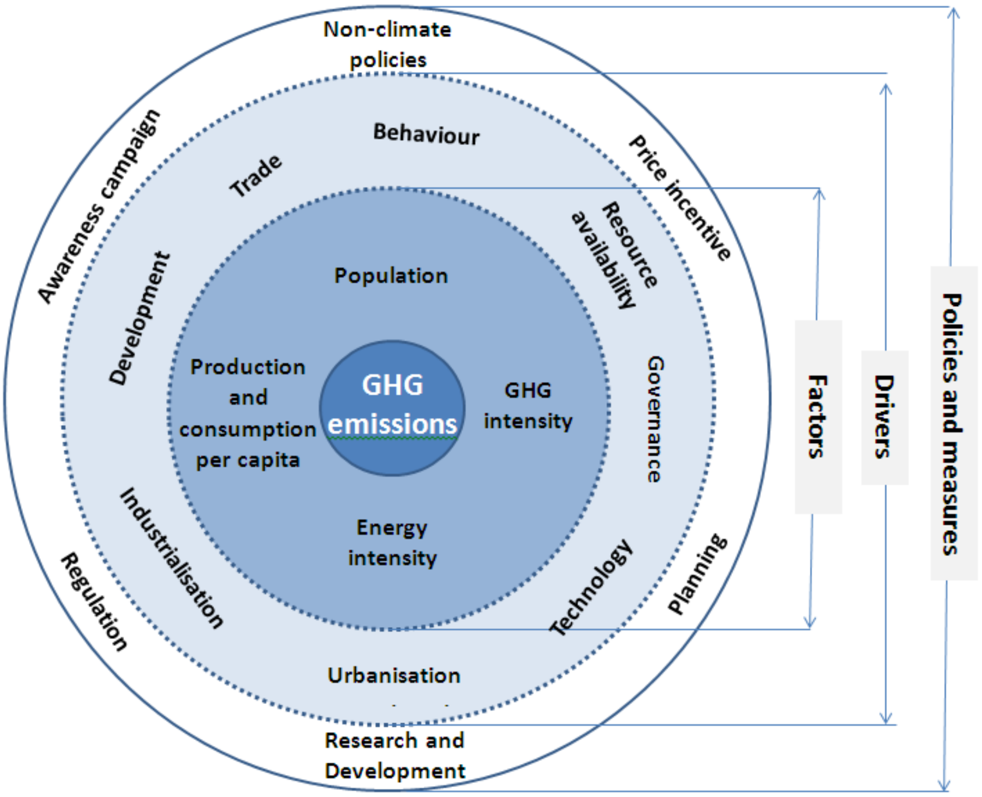

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Figure 5.8.1. Factors and drivers of emissions. The figure describes the interconnections between and among factors and drivers of emissions. Factors comprise the terms in a decomposition of emissions. Drivers refer to the processes, mechanisms and properties that influence emissions through the factors. Policies and measures affect the drivers that in turn change the factors. Factors and drivers may in return affect the policies, measures and other drivers.

The drivers of historic trends of GHG emissions have been multiple, interconnected and difficult to control or manoeuvre. Some drivers, however, have proved to be useful to mitigate GHG emissions. Technological change contributed to the decrease in energy intensity across regions; although the rebound effect has diminished the final effect of efficiency improvement on emissions. Resource availability and ease of use, in particular for fossil fuels, is another key driver that affects the development pathways for many countries; it needs to be addressed, possibly through economic measures, if a change in past trends is to be observed. Behavioural change is an overarching driver that affects other drivers such as consumption patterns and food and technological choices. So far, policies have proved ineffective in influencing behavioural choices in a way that curb the upward GHG emissions trends. Future policies, climate or non-climate ones, will have to deal with the complexity of the drivers and their interconnection, if the aim is to change the future GHG emissions trends.

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 can be afforded and what is preferred. For the high level factors, choice among options with different energy intensity for a given product or service require that lower energy-demanding ways are available to deliver a desired good or service, that they priced accessibly, and that they appeal to consumers. Choice among options with different carbon intensities requires that lower carbon energy sources are available and competitively priced, compared to fossil fuels. For drivers influencing these factors, choice of how much to consume are constrained by earning power of the consumers, prices of the items being consumed, and culture; particularly attractive pricing of products and services that desirable, energy efficient, and less reliant on fossil fuels. What is available to be consumed or used is constrained by the infrastructure and technologies available, particularly buildings, factories, transportation systems, etc that are energy efficient and less dependent on fossil fuels. Choices of what to consume, given the options that are accessible and affordable, are constrained by behavioural preferences due to culture, awareness and understanding of the consequences of choices for reduction in emissions. All of these constraints can be eased by technological development of both alternative energy generation methods and distribution systems, technologies for lower GHG emissions in infrastructure and manufacturing processes (noting that built infrastructure with multi-decadal lifespans can lock regions into high GHG emission options), and a society that is well informed about the consequences of their choices and motivated to make wise choices for products, services and activities that will reduce the GHG emissions for their chosen level of consumption.

5.9 Gaps in knowledge and data

Whereas the collection and processing of statistics of territorial emissions for almost all countries since 1970, as used in Section 5.2, is a great achievement, there is still a lot of uncertainty and variation in attribution dependent on the relative weight given to various greenhouse gases.

The calculation of consumption-based emissions requires an additional layer of processing on top of the territorial emissions, employing a rich economic data-set. The outcomes presented in Section 5.3.1 and 5.5.1 are dependent on various assumptions, and only available for years since 1990.

There are many statistical studies that connect emissions to specific activities, or that translate changes of activities to changes in emissions when all other things are kept equal. Yet, a statistical association is not the same as a chain of causality. Also, different studies often find different significant associations. As a case in point, from a cause-effect perspective, there is not a conclusive answer whether ageing, urbanization, and increasing population density as such lead to increasing or decreasing emissions. The results from the literature are scattered.

The literature provides no clear answer to the question what the main causes are of the different emissions levels among countries. The role of energy resource availability, energy price policies, overall economic development, technology state of development, the level of consumption and lifestyles are recognized, but there is no clear delineation of the contribution of each factor.

For behavior and technological change, there are case studies that establish emission reductions for specific policies and technologies, but there is no assessment in the literature of the overall magnitude of emission reductions that have been achieved, or are achievable through behavior-oriented policies. For technology, empirical studies that ask whether innovations have been emission-saving or emission-increasing are limited in scope; there is a rich theory literature on the potential of innovations to make production energy-saving, or emissions-saving, but not much evidence on the macro-effects and the rebound effect.

Finally, most if not all of the literature on co-benefits and risk trade-offs focuses on future potential gains. There is not much knowledge about historic co-benefits and risk trade-offs.

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