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Chapter 5: Drivers, Trends and Mitigation

Contents

Executive Summary

This chapter assesses the developments, over the past 40 years, of trends in emissions of the main greenhouse gases, as well as the proximate and ultimate causes for these trends, which we refer to as the GHG emissions drivers.

From the analysis of global trends in stocks and flows of greenhouse gases and short-lived species, it can be concluded that 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.

In fact, between 1970 and 2008, global anthropogenic CO2 emissions increased by about 80% while CH4 and N2O increased by about 45% and 40%, respectively, and fluorinated gases, which represented a minuscule amount in 1970, increased by about 650%.

Specific contributions to the overall increase in GHG emissions from sectors like transport, buildings, industry, waste and agriculture, forestry, other land use (AFOLU) and fisheries and aquaculture have been estimated and analyzed.

Transport sector, for instance, represents on average 22% of the global emissions, increasing from 3GtCO_2/yr in 1970 to about 7GtCO_2/yr in 2008 *(high confidence)*. Policies such as for pollution control, technologies such as biofuels, vehicle materials, fuel efficiency, and transport planning and management still hold promises to curb the growth in the sector GHG emissions *(medium agreement)*.

Industry GHG emissions have grown moderately from about 5GtCO_2/yr in 1970 to about 8GtCO_2/yr in 2008 with an increased growth rate realized from 2002 attributed to industry growth in China *(high confidence)*. The variety of potential mitigation measures for the sector includes energy efficiency, fuel switching, renewable energy, feedstock change, capture and sequestration of CO_2; measures that can be coupled with policies such as energy pricing and pollution controls *(medium agreement)*.

Available data for buildings sector indicates that emissions have increased by about 17% from above 3GtCO_2/yr in 1970 to nearly 4GtCO_2/yr in 2008 (*medium confidence* as data are not well specified). Sector GHG mitigation can be achieved through mandatory standards, voluntary programmes, policies and incentives backed by research *(medium agreement)*. Better response can be proliferated in reducing GHG when governments provide leadership in their own buildings.

Agriculture contributed 11.5% of the total global emission in 2008, whereas forestry and other land uses (FOLU) contributed 11.3%. Compared to 1970, in 2008 emission in agriculture has increased by 25.3%, although global population, a major driver of agriculture and GHG emission, increased by 82.7%. An increase in food production can be reached through breeding of stress-tolerant cultivars/breeds of crops, livestock, fish and forest trees that will increase food, feed and fuel production without enhancing GHG emission. Increasing use of resource conserving technologies will be required for enhancing production and GHG mitigation.

Waste GHG emissions represented in 2008 the 2.9 % of global GHG emissions, compared with 2.6 % in 1970 year *(medium agreement, robust evidence)*. Waste related GHG emissions increased by 193.5 % in the same period *(medium agreement, robust evidence)*. Municipal solid waste is a significant contributor to greenhouse gas emissions. The majority of these emissions are a result of landfilling *(high agreement, robust evidence)*. Countries have been incorporating alternative forms of waste management strategies for mitigation such as energy recovery from landfill gas capture, aerobic landfilling, pre-composting of waste prior to landfilling, composting of the organic fraction of municipal solid waste, controlled wastewater treatment and recycling to minimize waste, waste incineration with energy recovery and biofilters to optimize CH4 oxidation *(high agreement, robust evidence)*.

Global population has been doubled since 1970s to about 7 billion today, and per capita income in PPP has increased by 80%, leading to over 3.5 folds increase in Gross World Products in PPP. During this period, global GHG emission in GWP100 has increased by about 80%.

Studies have identified multitude of drivers to global GHG emissions including consumption, international trade, population, urbanization, human behaviour, economic growth, and energy use. Among others, consumption, population, economic growth and energy use are well established drivers to global GHG emissions in the literature. There are competing explanations on international trade and urbanization as a driver.

It is notable that most of the literature identified more than one driver and many also recognized the interdependencies between them. Furthermore, it is obvious that many of the drivers can be further divided into various subcomponents. As such, the question, "what is the driver of global GHG emissions?" can only be answered in the context of scale, level of detail, and the starting point,

Therefore it is necessary to provide a context under which drivers of GHG emissions are identified at different levels. A hierarchical framework is proposed, so that drivers can be systematically identified and compared using both production-based and consumption-based approaches in parallel.

In order to identify the main drivers for the GHG emissions trends a decomposition analysis known as the Kaya identity is used. In this identity global emissions are equal to the population size, multiplied by per capita output (Gross World Product), multiplied by the energy-intensity of production, multiplied by the carbon-intensity of energy. The identity helps to understand the mechanisms underlying the changes in emissions. However, the factors in the Kaya identity are not independent to each other, adding a level of complexity to the analysis of causes and effects. The Chapter tries to reach beyond proximate causes and drivers, such as production capacity or consumption patterns, to understand ultimate causes and drivers; for that purpose, the chapter is structure following the Kaya identity.

The first driver in the Kaya identity, population, has been an important driver of GHG emissions in recent decades. The direct effect of population on emissions is a proportional increase, but the indirect effects of population on emissions are diverse (*high agreement, robust evidence*).

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 has been stable at about a factor 50, though individual countries have changed their position in the ranking considerably *(high agreement, robust evidence)*.

The population has been increasing mainly in Asia, Latin America and Africa; with total emissions Asia growing fastest due to other factors and drivers *(high agreement, robust evidence)*.

Other demographic trends such as urbanization, ageing and household size have more subtle effects on emissions. Migration from rural areas to urban areas tends to increase emissions at its initial stage; while a further urbanization tends to decrease emissions. Ageing population seems to have an almost neutral effect on emissions, while the evidence on the effect of household size is not clear *(medium agreement, medium evidence)*.

The second driver analyzed is GDP per capita, which is often used as a proxy for economic development, production, and income.

Worldwide income has gone up during the period assessed with much variation over time and regions *(very high confidence)*. Mainstream economic theory points to technological change as the key long-term driver of growth but capital stocks and resource use have also tended to increase as part of the growth process *(medium agreement and evidence)*.

Economic growth was strong in Asia, the OECD also showed considerable growth levels, while Latin America showed lower growth over the entire period. Africa and the formerly centrally planned economies have seen setbacks in growth. At the same time, OECD countries have shown somewhat stable per capita emissions, but growth in developing countries seems more emission-intensive *(high confidence)*.

The role of sector shifts, say from agriculture to industry to services, is probably less important for the development of emissions than improved energy efficiency within the sectors *(low agreement, medium evidence)*.

Economic growth, in turn, is related to the level of consumption of goods and services; once the level of consumption is isolated as an individual driver of emissions, it is by far the most significant driver in both developed and developing countries *(high agreement, robust evidence)*. This is the conclusion of numerous studies that have undertaken a structural decomposition analysis to identify the role of different drivers.

The interlinkages among economic growth, consumption, and emissions are important for the attribution of emissions among regions and countries. There has been substantial growth in international trade, resulting in significant variation between the territorial-based and consumption-based GHG emissions of countries.

The general trend shows that consumption-based emissions are higher than territorial-based emissions for developed countries and lower for emerging economies *(high agreement, medium evidence)*. In fact, it is found that international trade allows developed economies with a lower than global average emission-per-value intensity to import higher emission-per-value intensity goods from emerging economies, and vice versa *(low agreement, medium evidence)*. The growth in international trade results in significant variation between the territorial-based and consumption-based accountings of GHG emissions of countries *(high agreement, robust evidence)*.

As trade serves as an instrument for exchange, it 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.

The third factor in Kaya identity is energy use per output, or energy intensity, that depends on a set of interrelated variables including demographics, technology and capital vintages, geography and climate, energy prices and taxes, lifestyles, and policies. Long-term statistical records show improvements in energy intensities of economic outputs (measured by GDP) by more than a factor of five since 1800 when traditional biomass fuels are included in the measure of energy inputs, corresponding to an average decline of total energy intensity of about 1% per year *(high confidence)*. Most regions show declining trends in energy intensity over the period 1970-2008 *(high confidence)* including most of developed countries and major developing countries such as India and China.

Changes in energy intensity over time can be decomposed into the effects of structural change – the shift to more or less energy intensive industries – the effects of changes in the mix of energy sources, technological change, and the quantities of other inputs such as capital and labor used. The change in energy intensity also depends on economic growth; fast economic growth leads to a higher turnover of the capital stock, thus offering more opportunities to switch to more energy-efficient technologies *(low to medium confidence)*.

The fourth factor in our identity is related to the carbon content in the energy resources. 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, too low to offset the increase in global energy use of about 2% annually. The last decade shows a significant slowing of decarbonization, particularly due to rising carbon intensities in some developing regions, and to the slowed turnover of the energy system in developed countries *(very high confidence)*.

The factors of the Kaya identity have various underlying drivers that are not independent to each other. As an example, consumption patterns are shaped not only by economic forces, but also by technological, geographical, political, sociological, and psychological factors.

Behaviour is an implicit and relevant driver of emissions, and is also a potential agent for change in emissions *(robust evidence)*.

Emissions are linked to behaviour from both the production and consumption side. Several studies indicate that behaviour plays a greater role on the consumption side, and that the level of consumption or the preference of goods and services that entail lower emissions are likely to affect the overall emissions *(medium agreement and confidence)*.

Voluntary reduction in energy consumption by individuals depends on their state of awareness and concern about climate change, their willingness to act, as well as their ability to change. Different social and cultural predispositions also affect the use of energy and materials.

Inherent behaviour in societies leads to large variations in consumption patterns and lifestyles. Moreover, not only current, but also past behaviour is seen as one of the most intractable barriers to changing energy behaviours *(low agreement, limited evidence)*.

Various policies and strategies are used across countries and across different levels with varying degrees of success to bring about behaviour change. Apart from technological solutions that could be directed at improving resource productivity by changing consumption patterns, literature also points to the need for reducing the levels of consumption *(medium confidence)*.

Technological change is an important driver for both the overall economic growth and the energy intensity of growth. Although some technological change leads to lower energy intensities and greenhouse gas emissions, much of it also results in increasing emissions. Technical innovations that potentially decrease emissions are partly offset by the "rebound effect", the phenomenon that makes resources demand for resources to increase when due to innovation or efficiency improvements the final products becomes cheaper. The balance of evidence suggests that the "rebound effect" reduces the energy savings brought by energy efficiency measures by 10-30% from the reduction expected by the direct effect.

Decision made on infrastructure have influenced the effect of technological change on energy intensity and therefore on GHG emissions. Infrastructural choices made in the post World War II period are still affecting current emission levels, as they determined, for example, the fuel of choice for decades thereafter. Indirectly infrastructure also guides the choices in technological innovation, as greatest profits are expected for technologies that will remain in future demand due to the existence of complementary infrastructure. This is the so-called lock-in effect. The mechanism is reasonably understood, but there are few data with which to quantify its role in facilitating or impeding reductions in GHG emissions.

Co-benefits and other trade-offs have also influenced the implementation of mitigation policies and measures and, therefore, the GHG emissions. Co-benefits can be positive or negative. They may include improvement of ambient and in-door air quality, sulfur dioxide emissions reduction, energy security and transport safety, among others, but also can lead to undesirable outcomes, as in bioenergy production through increased land competition, higher food prices, and loss of biodiversity if fuel plantations affect diverse ecosystems.

The key complexities for analyzing co-benefits include: choosing an appropriate baseline policy, understanding the importance of scale, and recognizing that net co-benefit calculations may hide critical details about winners and losers. Many co-benefits from mitigation turn out to be short-term effects, while the objective of climate change mitigation policies is in the long-term timeframe.

In conclusion, the decreasing trends in energy efficiency and the almost stable trend in the carbon content of energy resources have not been sufficient to offset the increasing trends in population and economic growth, and therefore have not been able to offset the increasing trends of global GHG emissions over the past 40 years. For the next decades, the past patterns suggest a continuous increase in global emissions due to continued increasing population, and energy-related emissions will form a major part.

At the same time, per capita emissions, which remained more or less stable over the period, indicate that the substantial income increase has been balanced by an equal increase in energy efficiency and slight decarbonisation of energy.

Though the territorial share of the OECD countries has decreased considerably, their average per capita emissions of approximately 16 $tCO2$ per year are still more than double the global average; for global emissions to go down, per capita emissions in the OECD countries must go down as well.

Reducing global emissions also requires the fast developing countries to change past trends. With a substantial part of the global population reaching middle and higher income levels, global emissions increasingly mirror the per capita emissions of these populations.

Thus, a major shift in the energy system worldwide will be required to bend downwards the global trends. We have to reduce energy per output, or to decarbonise energy supply, or both.

We need to pay special attention to infrastructure, construction and technological choices as these affect future emissions for several decades. Recent insights in the dynamics of technological change could give guidance to policymakers about how to embark on innovation policies more effectively.

In view of this assessment, technological change and individual behavior becomes key aspects for future efforts on climate change mitigation.

5.1. Introduction and overview

Building a better future starts by learning from the past. In this chapter, we assess the developments over the past 40 years, from the 1970s to the late 2000s. We present trends in emissions of the main greenhouse gases, and assess the proximate causes and ultimate causes for these trends, which we refer to as the drivers. We employ extended versions of decomposition analyses known as the Kaya identity and the IPAT identity. The IPAT decomposes the level of greenhouse gas emissions (Impact) into three components: the population size (P), the affluence (A) or consumption expenditure per capita, and the efficiency of technology (T) used to generate income. The Kaya identity is a refinement; it reinterprets income as output (e.g. using G for Gross World Product), and further decomposes the technology variable into energy per output (E/G) and emissions per unit of energy ($CO2/E$). For carbon dioxide, on a worldwide level, the equation reads as

$$CO2 = P \times (G/P) \times (E/G) \times (CO2/E)$$

The equation presents an identity. Emissions are equal to the population size, multiplied by per capita output, multiplied by the energy-intensity of production, multiplied by the carbon-intensity of energy. The identity helps to understand the mechanisms underlying the changes in emissions, but the identity does not imply causality. One cannot conclude from it that population growth as such increases emissions, nor does income growth necessarily lead to higher emission levels. The variables on the right-hand side develop jointly and not separately. A growing population can slow economic development when essential resources are scarce, but it also increases the potential development of new ideas, which increases the speed of innovation and economic growth. And innovations can be used to increase output while maintaining the same resource-intensity of production, but innovations can also be harnessed to decrease the resource-intensity, and thereby, to decrease the ultimate impact. We thus have to very carefully assess the literature and data, to identify causes for the big changes in emissions that we have seen over the past 40 years. We try to reach beyond proximate causes and drivers, such as increasing production capacity and income, to understand ultimate causes and drivers: mechanisms and policies that determine the level and direction of economic growth. But the distinction is delicate and a discussion of system boundaries is beyond the scope of this chapter.

The structure of the chapter is easily understood from the Kaya identity presented above. We start, in Section 5.2, with a presentation of the main trends on the variables on the left-hand side: the emissions of greenhouse gases and short-lived substances that potentially counter the greenhouse effect. The picture that emerges from Section 5.2 serves as the basis for the remainder of our chapter. The section tells us how much greenhouse gas emissions have increased, which substances contribute most, and when extrapolating trends, which substances are expected to contribute most in the future. Similarly, Section 5.2 will inform us about the regional distribution of emissions and the historic shift.

Section 5.3 is the methodological centrepiece of the chapter. It presents and discusses a more detailed version of the above Kaya identity, with a more detailed regional and sector structure. It shows how the Kaya identity can be used to assess the effects of regions and sectors that become more important over time, and how changes in emissions can be attributed to changes in the underlying variables such as population on a more detailed level: within regions and economic sectors. It also discusses the connection between two complementary approaches. The first approach attributes emissions to output, that is, the production of goods, while the second approach attributes emissions to consumption. While total emissions attributed are the same under both approaches, they present potentially very different pictures with respect to the variety over regions and sectors with respect to the emission intensity of consumption and production.

The next sections go into more detail into the variables on the right-hand side of the Kaya identity. We start with population, or more broadly, demography, in Section 5.4. This section presents the different trends in demographic variables, such as population size, ageing, and urbanization, for the major world regions, and it discusses the importance of changes in these variables for greenhouse gas emissions. The section will also present mixed evidence on the question of causality, that is, whether population size is approximately one-to-one connected to emissions, as the identity suggests, as briefly touched upon above.

Section 5.5 presents and discusses the trends and role of the affluence variable. It takes a broad view, and starts with a discussion of the drivers for economic development, and the question whether increased resource use is an inevitable consequence of development or not. The section continues with the more narrow terms of affluence as measured by per capita production and consumption. The transition from an agricultural society to an industrial, and ultimately the development of a service-oriented society implies that growth of the affluence variable in the Kaya identity is intertwined with the choice of technology, and this connection helps us to remember that one cannot assess the consequences of income growth ‘taking all other things unchanged’. The section connects back to Section 5.3 when it also presents consumption as a driver of emissions, and the role of trade and the fast-increasing trade flows and carbon embedded. The closing part of the section highlights that our perspective on trade should not be restricted to a mechanistic view of carbon streams. We assess evidence on the role of trade for the exploitation of comparative advantages, including energy-related advantages, and for the international exchange of technologies.

Section 5.6 and 5.7 apply the Kaya identity to specific sectors. In Section 5.6, we zoom into the energy sector, the sector that is the worldwide major contributor to carbon dioxide emissions. We present and discuss the trends in energy demand and the various determining factors. We provide a brief discussion on the concepts of energy-intensity and energy savings and the physical limits. This section will also address the supply side. As the green paradox literature has emphasized, through energy markets, the use of energy sources cannot be understood without addressing the economics of fossil fuel exploration and exploitation. As part of the assessment of energy supply the section will also present the trends in carbon-free energy sources and its underlying drivers.

Section 5.7 then covers the other major sectors: transport, buildings, industry, food and agriculture, and waste. For each sector, we will use the Kaya or IPAT identity and present the regional developments in the activity levels, and in the intensity of emissions per activity. We then assess the drivers for trends in both the size and emission intensity, to form a picture of future expectations.

The subsequent Sections 5.8 and 5.9 take an orthogonal view. These sections do not apply the Kaya identity to regions or sectors, but these sections consider two ultimate causes, behaviour and technology, and assess how developments therein have changed emissions through the various variables in the identity, while acknowledging differences between regions and sectors. Behavioural change as discussed in Section 5.8 takes a humanities perspective, and connects to fundamental and often normative issues also dealt with in previous chapters, such as the concept of sustainable development.

Section 5.9 deals with technological change. It discusses theory and evidence on the role of technological change in both overall productivity growth, affecting the affluence variable, as well as the direction of the direction of growth; whether it is resource saving or increasing the resource intensity of production. The rebound effect is a phenomenon also discussed here. It is the name used to describe the case that appliances, as an example, become more energy efficient, leading to demand for the appliances to more than proportionally increase, so that finally energy demand is not reduced but increased. The section concludes with an assessment of the role of technology as embedded in capital and infrastructure, and how it determines the future drivers and trends of greenhouse gas emissions.

Section 5.10 complements the analysis of trends and drivers of greenhouse gases with a consideration of their implications for other environmental and social issues such as ambient air quality and energy security. Finally, the findings of this chapter are summarized in Section 5.11, where we present the overall system perspective on drivers and trends.

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

The term “radiative forcing” is used in the IPCC to denote an externally imposed perturbation in the radiative energy budget of the Earth’s climate system(IPCC, 2001). A positive forcing (more incoming energy) tends to warm the system, while a negative forcing (more outgoing energy) tends to cool it. Anthropogenic radiative forcing includes changes in concentrations of well-mixed greenhouse gases, aerosols and tropospheric ozone. In this section we will explore emission trends for these agents and their precursors. For a description of the projected range of contribution of each to radiative forcing, see radiative forcing diagram for AR4, Figure SPM 2(IPCC, 2007, p. 4).

5.2.1. Sectoral and regional trends in GHG emissions

We begin by focusing on the trends in greenhouse gases from 1970 through 2008. The non CO2 greenhouse gases are converted to CO2 equivalents using 100-year GWPs. Figure 5.2.1 shows the trends in major greenhouse gases.

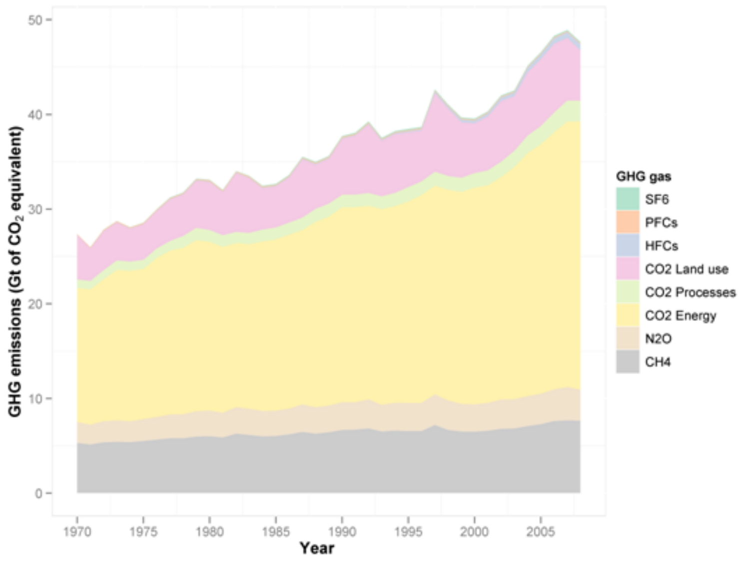


Figure 5.2.1. The principal greenhouse gases that enter the atmosphere because of human activities (JRC, 2011). Co2 continues to be the major anthropogenic greenhouse gas accounting for more than 75% of GWP adjusted emissions. Conversion of non CO2 greenhouse gases based on 100-year global warming potentials.

Between 1970-2008, global anthropogenic CO2 emissions increased by about 80%, CH4 and N2O by about 45% and 40% respectively. Fluorinated gases which represented a minuscule amount in 1970, increased by about 650% over the same period. Total GWP-weighted greenhouse gas emissions increased by about 75% since between 1970 and 2008(IEA, 2011).

CO2 is the most important anthropogenic greenhouse gas. Its increase is due primarily to the combustion of fossil fuels and land use change. In 2008, CO2 emissions exceeded 75% of anthropogenic emissions. The combustion of fossil fuels such as coal, oil and gas takes place in power plants, and transportation. CO2 is also released through the production of cement and other industrial goods. Emissions from land use change are due primarily to deforestation.

The AR4 placed uncertainty bounds on anthropogenic emissions of CO2(IPCC, 2007; Smith et al., 2011). For fossil carbon dioxide emissions in the 1990s emissions were estimated at 6.4 Gt plus or minus 0.4 Gt of carbon per year. Estimates of CO2 emissions associated with land use change averaged over this period were 0.5 to 2.7 GtC per year with a central estimate of 1.6 Gt per year.

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 municipal solid waste landfills. It is estimated that more than half of global methane emissions are related to human-related activities. Natural sources of methane include wetlands, gas hydrates, permafrost, termites, oceans, freshwater bodies, non-wetland soils, and other sources such as wildfires(EPA, 2006).

The third most abundant source of anthropogenic emissions comes from nitrous oxide (N2O) which is emitted during agricultural and industrial activities, as well as during combustion of fossil fuels and solid waste. 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 CO2, global uncertainty ranges for these emissions have not been quantified.

In addition to the long lived greenhouse gases (LLGHG): CO2, CH4 and N20, a second basket of gases was added in the Kyoto Protocol, the so-called F-gases that include hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride. These synthetic, powerful greenhouse gases are emitted from a variety of industrial processes. Fluorinated gases are sometimes used as substitutes for ozone-depleting substances (i.e., CFCs, HCFCs, and halons). 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”). 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.

GHG emissions are emitted from many societal activities. Using data from a wide range of sources, the GHG Flow Diagram (Figure 5.2.2) provides a comprehensive accounting of global GHG emissions. This flow chart shows the sources and activities across the economy that emits greenhouse gas emissions. Energy use is by far responsible for the majority of greenhouse gases. Many activities produce greenhouse gases both directly, through on-site and transport use of fossil fuels, and indirectly from heat and electricity that comes “from the grid.”

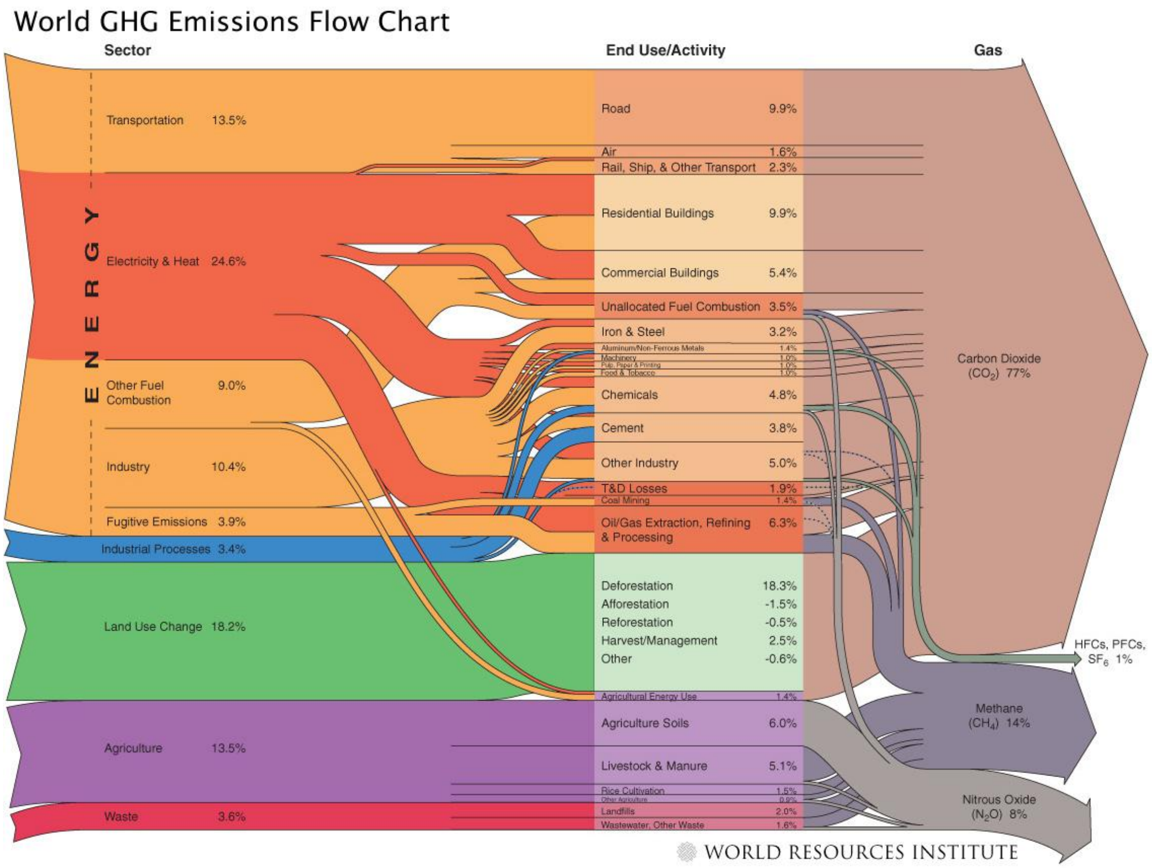


Figure 5.2.2. All data is for 2000. Calculations are based on CO2 equivalents, using 100-year global warming potentials from the IPCC (Houghton et al., 1995), based on a total global estimate of 41,755 MtCO2 equivalent. Land use change includes both emissions and absorptions. Dotted lines represent flows of less than 0.1% percent of total GHG emissions.

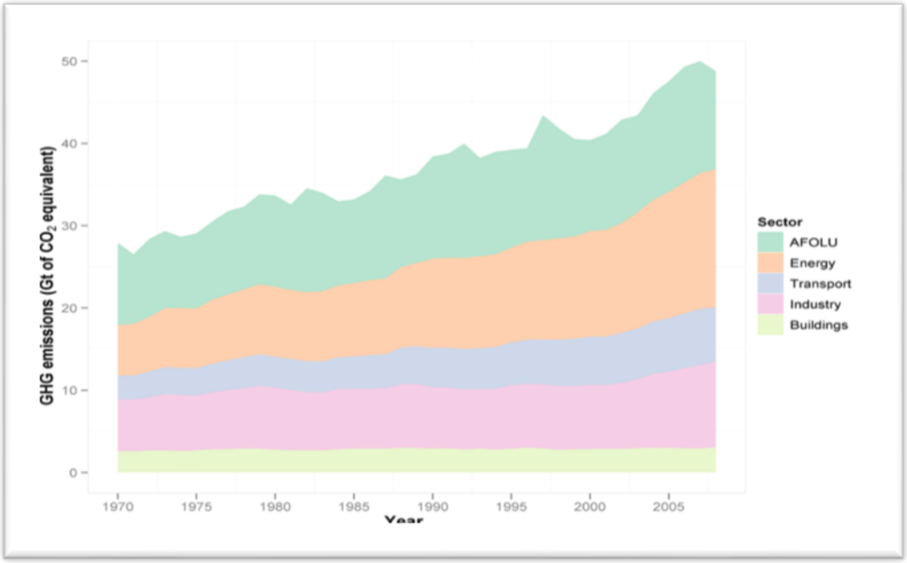


Figure 5.2.3. Trends in greenhouse gas emissions from 1970-2008 presented in terms of source categories identified in figure 5.2.2. Conversion of non CO2 gases based on 100 year global warming potentials.

It is also important to understand emissions growth at the regional level in order to fully appreciate the challenge facing the international community. Figure 5.2.4 decomposes global growth into its regional components. Growth rates in energy-related emissions of carbon dioxide in developing countries have recently increased rapidly(Blanford et al., 2009). Raupach et al. decompose emissions growth in several regions into the factors of the Kaya identity: population, per capita income, energy intensity of gross domestic product (GDP), and carbon intensity of energy(Kaya, 1990; Raupach et al., 2007). See Figure 5.2.5. The industrialization process tends to be energy intensive. Regions that are undergoing or have yet to undergo industrialization will face considerable challenges in controlling fossil fuel emissions without the availability of new, less carbon-intensive alternatives on both the supply and demand sides of the energy system. These challenges are discussed in detail in the next chapter.

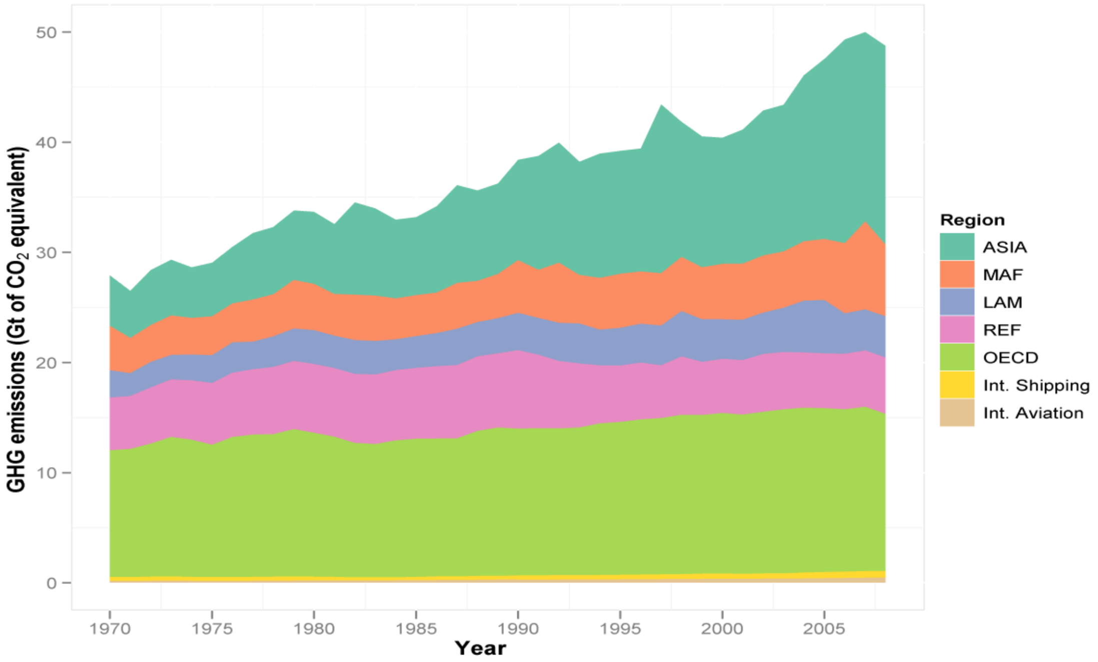
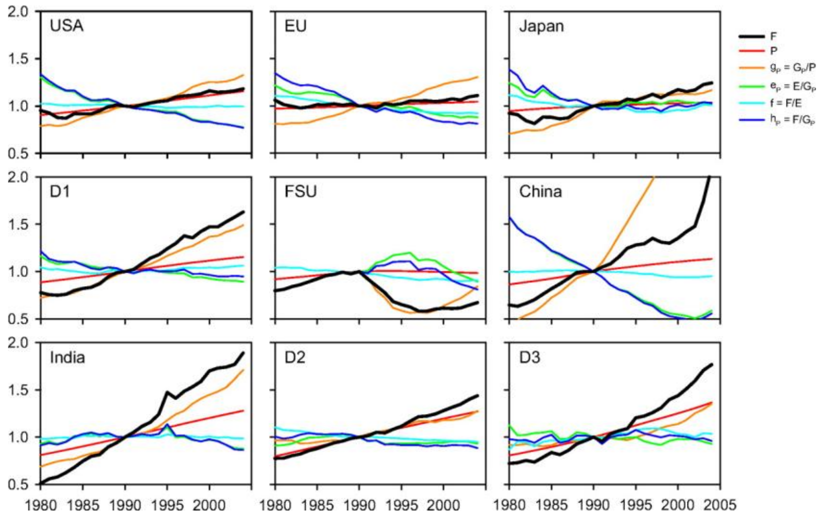


Figure 5.2.4. Greenhouse gas emissions at a regional level. Conversion of non CO2 gases based on100-year global warming potentials. REF, LAM, and MAF refer primarily to Central Europe, Latin America and Africa, respectively.

Factors in the Kaya identity, F = Pgef = Pgh, for nine regions.



Raupach M R et al. PNAS 2007;104:10288-10293

Figure 5.2.5. Factors in the Kaya identity, F = Pgef = Pgh, for nine regions. All quantities are normalized to 1 at 1990. Intensities are calculated with GPi (PPP). For FSU, normalizing GPi in 1990 was back-extrapolated. D1, D2, and D3 refer to Developed, Developing and Least-Developed countries, respectively.

5.2.2. Trends in Aerosols and Aerosol/Tropospheric Ozone Precursors

As noted in the radiative forcing diagram cited in the introduction, aerosols and tropospheric ozone also can contribute substantially to climate forcing. Trends in atmospheric aerosol loading, and the associated radiative forcing, are influenced primarily by trends in precursor emissions. Tropospheric ozone concentrations are impacted by a variety of emissions, including nitrogen oxides, carbon monoxide, volatile organic hydrocarbons, and methane. Trends from 1970 of these emissions are shown in the Figure 5.2.6.

A major aerosol precursor is sulphur dioxide, which is emitted primarily by fossil fuel combustion, but also metal smelting and other industrial processes. Global sulphur emissions peaked in the 1970s, decreased over the 1990s, and increased slightly to 2005, driven in large part by emissions from China. 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). Global emissions from 2005-2010 have not been comprehensively assessed, but may not have changed substantially, as emissions from China appear to have flattened, and emissions from OECD countries continued to fall(Lu et al., 2011 Accessed May 1, 2012; UNFCCC, 2012).

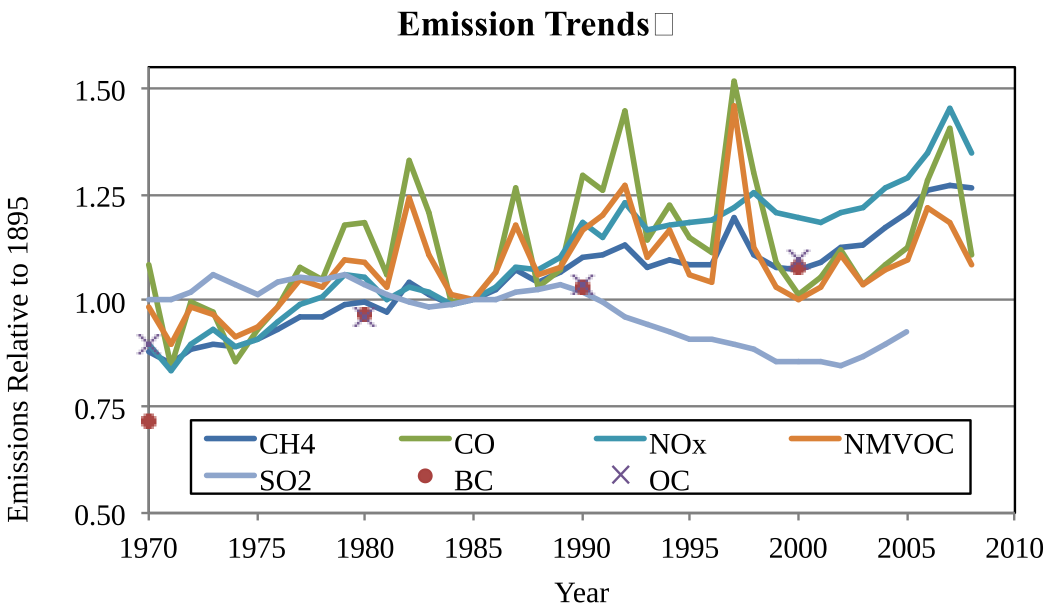


Figure 5.2.6. Time trends for global emissions for anthropogenic and open burning, normalized to 1985 values. Data from EDGAR 4.1, except for SO2 from (Smith et al., 2011).

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). These emissions are highly sensitive to combustion conditions, however, which results in a large uncertainty, estimated by Bond et al. to be roughly a factor of two(Bond et al., 2004). This implies a significant uncertainty in emission trends over time, but this has not been quantified. Emissions from 2000 to 2010 have not yet been estimated, but will depend on the trends in driving forces such as residential biofuel and coal use and petroleum consumption for transport, but also changes over this time in technology characteristics and the implementation of emission reduction technologies. According to IEA and BP statistics, end-use petroleum consumption in developing Asia, Middle East, Africa, and South America has increased steadily from 2000-2010(IEA, 2011; "BP Statistical Review of World Energy," 2011). Building coal consumption has been relatively constant, while residential biomass trends are not well constrained. Counter to these increases are increasing implementation globally of pollution controls, particularly for the transportation sector. The net effect on black carbon emissions trends is unclear.

Tropospheric ozone is also a contributor to anthropogenic forcing, and global emissions of ozone precursor compounds are also thought to have increased over the last four decades. Substantial inter-annual variability in CO and NMVOCs estimates are due to forest and grassland burning. Global uncertainty has not been quantified for these emissions. Schöpp et al. (2005) estimated an uncertainty of 10-20% for 1990 NOx emissions in various European countries(Schöpp et al., 2005). Methane emissions also impact background tropospheric ozone levels(IPCC, 2001).

5.3. Drivers of global emissions

Over the last four decades, the world has gone through rapid changes. Global population has been doubled since 1970s to about 7 billion today, and per capita income in PPP has increased by 80%, leading to over 3.5 folds increase in Gross World Products in PPP. During this period, global GHG emission in GWP100 has increased by 80%. What were the drivers of global GHG emission increase, and what analytical framework do we need to identify them?

In this section, we first provide a brief overview of the major drivers identified in the literature. More detailed reviews on each driver will be given under respective sections of this chapter. Second, we propose a framework to identify the drivers of global GHG emissions. Third, we present the main findings under the framework.

In general, drivers of global GHG emissions refer to the human activities that directly or indirectly cause 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.

As it will become obvious as this section proceeds, 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” is used in this section not necessarily to represent exact “causality” but to indicate “association” to provide insights on what constitutes overall changes in global GHG emissions.

Here we briefly review the literature that deals with the drivers of GHG emissions. Table 1 summarizes the review and provides a qualitative confidence statement regarding the drivers of global GHG emissions reflected in the literature.

Consumption

Multitude of literature identified consumption expenditures as one of the key drivers of GHG emissions (Morioka and Yoshida, 1995; Munksgaard et al., 2001; Wier et al., 2001; Hertwich and Peters, 2009a). Consumption-based accounting allocates GHG emissions from production activities to intermediate and ultimately final consumers (Suh, 2004; Huppes et al., 2006; Hertwich and Peters, 2009a; Davis and Caldeira, 2010). Consumption activities can be further divided into consumption per region (e.g., country), per product and per household type. Many studies of this line identified the consumption by wealthy nations as a key driver of global GHG emissions (Hertwich and Peters, 2009b; Davis and Caldeira, 2010). Literature also highlighted the growing consumption of emerging economies(Peters et al., 2007; Minx et al., 2011). Frequently identified product categories of which final consumption is identified as a major contributor include food and food services, energy and electricity, housing, and transportation(Huppes et al., 2006; EPA, 2009; Hertwich et al, 2010).

International trade

Consumption in wealthy nations induces production activities and associated GHG emissions not only within those nations but in other nations through international trade. Multitude of recent studies therefore identified international trade as a driver or enabling factor for global GHG emissions (Weber and Matthews, 2007; Peters and Hertwich, 2008; Li and Hewitt, 2008; Yunfeng and Laike, 2010; Peters et al., 2011a). Some literature highlighted the leakage effects, where tougher GHG emission regulation of a country leads to increasing imports from the countries with less stringent GHG emission regulation (Peters and Hertwich, 2008; Davis and Caldeira, 2010;

Peters et al., 2011a). Furthermore, international trade promotes economic growth, which in turn enables an increase in GHG emissions.

From an economic theory point view, however, international trade contributes to a more efficient allocation of resources, which may help mitigate GHG emissions (Feenstra, 2012). Increase in international trade generally accompanies accelerated spill-over of advanced technologies and increase in Foreign Direct Investment (FDI), which are generally viewed more favorably from the GHG emission mitigation point of view (Keller, 2009). Besides, like many other drivers, it is often a question whether international trade is a driver in itself or rather an “enabling factor” connecting production and consumption activities from different nations.

Population

Population growth has long been recognized as a major driving force behind growing global environmental impacts including GHG emissions (Ehrlich and Holdren, 1971a; O’Neill et al., 2010). It is important to recognize that multitude of other drivers for GHG emissions identified in the literature are not independent from population growth, which has been a highly conspicuous, persistent, seemingly irreversible underlying change throughout the last a few centuries.

Urbanization

Literature recognized urbanization as a source of GHG emissions as well as a way to mitigate them (Dodman, 2009b; Satterthwaite, 2009). Increasing urban population and its consumption obviously contribute to the growing GHG emissions, while urban infrastructure including housing, energy and transportation enables achieving higher efficiency.

Human behaviour

Human behavioural change is arguably the most fundamental source of changes that influence all human activities including reproduction and consumption, and its psychological and cultural contexts have been recognized as a driver to the changes in global GHG emissions (Proctor, 1998; Swim et al., 2011).

Economic growth

The connection between economic growth and environmental degradation has long been recognized in the literature (Grossman and Krueger, 1994; Arrow et al, 1996; Stern et al., 1996; Blodgett and Parker, 2010).

While economic growth has been identified as a major underlying driver of global GHG emission (Lim et al., 2009; Carson, 2010), some literature recognize economic growth as a way to mitigate GHG emission or GHG emission intensity on the ground of, so called, Environmental Kuznets Curve (EKC) hypothesis. The theoretical ground and empirical evidences of EKC have been debated (Stern et al., 1996; Suri and Chapman, 1998; Dasgupta et al., 2002; Harbaugh et al., 2002; Sari and Soytas, 2009; Carson, 2010). Empirical studies that confirm EKC hypothesis are generally based on direct emissions per Gross Domestic Products (GDP), while studies that incorporate life-cycle emissions (both direct and indirect supply-chain emissions) do not generally confirm EKC hypothesis. Direct emission intensity may decrease as income grows due to such causes as technological improvement, regulation, out sourcing, changes in economic structure. For instance, structural change toward a more service-oriented economy takes place as an economy grows, which generally entails lower GHG emission intensity. When supply-chain emissions and overall volume of consumption are taken into account, however, service sectors are shown to contribute major part of GHG emissions of developed nations (Suh, 2006; Nansai et al., 2009).

Energy use

Carbon-based fossil fuels are the dominant source of energy for industrial, commercial and household activities as well as for transportation and power generation. Therefore combustion of fossil fuel is directly responsible for emissions of CO_2, the dominant GHG. Emissions of other GHGs including CH_4 and N_2O are also associated with energy systems. Energy use has been studied as a major driver of global GHG emissions (Wier, 1998; Malla, 2009a; Bolla and Pendolovska, 2011). Energy use can be further divided into various energy use categories, and each can be further decomposed into underlying drivers. For example, GHG emissions from transportation can be further decomposed into e.g., average driving distance per household, number of households, mode of transportation, fuel economy of mode, and carbon intensity of fuel (Timilsina and Shrestha, 2009; Bishins et al., 2011).

Decomposition of contributing factors

Overall change in GHG emissions can be decomposed into contributing factors. As frequently mentioned earlier in this chapter, Kaya identity decomposes the overall GHG emission into population, GDP per capita, energy consumption per GDP and GHG emission per energy consumption(Raupach et al., 2007). Raupach et al., 2007 highlighted the rapid increase in per capita GDP and population as the major factor of increasing global GHG emissions, while the authors also observed significant regional variations. The IPAT equation decomposes the overall impact into population, income per capita and impact per income (Ehrlich and Holdren, 1971a). The Kaya identity is a production-based approach. Although the IPAT equation can be interpreted either as a production or consumption-based approach, we regard the IPAT equation as a consumption-based decomposition approach, which will be elaborated in the next section (5.3.1).

Another frequently applied approach in an input-output framework is the Structural Decomposition Analysis (SDA) (Greening et al., 1997; Ang, 2006; Wood, 2009). 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 GHG emissions (Wier, 1998; De Haan, 2001; Kagawa and Inamura, 2001; Peters et al., 2007; Nansai et al., 2007; Lim et al., 2009; Wood, 2009; Dong et al., 2010; Minx et al., 2011).

Multiple drivers and their interactions

It is important to note that most of the literature identified more than one drivers and many also recognized the interdependencies between them (Angel et al., 1998; Kagawa and Inamura, 2001; Peters et al., 2007; Nansai et al., 2007; Raupach et al., 2007; Malla, 2009b; Timilsina and Shrestha, 2009; Wood, 2009; Feng et al., 2009; Baiocchi and Minx, 2010; Blodgett and Parker, 2010; Davis and Caldeira, 2010; Mitchell, 2012). For example, economic growth, demographic changes, energy use and consumption expenditures are all mutually interlinked, and drawing a causal relationship between them is often a question of where to start in the circular network. Given the difficulties in drawing exact causal relationship between drivers, the question of drivers is inseparable from the question of ethics and responsibility.

Furthermore, it is obvious that many of these drivers can be further decomposed into various subcomponents. For example, changes in GHG emissions due to changes in energy consumption in general can be further decomposed into changes in population, in per capita energy use, in energy mix, and in GHG emission intensity for each energy type. Similarly, the influence of transportation can be further decomposed into population, per capita transportation requirement, modal shift, fuel efficiency of each mode, GHG emission intensity of each fuel type. Household consumption expenditure of a country can also be further decomposed into income groups, age groups, and regions.

Therefore the question, “what is the driver of global GHG emissions?” can only be answered in the context of scale, level of detail, and the starting point, which will be elaborated in the following section.

Table 5.3.1. Major drivers identified in the literature and their relationships with others*

Major drivers identified in the literature	Direct association among selected drivers (inducement from row to column)**							Qualitative uncertainty term***
	Consumption	International trade	Population	Urbanization	Human behavior	Economic growth	Energy use	
Consumption		↑				↑	↑	Well established
International trade	↑					↑	↑	Competing explanations
Population	↑			↑		—	↑	Well established
Urbanization	—				—	↑		Competing explanations
Human behavior	—		—	—			—	Speculative
Economic growth	↑	↑	—	↑			↑	Well established
Energy use						↑		Well established

*A synthesis from around 40 literature.

** Association between the drivers is marked by positive feedback that increases GHG emissions (↑), negative feedback that decreases GHG emission (↓), or mixed evidences that can affect either way (—).

*** Uncertainty term describes the level of confidence for the statement that the subject is a major driver of global GHG emission based on (1) the level of agreement in the literature and (2) abundance of evidence.

5.3.1. Framework of analysis

Identifying key drivers to global GHG emission needs a superstructure of analysis that defines the scale, level of detail and the starting point. In this section such a superstructure is proposed, under which key drivers of global GHG emission are identified. We introduce a hierarchical structure that provides a perspective when analyzing drivers of different level of decomposition following Suh et al. (forthcoming). Using a hierarchical structure, drivers can be identified at each level. For example, global population increase can be noted as a zero order or root driver, change in GHG emission intensity in the U.S. as a first order driver, and change in GHG emission intensity in the U.S. due to fuel mix change as a second order driver with country-fuel combination. We also distinguish production-based and consumption-based approaches and use them in parallel.

Fig. 1 illustrates how a hierarchical structure can be established. The order of decomposition is defined simply by the number of indices specified in the decomposition. For example, change in fuel mix (*l*) of power generation (*j*) of a country (*i*) is a fourth order driver, as it needs to specify at least three indices. The particular choice of indices in each order of decomposition in the figure is shown only for illustration, and other combinations of indices are possible.

Production-based approach

We start with the well-known Kaya identity, which appears on the top left of fig. 1. At a global level, the Kaya identity can be written as

(1)

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

$F^{(p)}$ 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). The E term in the Kaya identity can be cancelled out further simplifying it to (Raupach et al., 2007):

(2)

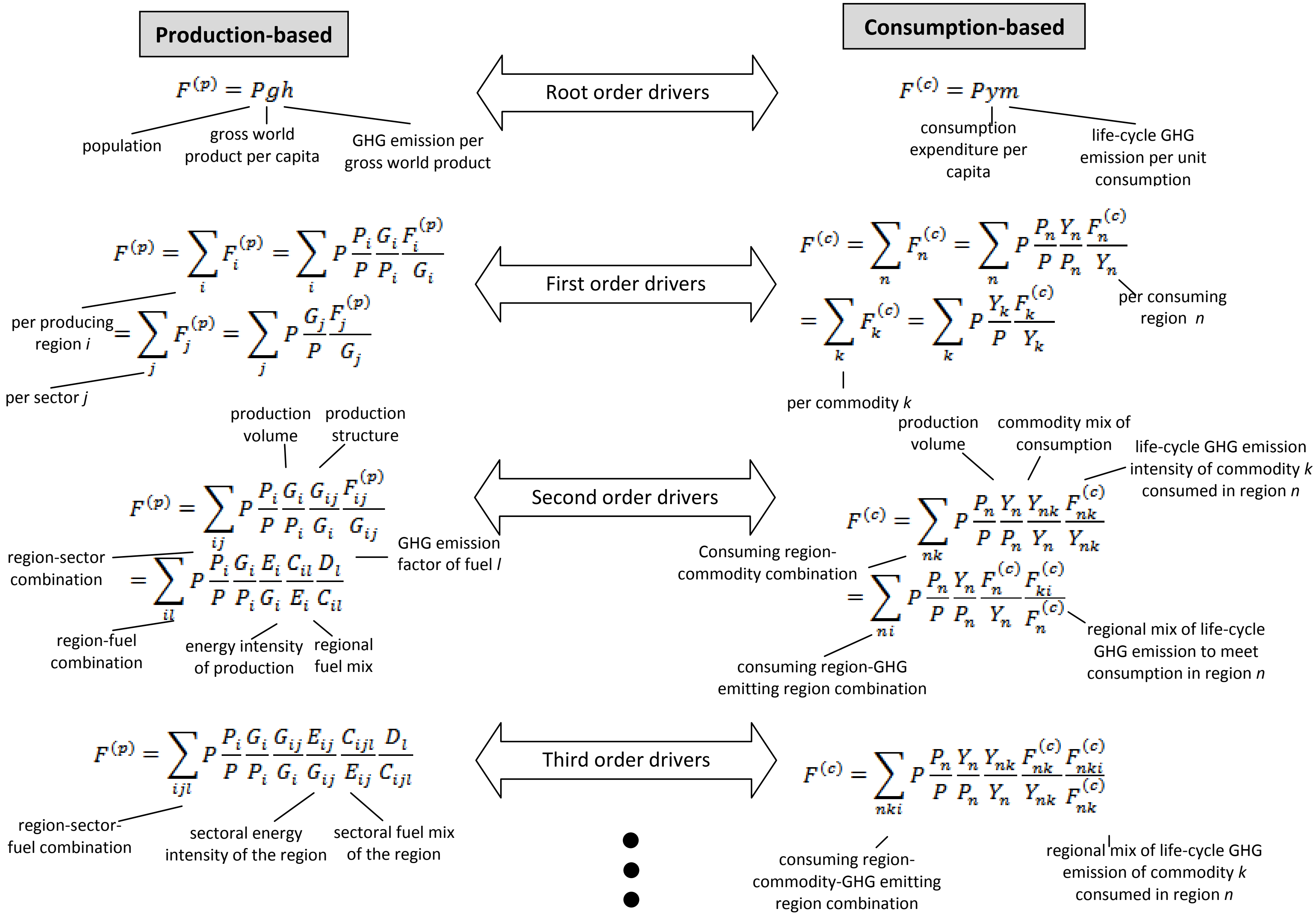
$$F^{(p)} = P\frac{G}{P}\frac{F^{(p)}}{G} = Pgh$$

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

(3)

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

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.



$$F^{(p)} = Pgh$$

$$F^{(p)} = \sum_i F_i^{(p)} = \sum_i P \frac{P_i}{P}\frac{G_i}{P_i}\frac{F_i^{(p)}}{G_i} = \sum_j F_j^{(p)} = \sum_j P \frac{G_j}{P}\frac{F_j^{(p)}}{G_j}$$

$$F^{(p)} = \sum_{ij} P \frac{P_i}{P}\frac{G_i}{P_i}\frac{G_{ij}}{G_i}\frac{F_{ij}^{(p)}}{G_{ij}} = \sum_{il} P \frac{P_i}{P}\frac{G_i}{P_i}\frac{E_i}{G_i}\frac{C_{il}}{E_i}\frac{D_l}{C_{il}}$$

$$F^{(p)} = \sum_{ijl} P \frac{P_i}{P}\frac{G_i}{P_i}\frac{G_{ij}}{G_i}\frac{E_{ij}}{G_{ij}}\frac{C_{ijl}}{E_{ij}}\frac{D_l}{C_{ijl}}$$

$$F^{(c)} = Pym$$

$$F^{(c)} = \sum_n F_n^{(c)} = \sum_n P \frac{P_n}{P}\frac{Y_n}{P_n}\frac{F_n^{(c)}}{Y_n} = \sum_k F_k^{(c)} = \sum_k P \frac{Y_k}{P}\frac{F_k^{(c)}}{Y_k}$$

$$F^{(c)} = \sum_{nk} P \frac{P_n}{P}\frac{Y_n}{P_n}\frac{Y_{nk}}{Y_n}\frac{F_{nk}^{(c)}}{Y_{nk}} = \sum_{ni} P \frac{P_n}{P}\frac{Y_n}{P_n}\frac{F_n^{(c)}}{Y_n}\frac{F_{ki}^{(c)}}{F_n^{(c)}}$$

$$F^{(c)} = \sum_{nki} P \frac{P_n}{P}\frac{Y_n}{P_n}\frac{Y_{nk}}{Y_n}\frac{F_{nk}^{(c)}}{Y_{nk}}\frac{F_{nki}^{(c)}}{F_{nk}^{(c)}}$$

Figure 5.3.1. Hierarchical decomposition of global GHG emissions with examples

The Kaya identity can be calculated for each region *i* or for each GHG emitting sector *j*:

(4)

$$F^{(p)} = \sum_i F_i^{(p)} = \sum_i P \frac{P_i}{P} \frac{G_i}{P_i} \frac{F_i^{(p)}}{G_i}$$

$$= \sum_j F_j^{(p)} = \sum_j P \frac{G_j}{P} \frac{F_j^{(p)}}{G_j}$$

This level of decomposition is referred to as first order decomposition and the drivers identified in this level are referred to as first order drivers.[1]

Two issues are noteworthy in the formulation of Kaya identity discussed thus far. First, it is notable that eq. (1) is suitable only for energy-related GHG emissions. Energy-related activities are the dominant source of GHG emissions. Nevertheless, it is not suitable to examine non-energy GHG emitting activities such as land use and land cover change, enteric fermentation, and Nitrogen fertilizer use. This problem can be easily solved either by using eq. (2) instead or by adding one more term to the right-hand-side of the eq. (1) that describes non-energy GHG emitting activities. The latter approach is practical and can use the same decomposition principles described in this section, but it is not shown in the figure for the sake of simplicity.

Second, even within the scope of energy-related GHG emitting activities, there is a disconnection between *G* and *E* in eq. (1). In principle, *G* should serve as a measure of energy using activity, which is generally measured by Gross World Product or GDP. However, significant part of the energy using activities does not constitute the Gross World Product or GDP. For example, use of non-market fuels, which is an important source of energy for many developing nations (Zhang et al., 2010; Zha et al., 2010; Zhang and Chen, 2010; Yang and Suh, 2011), and other household activities that generate GHGs such as passenger car driving are not easily measured by Gross World Product or GDP. As these activities and their changes become important part of the overall emissions and their changes, Gross World Product's or GDP's explanatory power on GHG emission diminishes. This would become more obvious when the Kaya identity is sliced into GHG emitting sectors later in this section. Those activities that cannot be adequately measured by Gross World Product or GDP can be calculated separately and then added to the main decomposition result. Appropriate units can be employed for those activities. The hierarchical structure is still maintained for those additives based on the number of indices specified.

Consumption-based approach

The I=PAT equation by (Ehrlich and Holdren, 1971a) refers to expenditure in the place that the Kaya identity does production. Here we propose an extended I=PAT equation as a consumption based approach.

Production-based and consumption-based decompositions are complementary to each other. Consumption-based approach takes a life-cycle perspective, and allocates GHG emissions

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[1] Drivers can be newly inserted, subtracted or reordered to enable additional insight. For example, suppose that the world is divided into two regions, A and B. Region A's GHG emission intensity was 3 kg/$, and that of region B was 0.5kg/$ at year = 0. At year = 1, GHG emission intensities of region A and B were reduced to 2.5kg/$ and 0.3kg/$, respectively but the regions share of Gross World Product has changed from 0.2:0.8 to 0.4:0.6 during the same period. As a result, average GHG emission intensity increased from 1kg/$ to 1.18kg/$. In this case, using equation (3), the result may identify increase in GHG emission intensity as a driver that increases overall GHG emission. In reality, however, GHG emission intensity has been reduced in all regions, and what has changed was the regional composition of Gross World Product. In this case, the effect of regional mix of Gross World Product can be isolated by reordering the drivers such that: $F^{(p)} = \sum_i F_i^{(p)} = \sum_i G \frac{G_i}{G} \frac{F_i^{(p)}}{G_i}$

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:

(5)

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

$F^{(c)}$ 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:

(6)

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

The extended I=PAT equation in (5) can be calculated for each consuming region n or for each commodity consumed k:

(7)

$$F^{(c)} = \sum_n F_n^{(c)} = \sum_n P\frac{P_n}{P}\frac{Y_n}{P_n}\frac{F_n^{(c)}}{Y_n}$$

$$= \sum_k F_k^{(c)} = \sum_k P\frac{Y_k}{P}\frac{F_k^{(c)}}{Y_k}$$

As shown in Fig. 1, the consumption-based approach can use various ways of decomposing the total GHG emissions. Consumption-based approach can better represent household activities such as passenger car driving by incorporating associated GHG emissions to consumption categories. Like Kaya identity, however, any GHG emitting activities that are not connected to monetary consumption expenditures such as subsistence farming cannot be adequately represented by consumption-based decomposition.

Decomposition methods

The contribution by each driver can be analyzed using various decomposition methods. In our analysis, we employed the Logarithmic Mean Divisia Index (LMDI) I method (Ang, 2006, 2007, 2008). Using LMDI, the overall changes in GHG emission by a driver can be calculated by

(8)

$$\Delta F = \sum_x \left(\frac{\Delta F_x}{\ln(\Delta F_x)}\right)\ln(\Delta Q)$$

Or

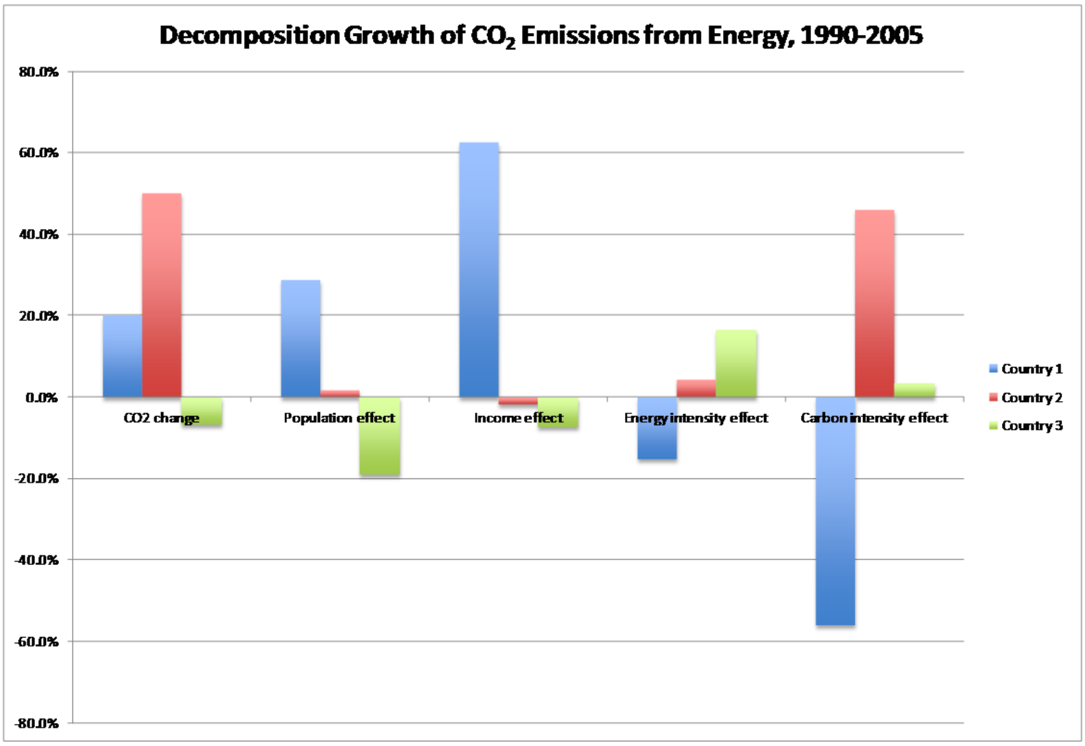
(9)

$$\Delta F = \sum_x \left(\frac{\Delta F_x}{\ln(\Delta F_x)}\right)\ln(\Delta Q_x)$$

Index x can be any index specified in the decomposition formula, Q can be any potential driver identified in the decomposition formula. Equation (8) is used for overall level terms such as population in equation (7), and equation (9) is used for the rest. Decomposition of the terms with multiple indices can be done separately and then added to make up the total change. Relative contribution by each driver can be calculated by relating the result with the total change in GHG emission.

5.3.2. Key drivers

Analysis is to be completed using newly developed data compatible to the data spine. Following graphics are shown only as an example. Key drivers will be identified for each level until third to fourth level.



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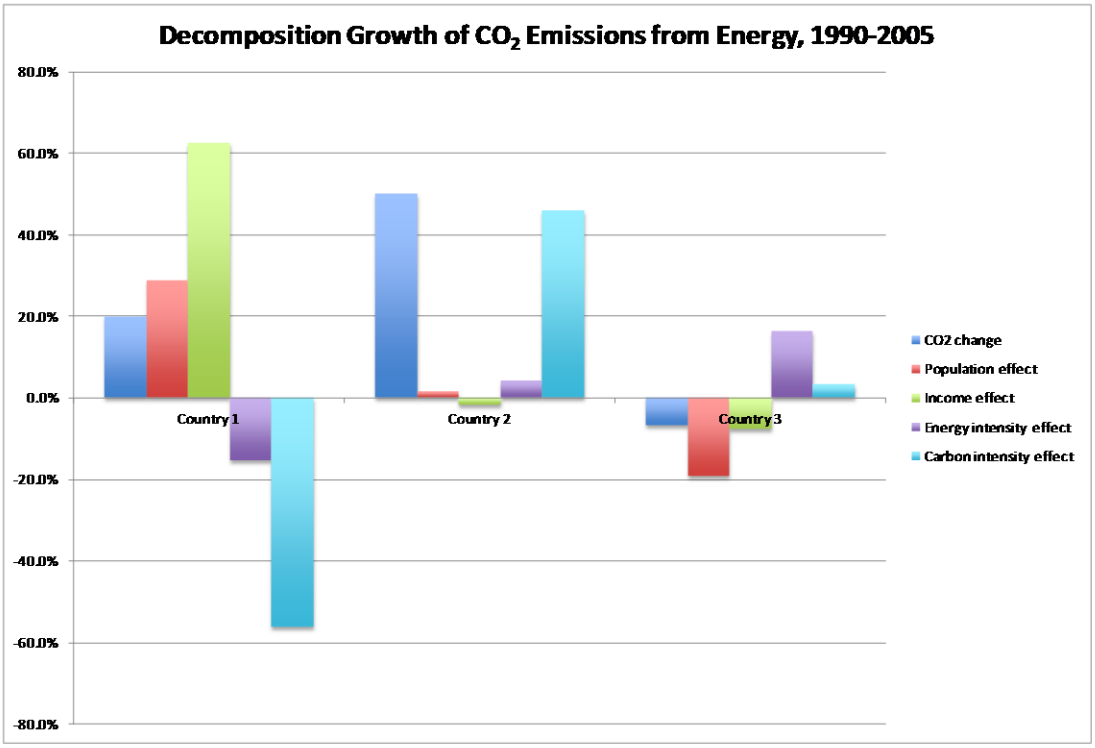

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5.4. Population and demographic structure

The Kaya identity discussed in Section 5.3 includes two terms related to population as a driver of GHG emissions: size (the number of people – explored in this section) and affluence (income per capita – analysed in the next section). The population size term suggests that emissions move proportionally with population but this section shows that various demographic processes (urbanization, aging, changes in average household size) are at work behind the plain average per capita emissions.

5.4.1. Population trends

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. 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. There is a 50-fold difference in per capita emissions between the highest (USA) and lowest (least developing countries) emitters across the nine global regions analysed by (Raupach et al., 2007).

Aggregating population and GHG emissions data according to the five IPCC RCP regions, Figure 5.4.1 shows that between 1971 and 2008 population growth was fastest in MAF; GHG emissions have increased most in ASIA while changes in population and emissions were modest in OECD90 and REF. The evolution of total population and per capita GHG emissions in the same period is shown in Figure 5.4.2. With some fluctuations, per capita emissions have declined slightly from rather high levels in OECD90 and REF, decreased somewhat from relatively lower levels in LAM and especially in MAF, while more than doubled in ASIA. These trends raise concerns about the future: per capita emissions decline slowly in high-emission regions (OECD90 and REF) while fast increasing per capita emissions are combined with relatively fast population growth in ASIA (Toth, 2012).

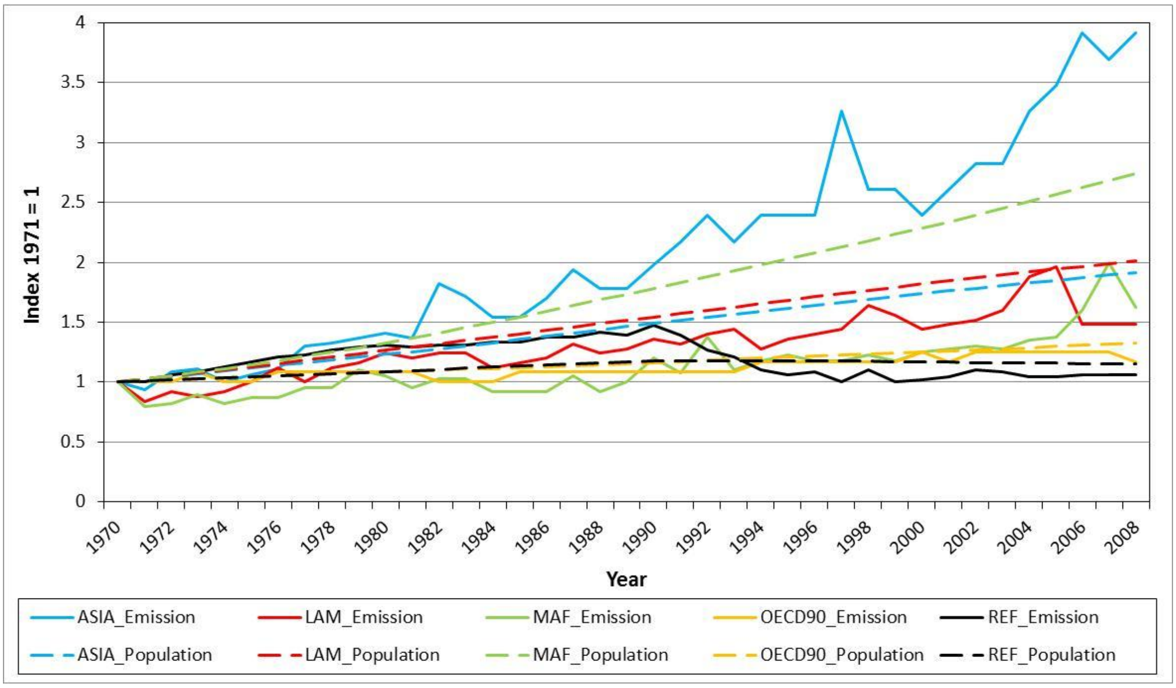

Figure 5.4.1. Indices of changes in population and total GHG emissions in the five IPCC RCP regions between 1971 and 2008. Source: (Toth, 2012).

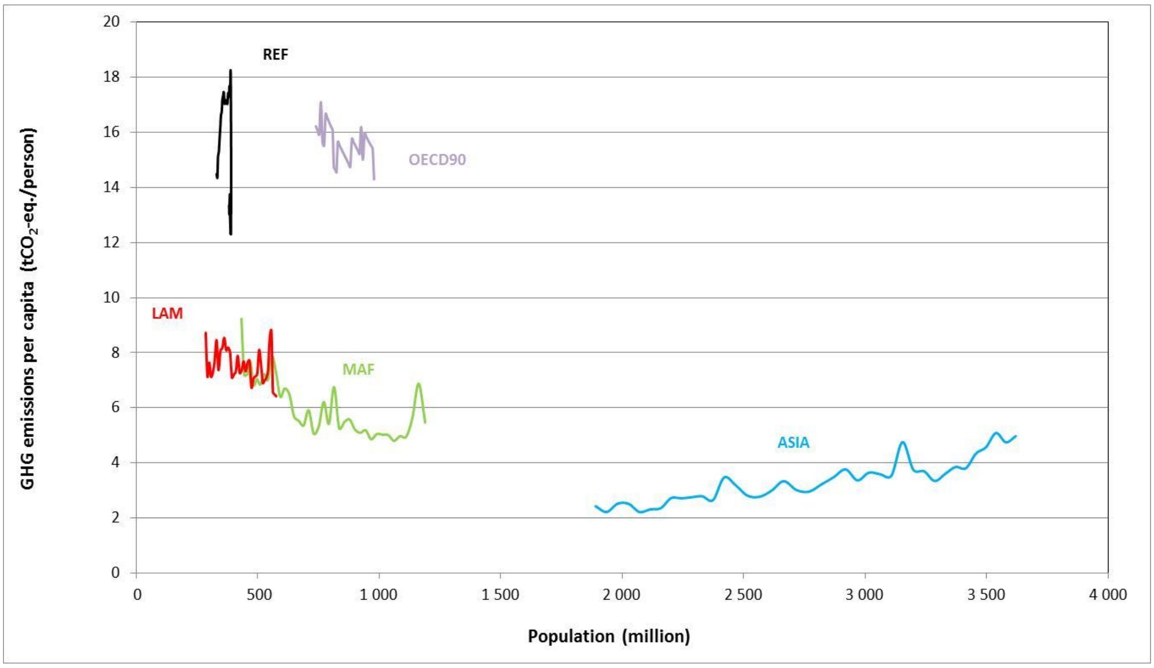

Figure 5.4.2. Trends in population and per capita GHG emissions in the five IPCC RCP regions between 1971 and 2008. Source: (Toth, 2012).

An increasing number of studies assess the role of various demographic attributes by applying the STIRPAT approach (Stochastic Impacts by Regression on Population, Affluence and Technology; (Dietz and Rosa, 1997). Those reviewed by O'Neill et al. (2012)confirm earlier observations that population size is proportional to GHG emissions, 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 dependent variable of the latter was CO2 emissions from all 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: the elasticity values estimated by (Poumanyvong and Kaneko, 2010) range from 1.12 (high-income countries) to 1.23 (middle income) to 1.75 (low-income) while the overall elasticity of 1.43 estimated by (Jorgenson and Clark, 2010) breaks down into opposite regional values: 1.65 for developed and 1.27 for developing groups. The contradicting results concerning whether an additional rich or poor person contributes more to increasing GHG emissions indicate the current status of knowledge in the attribution assessment based on decomposition techniques.

The gap between these coefficients and linear proportionality (coefficient of 1) imply that population growth goes hand in hand with structural changes that affect emissions (e.g. ageing), but that these are not fully captured in the statistical analysis. As the omitted variables are not identified, it is yet unknown whether they act as transmission channels, or that the correlation is spurious. To establish expectations on future emissions and its relation to population growth, there is need for further statistical studies that explicitly deal with the transmission channels.

5.4.2. Trends in demographic structure

5.4.2.1. Urbanization

Income, lifestyles, energy use (amount and mix) and the resulting GHG emissions differ considerably between rural and urban populations. Urbanization has been one of the global megatrends in recent decades that makes it a potential driver of increasing GHG emissions. 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 factors such as the level of development, rate of economic growth, availability of energy resources and technologies and others.The multivariate IPAT studies reviewed by BC O'Neill et al., (2010) 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. Regional differences between changes in urbanization rates and GHG emissions are presented in Figure 5.4.3showing 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 (Toth, 2012).

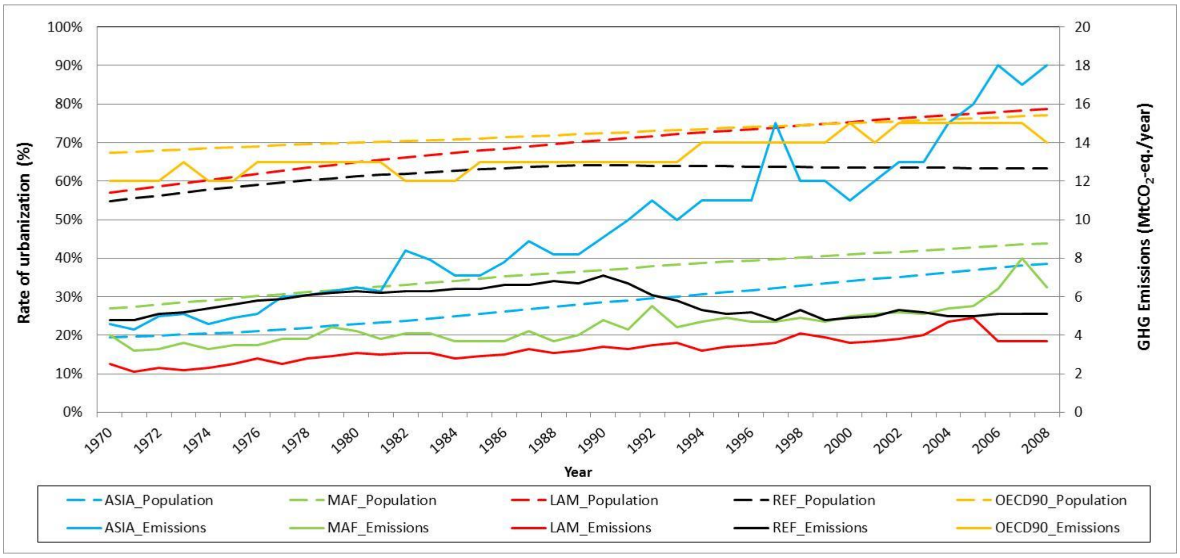

Figure 5.4.3. Trends in urbanization rates and total GHG emissions in the five IPCC RCP regions between 1971 and 2008. Source: (Toth, 2012).

Two main types of analyses explore the impacts of urbanization on GHG emissions in detail. The first type of studies counts all emissions associated with all activities in urban areas, including the production of goods and services, irrespective of the place of their final consumption. The second type of studies looks at emissions from urban households and compares them to those in rural areas. Both are relevant to policy: the first one shows the impacts of changing economic structure and location on emissions, the second indicates emissions driven by urban incomes, lifestyles and energy use.

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 factors (climate, resources, gateway status) and technical factors (urban design, electricity generation, waste processing) finds various outstanding factors, 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 local or regional nuclear power, is an obvious important driver for urban GHG emissions in several global cities in the examined sample.Transport related factors 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).

The contribution of cities to GHG emissions is exaggerated because of misinterpreting the system boundaries and globally less than 50% of GHG emissions originate within city boundaries. Accounting for the location of the final energy use associated with those emissions, the cities' share would be larger but one should also take into account that a part of that energy (and thus the related emissions) is used to supply goods and services to rural populations and areas (Satterthwaite, 2008). In a sample including European, North and South American, and Asian municipalities, per capita GHG emissions in cities are considerably below the national per capita emissions (30 to 82%) except for Beijing and Shanghai (Dodman, 2009a).

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). 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). This finding is important to consider when extrapolating past emission trends, based on past urbanisation, to the future, together with other related factors.

In addition to recognizing the generic world-wide patterns, it is important to understand the impact of urbanization on GHG emissions in the two most populous countries of the world, India and China. A comparison of household energy transition in India and China concludes that, despite differences in the amount of residential energy consumption (twice as much in China than in India), access to electricity (almost universal in China, only 90% in urban and just above 50% in rural India) and other aspects, patterns of the transition to modern fuels are similar: urban households in both countries utilize much larger shares of commercial energy, including electricity (Pachauri and Jiang, 2008) and Pachauri (2012) for both countries, Rao and Reddy (2007) for India.

An index decomposition analysis exploring five factors (CO2 emissions coefficient, energy substitution, energy intensity, income and population) driving urban and rural CO2 emissions in China between 1991 and 2004 concludes that the population effect increased residential CO2 emissions in urban China but decreased it in rural China (Zha et al. 2010). Another study of the impact of six factors (population, urbanization, carbon intensity, composite as well as urban and rural per capita consumption) on indirect CO2 emissions finds that between 1997 and 2007 urban per capita consumption exerted the largest impact on emissions (Liu et al., 2011). Per capita commercial energy use is found to be 6.8 times higher in urban areas in China where in the 35 largest cities containing 18% of the population amounted to about 40% of energy use and GHG emissions of the national totals in 2006 (Dhakal, 2009). An IPAT model covering urban-rural households in five regions in China finds that larger incomes, living space and higher rates of electrical appliances in urban households lead to higher per capita emissions than in rural areas (Feng et al. 2009). In contrast, a shocks decomposition analysis concludes that urbanization in China has been associated with energy savings and declining emissions (Dong and Yuan, 2011). Yet another study finds that CO2 emissions in rural areas of China were increasing between 1979 and 2007, largely due to increasing use of commercial energy (coal and electricity). If biomass energy is ignored, the share of CO2 emissions in the national total follows an inverted U-shaped path and reached a peak at 47.4% in 2000. By including biomass energy, CO2 emissions from rural energy use fluctuated between 45 and 56% between 1979 and 2001 and started to decline in 2002 but was still at 41% in 2007 (Zhang et al., 2010). A survey of energy consumption of rural households in a small region finds that biomass, coal and LPG are the most common fuels and there is no correlation between income level and energy consumption although households with higher incomes clearly prefer LPG use (Tonooka et al., 2006).

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.

5.4.2.2. 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. This section reviews studies about historical pathways in the second category. We emphasize that all results below are conditional on income, and thus should be taken as an additional effect to the income generating effect mentioned above.

A study of the impacts of population, incomes and technology on CO2 emissions in the period 1975-2000 in over 200 countries and territories divided into four income groups finds that the share of the population in the 15-64 age group has the least impact on emissions: negative impact in the high-income country group, positive impact at other income levels (Fan et al., 2006). This is partly consistent with the finding that 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). An extended analysis finds that the age-group 20-34 has a higher demand for transport while the residential electricity demand is positive correlated to the above-70 cohort. Ageing populations will decrease emissions from transport while residential electricity demand will increase, vis-a-vis a situation with the same population but without ageing (Liddle, 2011). Data for 26 OECD countries in the period 1960-2005 show that CO2 emissions rise as the shares in the total population of older generations (60 and above) increase what is a clear indication that the cohorts born after 1960 have higher emission-intensity (Menz and Welsch, 2011).

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). A more detailed analysis of the factors affecting the energy consumption of the elderly (diversity, thermal efficiency of housing, poverty, expenditures on leisure services and goods) concludes that thermal comfort and heating needs, domestic consumables and other lifestyle choices (leisure activities, long haul air travel, etc.) may increase carbon emissions as the proportion of older households gets higher (Hamza and Gilroy, 2011). In Germany the increasing share of old people and their different consumptions patterns (relative to those of younger age groups) significantly affect household energy use and GHG emissions: energy for heating increases but motor vehicle fuel consumption decreases, resulting in higher CH4 but lower CO2 and N2O intensities of consumption (Kronenberg, 2009).

Linkages between aging population and changes in residential energy demand are similar in the USA: the elderly use more residential energy than their younger counterparts (ceteris paribus, leading to higher GHG emissions) but, with increasing energy prices, this becomes an increasingly important financial issue for them (Tonn and Eisenberg, 2007). Another study concludes that in the US CO2 emissions per person steadily increase with age and peak when people are in their 60s (Zagheni, 2011).

A closely related but largely unexplored issue is the willingness to adopt energy conservation measures. One study in Greece finds that people with higher electricity consumption and in higher age groups are less willing to adopt emission saving measures (Sardianou, 2007). This finding indicates that the elasticity of demand is lower in an ageing society than in a young society.

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 factors. 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 factors 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 factors, lifestyles and population density, age and house type affect energy use positively while the effects of household size and urbanization tend to be negative, with a few exceptions.

5.5. Consumption, production and trade patterns

5.5.1. Economic growth & development

Income has risen globally but there is much variation over time and regions as shown in the figures below. Economic theory suggests that technological change is the key long-term driver of growth but capital stocks and resource use have also tended to increase as part of the growth process. Productivity is lower in developing countries than in the developed world and increasing productivity might seem a way to raise incomes in the developing world with little emissions impact. However, actual such catch-up growth in developing countries may be more capital and resource and, therefore, emissions-intensive.The degree to which increased resource and energy use is necessary to generate economic growth remains controversial as does the impact of growth on emissions.

Global trends in GDP and emissions vary dramatically by region as shown in the figure:

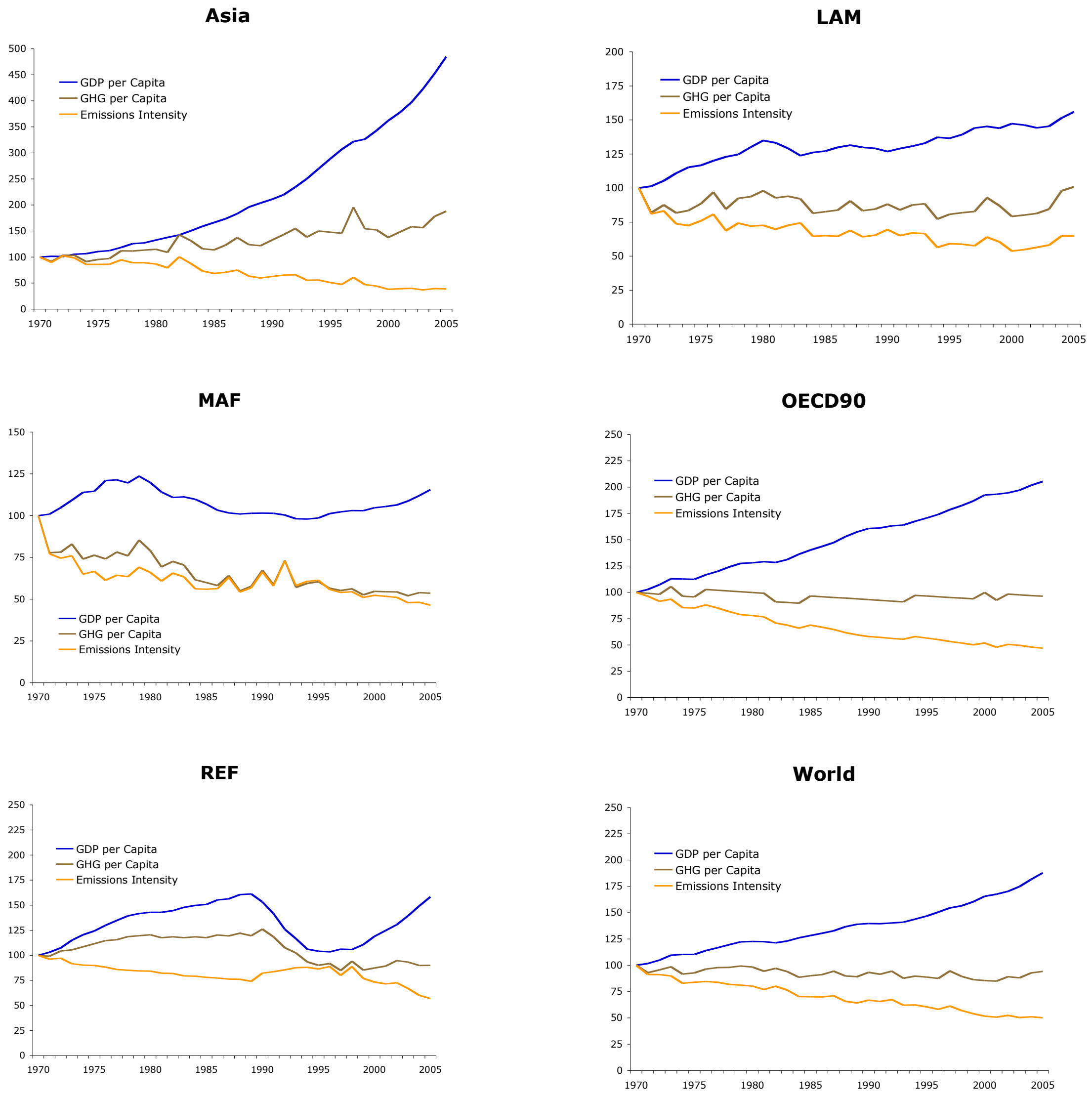

Figure 5.5.1. GDP per capita, GHG emissions per capita, and emissions intensity (GHG/GDP) for RCP regions and the World, 1970-2005. 1970 = 100. GDP is computed in constant 2000 PPP adjusted US Dollars.

Economic growth was strong in Asia and to some degree the OECD over the entire period and low in Latin America. MAF and REF 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. These have increased in per capita terms globally over this period. Also, the levels of these variables vary a lot globally as shown in the next figure:

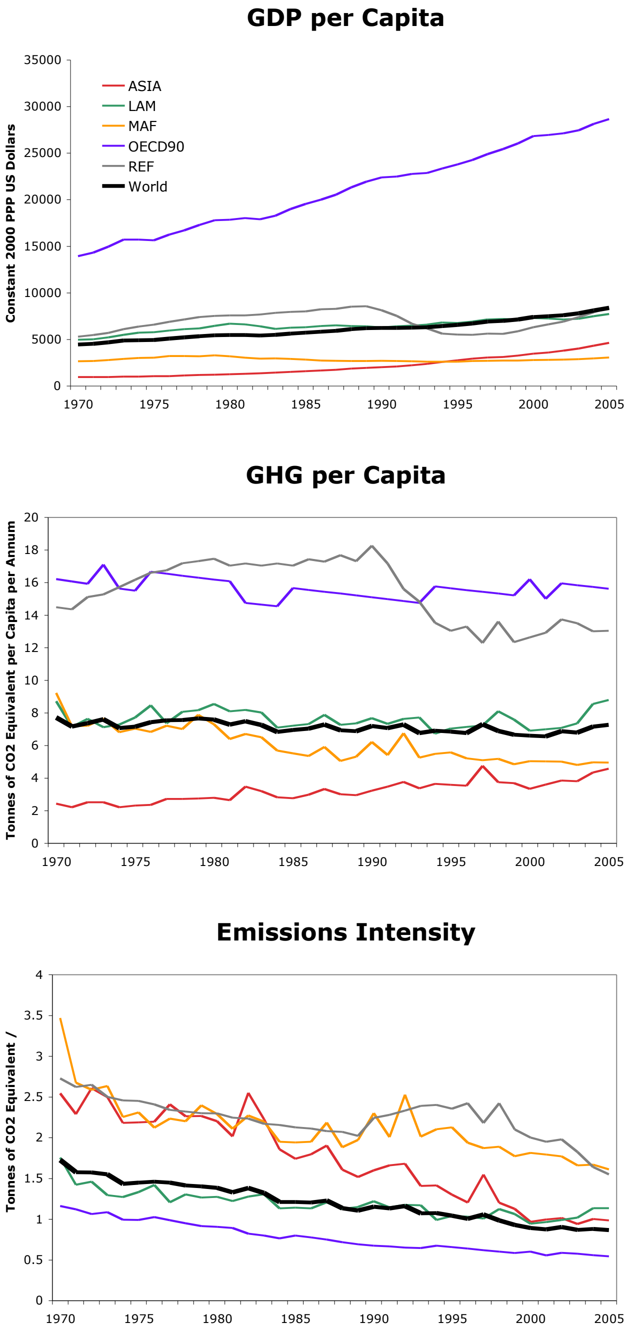

Figure 5.5.2. GDP per capita, GHG emissions per capita, and emissions intensity (GHG/GDP) for RCP regions and the World, 1970-2005. GDP is computed in constant 2000 PPP adjusted US Dollars

The Kaya identity simply treats economic output per capita as a scale effect that has a one to one effect on energy use and greenhouse gas emissions. But the Kaya identity is an accounting identity, not a causal model and in reality the relationship between economic growth and emissions may be more complex. Additionally, economic growth is not exogenous but driven by various deeper variables. 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, catch up growth in developing countries might be more emissions intensive than growth 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). In the short run, 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 as the key driver of economic growth in the long-run (Aghion and Howitt, 2009). 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 high-quality energy resources can constrain economic growth and that relaxation of these constraints 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).

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). More recent research (e.g. 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. But 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, in press). These will be discussed in the following sections.

5.5.2. Production Trends

As economic development progresses, the shares of agriculture, manufacturing, and services in output and employment changes in characteristic ways the income levels at which transitions between industries occurs differs between countries. However, the sectoral shift to services has less effect on energy use and emissions than commonly thought. Increase in energy productivity in manufacturing (and agriculture) is more important in reducing the energy intensity of the economy. The transition from centrally planned to market economies has been an important factor in reducing emissions intensity in China and Eastern Europe

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).

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 - a phenomenon known as Baumol's disease (Baumol, 1967). Because of the price decline, it appears that the share of manufacturing industry in the economy is falling when in real output terms it might not be (Kander, 2005). When the relative sizes of industrial sectors are computed in constant prices far less decline in the share of manufacturing is found (Henriques and Kander, 2010). The productivity gains in manufacturing also reduced in energy intensity in the sector. Also, not all service sectors are low in energy intensity. Transport is clearly energy intensive and retail and other service sectors also depend on energy-intensive infrastructure.

Krausmann, Schandl, and Sieferle (2008) show that in the long-run in Austria and the UK the phase of the socio-ecological transition transforming the industrial society into the service economy or post-industrial society did not lead to dematerialization (i.e. a declining use of materials and energy). It was systematically linked to an increase in per capita energy and material consumption and the integration of all parts of the economy into the industrial metabolism.

Henriques and Kander (2010) study ten developed (USA, Japan, and eight European countries) and three emerging economies (India, Brazil, and Mexico) and find 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 shown by Sue Wing (2008), who using a much finer disaggregation of industries finds that structural change explained most of the decline in energy intensity in the United States (1958-2000), especially before 1980.

The transition from centrally planned to market economies is an important factor in the effect of economic development, on greenhouse gas emissions. China serves as a case in point. It had a very high energy intensity before 1980, which 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, in press) and weakening of energy efficiency policy institutions over time (Zhou et al., 2010). On the other hand, China's carbon intensity of energy supply has increased steadily over time (Stern and Jotzo, 2010). The emission intensity has declined since 2005 as the central government has adopted more ambitious energy and emissions intensity reduction policies but remains at a high level vis-a-vis for example the EU due to China's heavy dependence on coal. 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)).

5.5.3. Consumption trends

Increasing consumption has been the key driver of greenhouse gas emissions over the last twenty years. Between 1990 and 2008, there has been a 3% reduction in the emissions from Annex B countries taking a territorial perspective to carbon accounting while emissions associated with consumption in Annex B has increased by 11% over the same time period ((Peters et al., 2011a); (Wiedmann et al., 2010).

Numerous studies have used structural decomposition analysis to quantify the impact of drivers behind changes in greenhouse gas emissions over time in both developed and developing countries (De Haan, 2001), (Peters et al., 2007), (Baiocchi and Minx, 2010), (Wood, 2009), (Weber, 2009)). The analysis has proved extremely useful in isolating the relationship between individual drivers of greenhouse gas emissions. The studies calculate the driver of emissions including the intensity per $, shifts in production structure, as well as changes in the composition and the level of consumption influence emissions. In most studies, changes in the level of consumption were the most significant driver of emissions. 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).

Several country-specific studies have also indicated consumption as being the key driver of emissions. De Haan, 2001 analysis of the Netherlands demonstrated that final demand changes were responsible for a 31% increase in emissions over 11 years (1987 to 1998). Peters et al.(2007) demonstrated an emissions increase of 129% over 10 years due to increases in final consumption in China. Baiocchi and JC Minx(2010) analysis of the UK demonstrated that increases in final demand led to an increase in CO2 emissions by 48.5% between 1992 and 2004. Employing the technique of decomposition analysis indicates that production emissions from Annex B countries have fallen slightly during the 1990s due to a reduction in emissions intensity that helped to offset increases in consumption and population (see figure below). The two latter factors, however, prevailed in the 2000s leading to a rise in CO2 emissions, reaching the same level in 2008 as in 1990. Consumption emissions of Annex B countries rose faster than production emissions in the 2000s, clearly showing that emissions embedded in export to Annex B countries if internalized, would increase the carbon intensity of production emissions in these countries. Country level production and consumption emissions for this analysis were taken from Peters et al. (2011) and statistics on GNE and population from the World Development Indicators database compiled by the World Bank (World Bank, 2011).

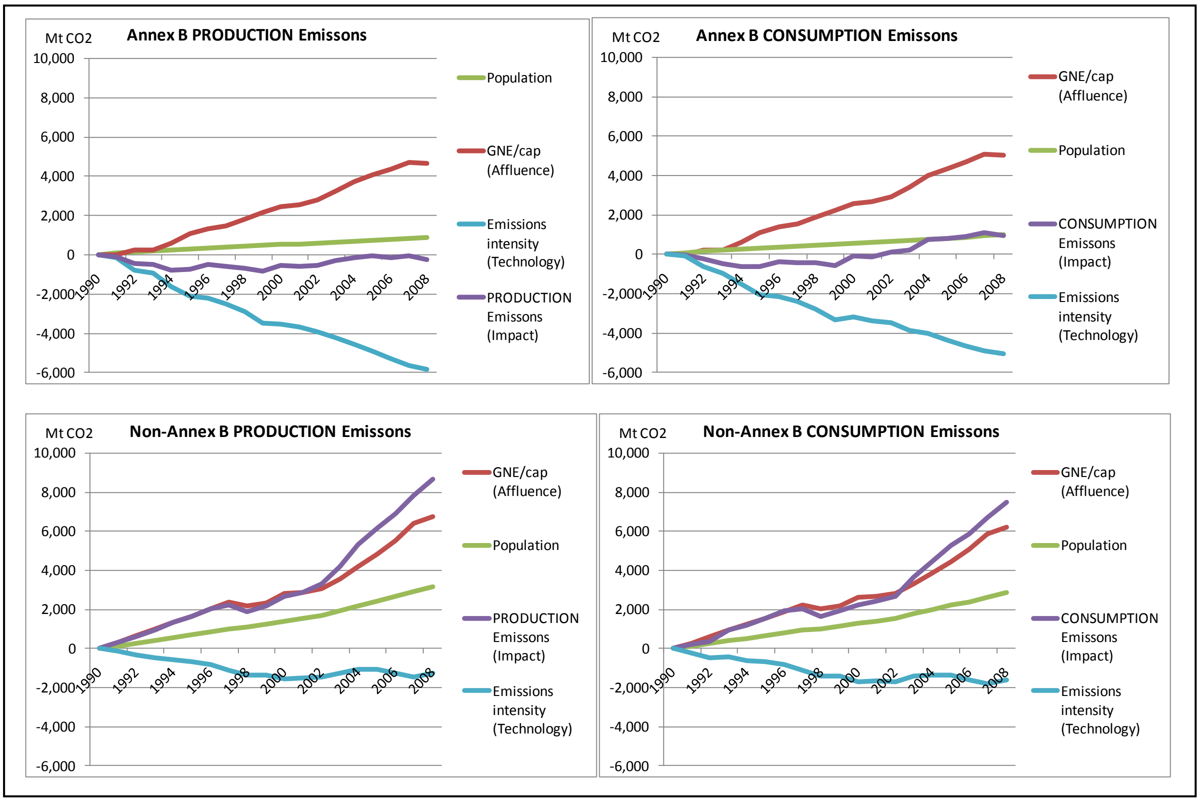

Figure 5.5.3: Change in Annex B and Non-Annex B countries production and consumption emissions 1990 to 2008

5.5.4 Embedded carbon in trade

Between 1971 and 2010, world trade has grown by 10% a year on average and has doubled nearly every 7 years (World Trade Organisation, 2011).The growth of world gross domestic product (GDP) was significantly slower, with 3.1% per year on average. The ratio of world exports of goods and commercial services to GDP in real terms has increased steadily since 1985, and increased 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 grow from 5.4 to 10 billion tonnes.

At the same time trade openness has increased 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 or the world as a whole, as did the share of developing countries' exports in the value of total world exports. For example, 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).

Between 1990 and 2008, global carbon dioxide emissions increased between 39% and 41% (Le Quere et al., 2009), (Peters et al., 2011a). The majority of this growth occurred between 2000 and 2008, representing 70% of the total growth in CO2 emissions (Le Quere et al., 2009). In 2000, CO2 emissions were 10% higher than 1990 (Peters et al., 2011a). Between 2000 and 2008, CO2 emissions grew a further 29%. All of the growth in carbon dioxide emissions has occurred in non-Annex B countries while CO2 emissions in Annex B countries have stabilised. The growth relates to the rapid increase in international trade between Annex B and non-Annex B countries. Due to the collapse of the former Soviet Union in the early 1990s, growth in emissions was slower between 1990 and 2000. However, between 1990 and 2010 it is possible to establish the proportion of this increase associated with trade between Annex B and non-Annex B countries. Demand for products by Annex B countries is responsible for 20% of the growth in CO2 emissions in non-Annex B countries (Peters et al., 2011a); partly supported by (Davis and Caldeira, 2010).

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 product, using the most common form of analysis, an “Environmentally Extended Multi-Region Input-Output Analysis" (Davis and Caldeira, 2010)(Minx et al., 2009). In 2008, this figure increased to 7.8 Gt CO2, an increase of 62% between 1990 and 2008 and an 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, traded carbon dioxide emissions grew by a further 26%, demonstrating a more recent and rapid increase in traded emissions (Peters et al., 2011a). In 2005, China accounted for 25% of the total global traded CO2 emissions, with China’s export emissions being 1.7 Gt(Weber et al., 2008)compared to the global total of 6.8 Gt (Peters et al., 2011b).

The underlying driver of this trend is a rise in consumption that has been met by an increase in trade as opposed to an increase in domestic production in Annex B countries, 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). This is clearly different from definitions of “strong leakage" defined as the relocation of industry to other country to avoid climate change policy (Muñoz and Steininger, 2010). “Weak leakage” has led to the trend where Annex B carbon dioxide emissions have stabilised and the carbon dioxide emissions embedded in trade has increased (Peters et al., 2011a). There are limited global studies but numerous national-level studies to support and confirm the time series analysis (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). Additionally, statistics on the CO2 emissions associated with international shipping support (Peters et al., 2011a) findings with (Heitmann and Khalilian, 2011)highlighting that international shipping has grown at a rate of 3.1% per annum for the past three decades. (Eyring et al., 2010) also highlight the 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.

While (Peters et al., 2011a)provide results from 1990 and 2008; results for 2004 are shown more regularly due to the availability of a complete international dataset of national input-output tables which form the predominant basis for calculating trade-embedded emissions. 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(Davis and Caldeira, 2010; Peters et al., 2011b).

Trade has allowed countries with a higher than global average emission intensity to import lower emission intensity goods and vice versa. Using the data from GTAP7, for each of the 113 world regions, the ratio was calculated of emissions embedded in exports to the emissions embedded in imports given domestic intensities. This ratio reveals whether a country saves on emissions through trade or increases emissions through trade. Scandinavian regions have ratios larger than one implying their consumption base emission accounts would be lower if they were domestically self-sufficient. This is in contrast to China where emissions would increase. Taking the total traded emissions each country can be considered responsible for (imports+exports)/2 and dividing this figure by the ratio gives the traded emissions under a domestic technology assumption. Finding the difference between this figure and the emissions embodied in trade reveals the emissions saving through trade independent of trade surpluses, country differences and only dependent on the structure of trade.

Initial findings suggest that the level and structure of trade in 2004 reduced global emissions by 6%. This result implies comparative advantage is present at the global arena and countries will trade with those able to produce products more efficiently that they can themselves. Further work is needed to discover whether this reduction due to trade is present each year and if there is a trend towards trade further decreasing global emissions.

5.6. Energy demand and supply

5.6.1. Energy demand

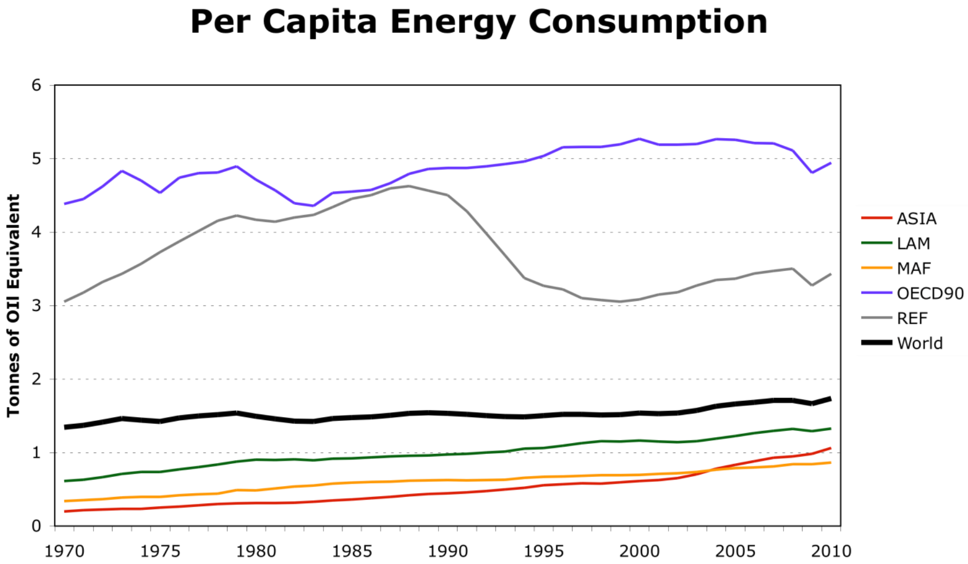

Figure 5.6.1. Sources: BP Statistical Review of World Energy 2011; Edgar

The figure shows trends in global and regional per capita energy consumption over the last four decades. 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 154%, in the Middle East and Africa by 154%, and in Asia by 442%. The impact of the recent recession and the two oil price shocks in the 1970s are very pronounced in the OECD data and less so in the rest of the world. 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 transition economies data.

Across countries at each point in time, the relationship between (the logarithms of)per capita energy use and per capita income is almost linearly proportional, when income is measured in purchasing power parity (PPP) terms(IEA, 2011). This relationship is consistently found over the last four decades(Stern, 2012). However, when market exchange rates are used, energy use per capita is found to be a concave or S shaped function of income per capita, (Medlock and Soligo 2001,Lescaroux 2011).

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 and cointegration analysis. 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 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 over a three and four decade period respectively.

5.6.2. Energy efficiency and Intensity

Energy efficiency can be defined in engineering terms as the ratio of the desired (usable) energy output to the energy input of any energy conversion process. For example, for anautomobile engine, this is the ratio of the mechanical energy supplied to the energy input of gasoline. This definition of energy efficiency is sometimes called first-law efficiency (Nakicenovic, Gilli, and Kurz 1996, Nakicenovic, Gilli, and Kurz 1996, Grübler et al. 2012).The ratio of theoretical minimum energy use for a particular task to the actual energy use for the same task is called second-law or exergy efficiency. 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 efficiently energy is used to generate a unit of value added. However, energy intensity depends on many factors other than technical efficiencies, as discussed below, and is a poor indicator or measure of actual energy (conversion) efficiency (Ang 2006, Filippini and Hunt 2011, Stern 2012). However, other economic studies, for example using distance functions or index numbers, often define energy efficiency in relative terms as the ratio of energy used to the minimum energy use required using the current best practice technology, everything else being constant (Stern 2012, Filippini and Hunt 2011).

First-law energy efficiency is often very low, especially in the supply of many energy services, and there is great scope for improvement. For example, in the supply of lightingusing incandescent light bulbs and coal fired thermal electricity generation, only about 1% of the primary energy used is transformed to illumination services provided to the end-user (see Figure 5.6.2 below). In absolute terms, the majority of losses occur at the thermal power plant(Grübler et al., 2012). In this example, abundant opportunities for improving efficiency exist at every link in the energy chain. They include shifting to more efficient fuels (e.g., natural gas) and more efficient conversion, distribution, and end-use technologies (e.g., combined cycle electricity generation, fluorescent or LED lighting technologies), as well as behavioral change at the point of end-use (e.g., reducing idle times).

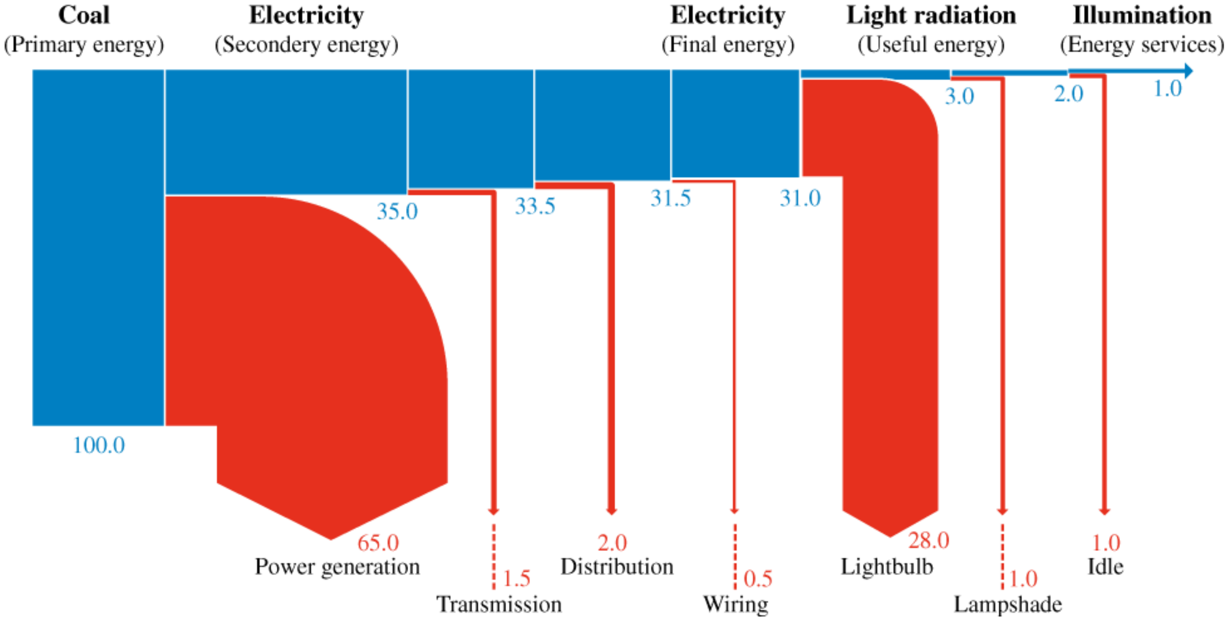

Figure 5.6.2. Illustrative example of the compound first-law efficiency of an entire energy chain to provide the energy service of illumination. Index: primary energy entering system=100%. (Grübler et al. 2012,)

In 2005, the global efficiency of converting primary energy sources to final energy forms, including electricity, was about 67% as shown in the Figure 5.6.3 (330 EJ over 496 EJ). The efficiency of converting final energy forms into useful energy is lower, with an estimated global average of 51% (169 EJ over 330 EJ). The resulting average global efficiency of converting primary energy to useful energy is then the product of the above two efficiencies, or 34%. In other words, about two-thirds 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).

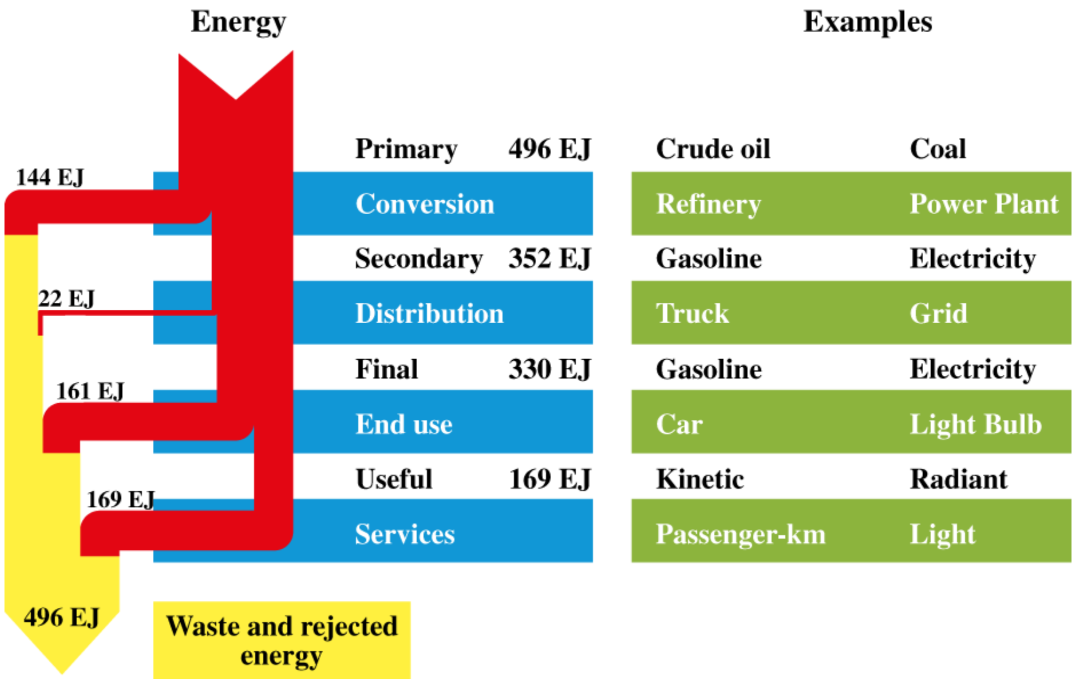

Figure 5.6.3. Global energy flows of primary to useful energy, including losses, in EJ for 2005. Source: adapted from(Nakicenovic et al., 1996), Grübler et al. 2012).

How much energy is needed to supply a particular energy service and, therefore, what scope is there for improving energy efficiency? While a device such as a heating furnace might have a very high first law efficiency – most of the energy input is converted to heat delivered – it might have a low second law or exergy efficiency compared to an alternative device such as a heat pump. Estimates of global and regional primary-to-service second-lawor exergy efficiencies vary typically from about 10% to as low as a few percent of the thermodynamically minimum feasible (see also R. Ayres 1989, Gilli et al. 1990, (Gilli et al., 1996), (Nakicenovic et al., 1996), R. U. Ayres, Ayres, and Warr 2003, and Warr et al. 2010).The theoretical potential for efficiency improvements is thus very large, and current energy systems are nowhere close to the most efficient levels suggested by the Second Law of Thermodynamics. Though the full realization of this potential is impossible to achieve, low second-lawor exergy efficiencies identify those areas with the largest potentials for efficiency improvement. For fossil fuels, this implies the areas that also have the highest emission mitigation potentials.

Measures of energy intensities across countries, industries, or products, yield valuable insights into potentials for efficiency improvements related to various activities (comparing current intensities to best practice), and are applied widely in the corresponding energy efficiency improvement and greenhouse gas (GHG) mitigation 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 across different systems (global and/or national economies, regions, cities, etc.). However, its simplicity comes at a price: The indicator is affected by a number of important measurement and definitional issues and it is a crude and inaccurate indicator of the true technical efficiency with which energy is used in a country, sector or a region (Ang 2006,Filippini and Hunt 2011) with many factors besides technical efficiency driving difference in energy intensity across countries and time.

Energy intensities are strongly affected by which energy and economic accounting conventionsare used, which is not always disclosed prominently in the reporting reference. For energy, the largest determining factors are whether primary or final energy is used in the calculations, and if non-commercial (traditional biomass or agricultural residues, which are of particular importance in developing countries) are included or not. Another important determinant is which accounting method is used for measuring primary energy. The main two conventions are the “substitution” method where all energy is converted into the hypothetical amount of fossil energy that would have been required, e.g. wind electricity results in some three times as much primary energy requirements. The other is the “direct” method that simply uses the kinetic energy of wind or water to convert to primary equivalent resulting in about 10% more primary compared secondary electricity output.

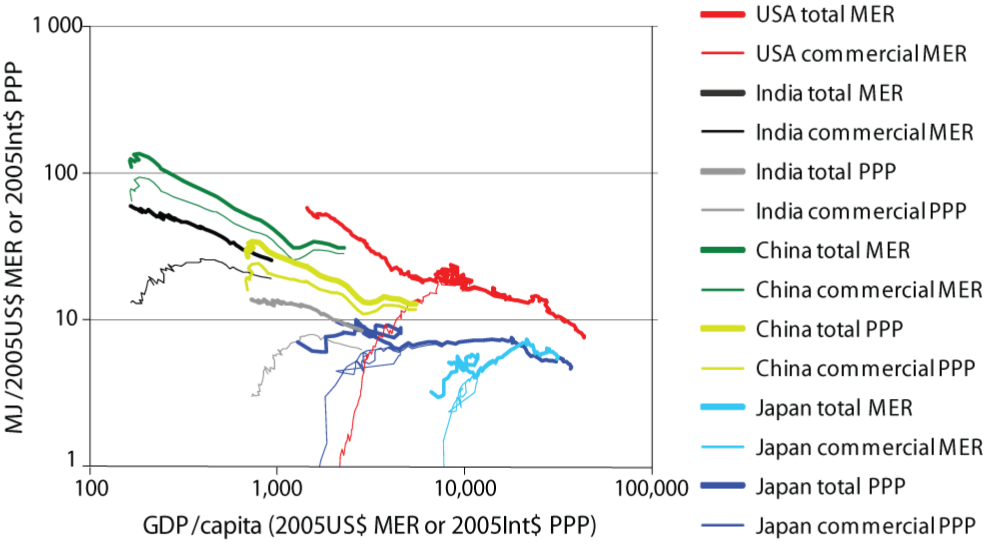

Figure 5.6.4. Energy intensity improvements and per capita income - US (1800–2008), Japan (1885–2008), India (1950–2008), and China (1970–2008). Source: (Grübler et al., 2012). Note: Energy intensities (in MJ per $) are always shown for total primary energy (bold lines) and commercial primary energy only (thin lines) and per unit of GDP expressed at market exchange rates (MER in 2005US$) 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 factor is theexchange 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. Figure 5.6.4 illustrates some of the differences in the evolution of historical primary energy intensity for four major economies in the world: China, India, Japan, and the United States.

The (thin red) curve shows the commercial energy intensity for the U.S. Commercial energy intensities increase during the early phases of industrialization, as traditional and less efficient energy forms are replaced by commercial energy. When this process is completed, commercial energy intensity peaks and proceeds to decline. This phenomenon is sometimes called the “hill of energy intensity.” (Reddy and Goldemberg, 1990) and many others have 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. In the US, for example, the peak of commercial energy intensity occurred during the 1910s and was higher than Japan’s subsequent peak, which occurred in the 1970s. 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.

Figure 5.6.4 also shows energy intensities for China and India for two alternative measures of converting national GDP to an internationally comparable level: using MER or PPP exchange rates. In the cases of India and China, MER energy intensities are very high, resembling the energy intensities of the now industrialized countries more that 100 years ago. This gives the appearance of very low energy efficiency in producing a unit of economic output. However, China and India’s PPP-measured GDPs are much higher than official MER-based GDPs suggest. Consequently, with the same dollar amount, a consumer can purchase more goods and services in developing countries than in more industrialized countries. PPP-measured energy intensities are thus generally much lower for developing countries, indicating substantially higher energy efficiencies 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 1%/year (Gilli et al., 1990;Fouquet 2008). Improvement rates can be much faster, as illustrated in the case of China discussed above (2–3%/year for PPP- and MER-based energy intensities, respectively). 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): with declining GDP, energy intensities deteriorate – i.e., increase rather than decline.

Energy intensity has declined globally over the last several decades and has declined in all developed countries and the major developing countries including India and China. When traditional biomass fuels are included in the measure of energy input, energy intensity has declined over time over the last two centuries at least in most countries that have been investigated (Gales et al., 2007). However, when only modern commercial fuels – fossil fuels, nuclear, hydro-electric power are considered energy intensity follows an inverted U-shaped path (Gales et al. 2007,Lescaroux 2011, Reddy and Goldemberg 1990). A very steep decline was seen in China from 1979 to around 2000 before the trend flattened (Stern and Jotzo, 2010). 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 convergence in energy intensities among developed economies but not in samples of both developed and developing countries (Le Pen and Sévi, 2010) though this is just a general tendency and not all countries may be converging.

The literature on economy-wide energy intensities, their trends, and drivers is vast. When measured using PPP exchange rates energy intensity does not seem to have a simple relationship with GDP per capita (Stern, 2012), but when market exchange rates are used energy intensity decreases with income (Lescaroux, 2011). There are large differences energy intensity for countries with similar levels of GDP per capita, whichever exchange rates are used. Differences in energy intensities among countries and over time have been explained by a set of interrelated variables including demographics (size, composition, and densities – e.g., urban versus rural population), economics (size and structure of economic activities/sectors – e.g., the relative importance of energy-intensive industries versus energy-extensive services in an economy; per capita income levels), technology and capital vintages (age and efficiency of the production processes, transport vehicles, housing stock, etc.), geography and climate, energy prices and taxes, lifestyles, and policies, just to name the major categories (GEA, 2012).

Changes in energy intensity over time can be decomposed into the effects of structural change – the shift to more or less energy intensive industries– the effects of changes in the mix of energy sources, technological change, and the quantities of other inputs such as capital and labor used (Stern 2012,Wang 2011). Globally, structural change and fuel mix play a smaller role in determining trends in energy use and CO2 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). For the United States too, 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, Sue 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 produce more output per Joule.

Some differences in energy intensity between countries are easily explained. Countries with cold winters and formerly centrally planned countries tend to be more energy intensive, though the latter group of countries have caught up significantly to market based economies in recent decades(Stern, 2012). The role of industry structure, resource endowments, and other policies explaining these differences are mainly a subject for future research (Ramachandra et al., 2006).The recent literature does not provide a clear picture (Matisoff 2008,,Wei, Ni, and Shen 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, while countries that have low prices tend to have high consumption (Platchkov and Pollitt, 2011). Filippini and Hunt (2011) estimate a price elasticity of demand for total energy use of between -0.2 and -0.45 for the OECD countries.

5.6.3. Carbon-intensity, the energy mix and resource availability

Carbon intensity is the ratio of emissions of carbon dioxide (CO2) per unit of primary energy used.It is probably the component of the Kaya identity that is most likely to be able to significantly address the climate change problem though reductions in energy intensity obviously help. Decarbonization refers to the rate at which the carbon intensity of energy is reduced.

Each of the main fossil fuels has been progressively lighter in carbon per unit of energy released when burned.Coal, the dominant fossil fuel from 1880 to 1960, contains approximately one hydrogen atom per carbon atom.Today's dominant fuel, oil, contains two hydrogen atoms for every carbon.The hydrogen to carbon ratio in gas, the primary fuel whose share is rising most rapidly today, is four to one.More recently energy sources that have no direct carbon emissions such as hydropower and nuclear fission lighten our carbon diet. Hydrogen-rich fuels release more energy for every carbon atom that is oxidized to CO2 during combustion (Grubler et al., 1999).Increasingly, energy is converted into a readily usable form (e.g. electricity) prior to transportation. The result was a shift from fuels such as coal with a high carbon content to energy carriers with a lower carbon content such as natural gas, as well as the introduction of near-zero carbon energy sources such as hydropower and nuclear, has resulted in the decarbonization of energy systems (Grübler and Nakićenović 1996,Grubler 2008)).

Figure 5.6.5 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). The dashed line indicates the same trend but excluding biomass CO2 emissions, assuming they have all been taken up by the biosphere under a sustainable harvesting regime (biomass regrowth absorbing the CO2 released from biomass burning). Historically, emissions related to land-use changes (deforestation) have far exceededcarbon releases from energy-related biomass burning, which suggests that in the past, biomass, like fossil fuels, has also contributed significantly to increases in atmospheric concentrations of CO2(Grübler et al., 2012)

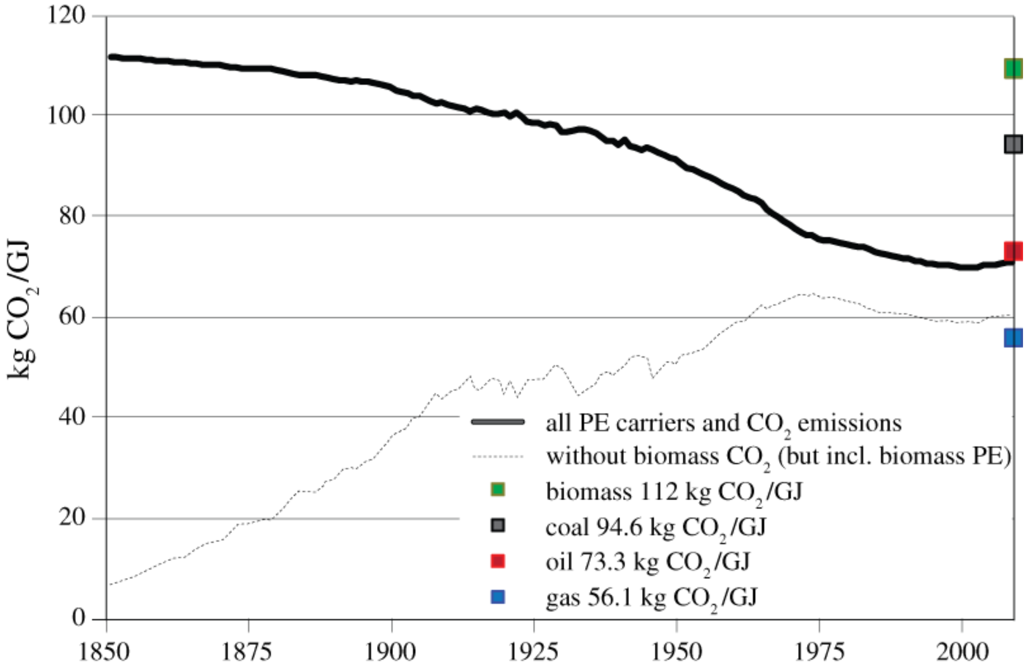

Figure 5.6.5. Decarbonization of primary energy (PE) use worldwide since 1850 (kg of CO2 emitted per GJ burned). Note: For comparison, the specific emission factors (OECD/IPCC default emission factors, LHV basis) for biomass (wood fuel), coal, crude oil, and natural gas are also shown (colored squares). 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. Again, the significant slowing of historical decarbonization trends since the energy crises of the 1970s is noteworthy, particularly due to rising carbon intensities in some developing regions (IEA 2009,Stern and Jotzo 2010).

Decarbonization can be expected to continue over the next several decades as natural gas and non-fossil energy sources increase their share of total primary energy use. Some future scenarios (for a review see Fisher and Nakicenovic (2008) anticipate a reversal of decarbonization in the long term as more easily accessible sources of conventional oil and gas become exhausted and are replaced by more carbon-intensive alternatives. Others foresee continuing decarbonization because of further shifts to low-carbon energy sources, such as renewables and nuclear energy. Nonetheless, virtually all scenarios foresee some increases in the demand for energy services as the world develops. Depending on the rate of energy efficiency improvement,[2] this mostly leads to higher primary energy requirements in the future. As long as decarbonization rates do not significantly accelerate, this means higher carbon emissions compared to historical experience.

In the long-run, fossil fuel supply is driven by both geology – the location of oil and gas reservoirs and coal deposits and our knowledge of them and investment in exploration and development of resources that itself determineddriven by technological change in these processes themselves and

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[2] The growth in emissions can be conveniently decomposed by the following identity (where annual percentage growth rates are additive) covering their main determinants of emissions and their growth: population, income, energy efficiency, and carbon intensity: CO_2 = Population x GDP/capita x Energy/GDP x CO_2/Energy (proposed by (Ehrlich and Holdren, 1971b) and applied for CO_2 by (Kaya, 1990)). Due to spatial heterogeneity in trends and variable interdependence, caution is advised in interpreting component growth rates of this identity.

the demand for fossil fuels. The global hydrocarbon endowments are not known with a high degree of certainty. Reserves are the part of hydrocarbon resources that are known with high certainty and can be extracted with currently available technologies at prevailing prices. There is little controversy that oil and gas reserves are limited, the former would last on the order of about 40 years and the latter about 70 years at the current rates of extraction. It is thus not surprising that there is considerable debate about whether the world is at or close to peak oil production that would result in the production of oil declining in the future under business as usual. Discoveries of conventional oil peaked in the 1960s globally despite intensive effort to find oil (Murphy and Hall, 2011). New discoveries are increasingly expensive to extract and increasingly in deep water (Murphy and Hall, 2011).Oil production has been essentially flat since early 2005, despite prices that started at $50/b, climbed briefly to $147 and presently stand at $80. Those price changes neither raised nor lowered production, nor resulted in increased rates of discovery worldwide (outside Brazil) in a flush of new investment. These facts suggest that, up to 2008 and the onset of recession, the industry was working at maximum capacity and failing to grow (Miller 2011, Murphy and Hall 2011).

However, in the last few years there have been very substantial discoveries of unconventional natural gas, particularly in the United States where production using hydraulic fracturing has increased substantially (Howarth et al., 2011).

In general, the resources of unconventional gas, oil and coal are huge (GEA, 2012; H. H. Rogner et al., 2012) estimate oil resources to be up to 20 000 EJ or almost 120 times larger compared to the current global production; gas up to 120 000 EJ or 1300 times larger than current production, while coal resources might be as large as 400 000 EJ or 3500 times larger than the current production. These upper estimates of the hydrocarbon endowments clearly indicate that even a small fraction of them cannot be utilized given the planetary boundaries especially those related to climate change. It is, however, important to note that the global abundance of resources does not mean that even a small part may ever become commercial and technologically extractable in addition to the limits of planetary environmental boundaries. Furthermore, the global resources are unevenly distributed and are often concentrated in some regions and not others (U.S. Energy Information Administration, 2010).

Table 5.6.1. Global hydrocarbon resources and additional occurrences compared with historical production, production in 2005 and reserves (H. H. Rogner et al., 2012)

	Historical production through 2005	Production 2005	Reserves	Resources	Additional occurrences
	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]
Conventional oil	6 069	147.9	4 900 - 7 610	4 170 - 6 150	
Unconventional oil	513	20.2	3 750 - 5 600	11 280 - 14 800	> 40 000
Conventional gas	3 087	89.8	5 000 - 7 100	7 200 - 8 900	
Unconventional gas	113	9.6	20 100 - 67 100	40 200 - 121 900	> 1 000 000
Coal	6 712	123.8	17 300 - 21 000	291 000 - 435 000	
Conventional uranium[b]	1 218	24.7	2 400	7 400	
Unconventional uranium	34	n.a.		7 100	> 2 600 000

5.7. Key Sectors

5.7.1. Transport

The transport sector is still one of the fastest growing sectors in terms of energy consumption and GHG emissions regardless of some improvements in technology and diversification of fuels that are being introduced in recent years.

Transport accounts for a significant share of the global fossil fuel combustion-related CO2 emissions. In 1990 and 2007 the share of transport GHG emissions to total GHG emissions was 22% and 23% respectively. Similar shares of 22% in 2020 and 23% in 2030 have been estimated based on IEA (2009) estimates. Based on the same estimates, transport GHG emissions will double in 2030 (9.332Gt) compared to the 1990 GHG emissions (4.574Gt).

CO2 contributes 90% of the transport GHG emissions mainly from fuel combustion. Non CO2 gases that are important are CH4[3] (0.1-0.3%), N2O (2-2.8%) as they occur in the vehicle exhaust gases. Other sources are NOx, VOCs, CO, with NOx tending to be a major contributor to tropospheric ozone. F-gases associated with vehicle air conditioning are also considerable contributing 5-10% of transport GHG emissions. Transition from CFCs to HFCs, consumption of gases but contribution to GHG emissions continues to reduce(Helmreich, 2009).

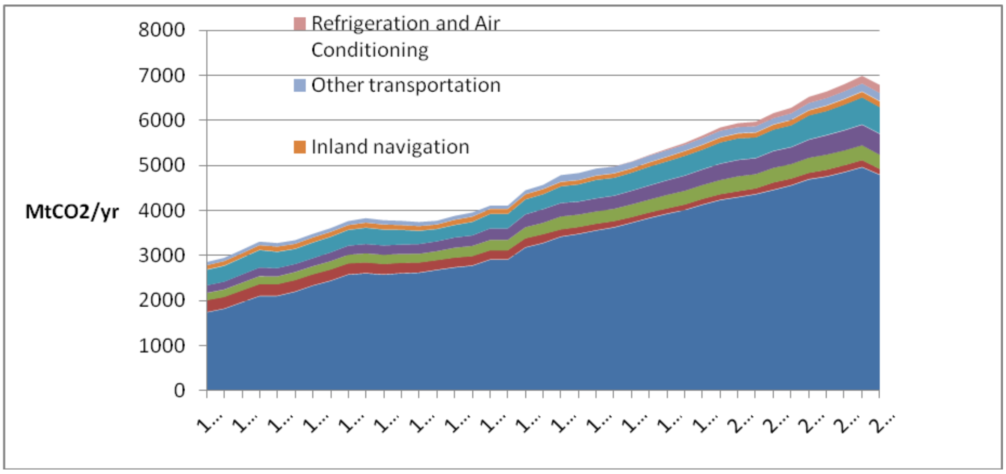

Figure 5.7.1. Historical transport GHG emissions

The transport sector is still dominated by the road sector which globally acounts for 75% of the GHG emissions, 25% of which is from freight transport (Figure 5.7.1). Road transport figure is higher in the EU where the road transport share of GHG emission is higher than 80% with freight also being higher at about 38-44%. For road transport, the increases in emissions in both industrialized and developing countries are more steady and continuous, with the exception of 2008, when the combination of a peak in fuel prices and the starting recession caused a decline in emissions (Olivier et al., 2011). The main driver in the road transport is the Light Duty Vehicle, although there is some transition to cars where incomes are high. Freight transport, particularly the trucks are the second cause of road GHG emissions. IPCC(2007) indicate that road transport is going to dominate the transport sector up to 2050 driven by both LDVs and freight vehicles and the major region causing the emissions will continue to be the OECD countries although some significant expansion will be realized in China and Latin America(IPCC, 2007; Helmreich, 2009).

The transport sector is still largely dependent on the fossil fuels and the dependence of transport on fossil fuels is consistently above 90%, averaging 95% globally and reaching as high as 98% for the

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[3] Also includes GHG contribution from the fuel mining and processing.

EU.(IPCC, 2007). Unless fossil fuels become scarce or there are dramatic changes in fuel demand, the fossil fuel demand is expected to grow to double current consumption by 2050 (IPCC, 2007).

The drivers for the transport sector are many. Population together with income growth are two most powerful driving forces behind demand for energy ("BP Statistical Review of World Energy," 2011). This is compounded by trade that is on the increase enhanced by globalization. Land use changes including planning and public transport also shape GHG growth from transport sector but these drivers are effective over large time scales(ITF, 2010). Whilst there is link between people mobility and GHG emissions, the link is weak because of the varying emission factors of the various transport modes that can be used(Bakas, 2011). Environmental concerns also are a driver for addressing GHG emissions e.g. congestion, noise, pollution, traffic accidents as some mitigation policies have come about as defaults in countries where air pollution policies and legislations have been introduced . The impact of the Clean Development Mechanism, as an instrument to reduce transport GHGs has been minimal as only 15 (0.3%) transport projects have so far been registered.

There may be some efforts being done to reduce transport sector GHG emissions but in the short run to 2020, the strong growth of transport demand especially road and air will neutralize the positive effect of technological measures on CO2 emissions. Current trends of development are not conducive to reduction of GHG emissions in the Transport sector (Helmreich, 2009). In the long run to 2050, uncertainty exists in terms of policy and technological trends and hence the impact on GHG emissions. The deployment of carbon tax and introduction of new technologies such as new infrastructure, new fuels and vehicle materials, transport management systems and behavioral change are expected to contribute to reduce CO2 emissions. The uncertainty relates to how these options will affect transport and energy demand. Among the options for reducing direct fossil fuel CO2 emissions from the road transport sector are substitution with biofuels and electric vehicles, apart from increasing the fuel efficiency. From the perspective of climate change, an integrated view is required to evaluate the overall effect of these shifts, since increasing use of these alternatives will generate increased greenhouse gas emissions in the power generation and agricultural sectors (Olivier et al., 2011).

5.7.2. Buildings

The data that are available for buildings relate largely to residential and other sectors for the period from 1970 to 2008.

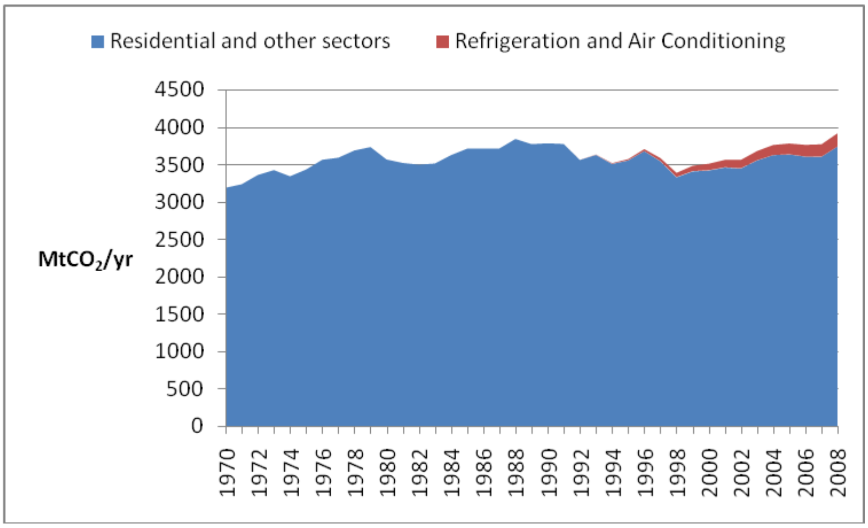

Figure 5.7.2. Emissions of the residential sector 1970-2008

These data indicate that emissions from buildings (houses and offices for the residential sector and service sector) have remained rather flat over the entire period despite the global growth in the buildings stock. Global emissions increased since 1970 to 2008 by 17%, with rising CO_2 emissions from developing countries nullified in the 1970s and 1900s by decreases in the USA and in the 1990s by the economic decline of the EIT countries(Olivier et al., 2011).

Globally buildings are responsible for more than 40 percent of global energy used, and as much as one third of global greenhouse gas emissions, both in developed and developing countries (*UNEP 2008 Annual Report*, 2009). Of this 21% of greenhouse gas emissions are from the residential sector and 17% from the commercial sector and 10% from industrial buildings (EPA, 2009). The buildings emissions are expected to grow to 110% by 2030(IPCC, 2007).

In the US, buildings GHg emissions are signficant. Buildings account for 72 percent of U.S. electricity use and 36 percent of natural gas use, with energy demand exceeding that of transport and that of industry sectors. Carbon dioxide emissions from U.S. buildings exceed the combined emissions of Japan, France, and the United Kingdom(US DOE, 2008).

The services demanded of buildings that include lighting, warmth in the winter, cooling in the summer, water heating, electronic entertainment, computing, refrigeration, and cooking, require significant energy use. The cause of the greenhouse gas emissions in buildings is largely attributed to electricity use.

This energy use is then driven by the following:

- 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
- Building size (the amount of commercial floor space and the size of homes)
- Service demands (lighting and space conditioning, electronics, process loads)
- Real energy prices

Beyond that, the building sector’s emissions in the future will be influenced by a wide range of factors, including technology, expansion of sector, building creativity (in terms of architecture), fuels used for buildings and their emissions to name a few. Beyond these are societal drivers that shape demand for buildings and the facilities they offer. For instance in low income communities decent and affordable housing remains a challenge in many African countries (UNEP, 2007).

In the next 30 years more building stock (double in developing countries but stagnant in developed countries) will be built to provide for shelter and apart from increasing GHG emissions that also provides an opportunity to deploy GHG mitigation options that can achieve significant emissions reductions in the building sector. Mandatory codes and standards, voluntary programmes, policies and incentives backed by research can make a significant mitigation effect on the buildings emissions. Governments are better placed to take the lead by adopting green building standards and different kinds of technologies in their own buildings and also promoting same to the rest of community. As much as 30% of the buildings sector emissions can be reduced. The potential estimated by IPCC(2007)to reduce building emissions is 29%

Overall commercial energy use has grown, and only recently has some improvement in energy intensity been noted (US DOE, 2008) but energy efficiency in homes has become more prevalent in the past several years, largely in the OECD countries.

5.7.3. Industry

The energy demand and hence GHG emissions in the industry sector varies across regions and countries, depending on the level and mix of economic activity and technological development, among other factors. The historical GHG emissions for the industry sector from 1970 to 2008 shows that the manufacturing industries and construction was the dominant subsector/source for the bulk of the GHG emissions that grew from about 5GtCO2/yr to slightly above 8GtCO2/yr in 2008. GHG emissions, due to energy industries, cement production and chemical production, although smaller, have also been on the increase in the same period. GHG due to production of metals though has been decreasing. The industry sector GHG emissions increased moderately by about 16%, with increasing emissions by developing countries but some acceleration was realized 2002 due to industrialization of China when it joined the World Trade Organization in 2001 (Olivier et al., 2011).

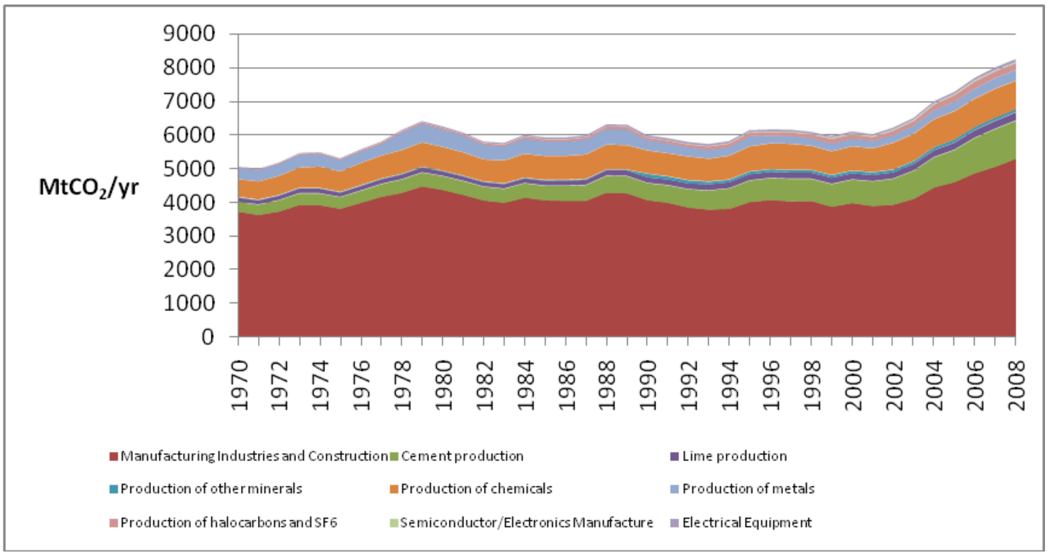

Figure 5.7.3. Historical Emissions of the Industry sector 1970-2008

Literature indicates that manufacturing industries can include food, paper, chemicals, refining, iron and steel, nonferrous metals, and nonmetallic minerals, among others and nonmanufacturing industries includes agriculture, mining, and construction(EPA, 2008). Although categorization in Figure 5.7.3 does not demarcate these categories in a similar way, the industry sector energy demand is said to be dominated by the chemicals, iron and steel, nonmetallic minerals, paper, and nonferrous metal manufacturing (EPA, 2008). These industries account for more than 60 percent of all energy used in the industrial sector consisting of chemicals (33 percent), iron and steel (14 percent), non-metallic minerals (7 percent), pulp and paper (4 percent), and nonferrous metals (3 percent).Consequently, the quantity and fuel mix of future industrial energy consumption will be determined largely by energy use in those five industries.

In addition, the same industries emit large quantities of carbon dioxide, related to both their energy use and their production processes. Worldwide industrial energy consumption is estimated to grow from 191 quadrillion Btu (or 201.5 EJ) in 2008 to 288 quadrillion Btu (or 303.8EJ) in 2035(*International Energy Outlook 2011*, 2011).

Drivers for GHG in industry are largely the fast growth in developing countries (*Shell Energy Scenarios to 2050*, 2008), the challenge to meet food, feed and fibre for the fast growing population and demand for energy intensive goods such as air conditioners, cars, the growth and location of resource-based industries (*WRI Annual Report 2010*, 2011).

There is a wide range of GHG mitigation options in the industry sector that include, energy efficiency (e.g. boiler/motor efficiency improvements), fuel switching (e.g. coal to natural gas), application of renewable energy (e.g. biomass based energy), feedstocj change (e.g. blending), material efficiency (e.g. recycling), control of nonCO$_2$ gases and CO$_2$ sequesteration (e.g. capture and use)-(IPCC, 2007). These technological options have to be coupled by policies e.g. energy pricing, pollution control and carbon incentives and taxes.

CDM has also not fared well as an instrument to offset GHG emissions from industry as only 8% of the registered projects can be considered industrial. This excludes destruction production and consumption of halocarbons anf sulfur hexaflouride which woukld add another 0.6%.

5.7.4. Agriculture, Forestry, Other Land Use (AFOLU) and Fisheries & Aquaculture

Agricultural lands occupy about 40–50% of the Earth's land surface and areexpanding(UNFCCC, 2012). About 70% of theagricultural lands are used for pasture, 27% are arable landsmainly devoted to annual crops and 3% for permanent crops.This section analyses the trends in GHG emission in the AFOLUFA sectors, identifies the main drivers and suggests technological changesin relation to food security and GHG mitigation.

Agriculture contributed 11.5% (5,629 Mt CO2 eq.) of the global emission in 2008 (IPCC, 2012). Enteric fermentation contributed 37.4% of this emission followed by direct soil emission (14.8%), rice cultivation (14.0%), manure application in agricultural soil (10.9%), savannah burning (9.1%), manure management (6.2%) and indirect N2O from agriculture (4.9%). Asia contributed the largest (41.1%) amount of the emission followed by MAF (18.8%), OECD90 (18.1%), LAM (16.9%) and REF (5.1%) countries. Compared to 1970, emission in agriculture increased by 33.9% in 2008. The increase was largest (107.4%) in soil emission because of increased application of nitrogenous fertilizer, followed by manure application (53.9%), enteric fermentation (41.7%) and manure management (31.9%). Emission from rice cultivation, however, decreased by 21.4%. During this period, emission increased in LAM (83.3%), MAF (59.8%), Asia (43.7%) and OECD 90 (8.1%) but decreased in RAF countries (38.9%).

The forestry and other land uses (FOLU) contributed 11.3% (5,498 Mt CO2 eq.) of the global emission in 2008 (IPCC, 2012). Forest fires-post burn decay was the largest contributor (46.4%) followed by forest fires (29.9%) and peat fires and decay of drained peat lands (23.5%). To this emission, contribution of MAF countries was largest (40.4%) followed by Asia (36.8%), LAM (14.2%), REF (4.7%) and OECD 90 countries (3.9%). Emissions in this sector increased by 7.7% from 1970 to 2008. There was large increase in peat fires and decay of drained peat lands (161.8%) and forest fires-post burn decay (49.5%). But in the grassland fires and forest fires the emission decreased by 70.1% and 42.6%, respectively. In Asia and OECD 90 countries emission increased by 119.8% and 103.4%, whereas in LAM, REF and MAF countries it decreased by 38.9%, 36.8% and 7.0%, respectively (IPCC, 2012).

The driversof the AFOLUFA sector work at 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 pressureand demographic structure, infrastructure and market access, non-farm opportunities and labour scarcity, capacity of natural resources, poverty) levels affecting food security and GHG emission (Hazell and Wood, 2008). Global population increased by 82.7% from 3.71 to 6.78 billion during 1970 to 2008 but cropped area increased only by 16.3%, from 1.35 billion ha to 1.57 billion ha(FAO, 2009). As a result per capita land availability declined by 36.2%, from 0.364 ha to 0.232 ha. Productivity of crop, however, has increased considerably. For example, cereal production has doubled from 1.76 billion ton to 3.55 billion ton during the period. Consumption of livestock and aquaculture products is increasing because of increased income and production.Expansion of aquaculture is causing conversion of coastal lands into intensive artificial production in parts of Asia, Africa and Oceania causing loss of carbon to atmosphere. The world population is expected to increase to 9.3 billion in 2050 causing greater demand for food but per capita land availability will be reduced to 0.152 ha (UNFCCC, 2012). This will necessitate intensification of agriculture and influence GHG emission.

Large-scale agro-industrial expansion is the dominant driver of deforestation. Across the tropics the total net increase in agricultural area was more than 100 million ha between 1980 and 2000, and more than 55% of new agricultural land came from intact forests, 28% from disturbed forests and 8% from shrub land (Gibbs et al., 2010). Land-use change for production of biofuel and livestock expansion is another driver of agriculture influencing GHG emission.

The technical mitigation potential of global agriculture by 2030 is estimated to be 5.5–6 Gt CO2 eq. year-1. The largest part (89%) of this mitigation will come from soil carbon sequestration and 9%

through methane mitigation (UNFCCC, 2012). The economic potential, however, is 1.5–1.6 Gt CO2 eq. year-1 at 20 US$ t-1 CO2 and 4–4.3 Gt CO2 eq. year-1 at 100 US$ t-1 CO2. An increase in food, feed and fuel production without enhancing GHG emission can be achieved through breedingof stress-tolerant, high yielding cultivars/breeds of crops, livestock, fish and forest trees.Increasing efficiency of water, nutrient, energy and labour may enhance production and mitigate GHG emission (Pathak et al., 2011).Because of scarcity of land andavailability of new technologies many of the underperforming or waste lands will be rehabilitatedcontributing towards enhanced food production and influencing GHG emission.

5.7.5. Waste

Current global rates of post-consumer waste generation are estimated to be 900-1300 million tons/yr, rates have been increasing in recent years, especially in developing countries with rapid population growth, economic growth and urbanization, and this figure could rise 40% by 2020 (Barker et al., 2008)(Jacquet et al., 2010). For example, 89 billion plastic water bottles are sold every year throughout the world, and as garbage these bottles and other residues go to the ocean forming the denominated ¨garbage island ¨ as the constituted by 6 millions tones of plastic between California and Japan, or form accumulations in the coasts, rivers, lakes, and others. Waste has an economic advantage in comparison to many biomass resources because it is regularly collected at public expenses. (Barker et al., 2008) ;(Jacquet et al., 2010).

Waste GHG emissions represented in 2008 year the 2, 9 % of total GHG emissions from all sources, compared with 2, 6 % in 1970 year. The GHG emissions in 1970 year were 734 M ton CO2 and in 2008 year 1400 M CO2, with an increment of 193, 5 %(Gerlagh and van der Zwaan, 2012).

Table 5.7.1. Total emissions from GHG emissions from waste by Region and for substance 2008 year (MtonCo2/year)2

Region	Total GHG Emissions 2008 year	CH4	CO2	N2O
Asia	573,059	521,7241	1,23	50,1052
OECD 90	399,951	337,3533	29,1755	33,4234
MAF	164,055	149,2686	---	14,787
REF	141, 712	131,7217	0,868	9,123
LAM	141,634	132,488	0,239	8,91

Source: Systematization of data from Gerlagh, R., 2012

Table 5.7.2. Trends of emissions from waste for selected years (M ton CO2 /year)2A

Region	1970	1975	1980	1985	1990	1995	2000	2005	2008
Asia	199,3	224,3	259,1	394,3	352,3	410,1	473,0	538,3	573,1
OECD 90	364,0	398,6	434,9	462,6	501,9	472,6	414,8	399,2	399,9
MAF	49,7	58,3	69,1	82,1	98,9	116,5	136,7	156,7	164,1
REF	68,3	80,1	92,3	106,6	122,2	114,1	121,4	133,8	141,7
LAM	52,6	60,9	73,7	86,7	99,2	114,4	129,0	139,6	141,6

Source: Systematization of data from (Gerlagh and van der Zwaan, 2012)

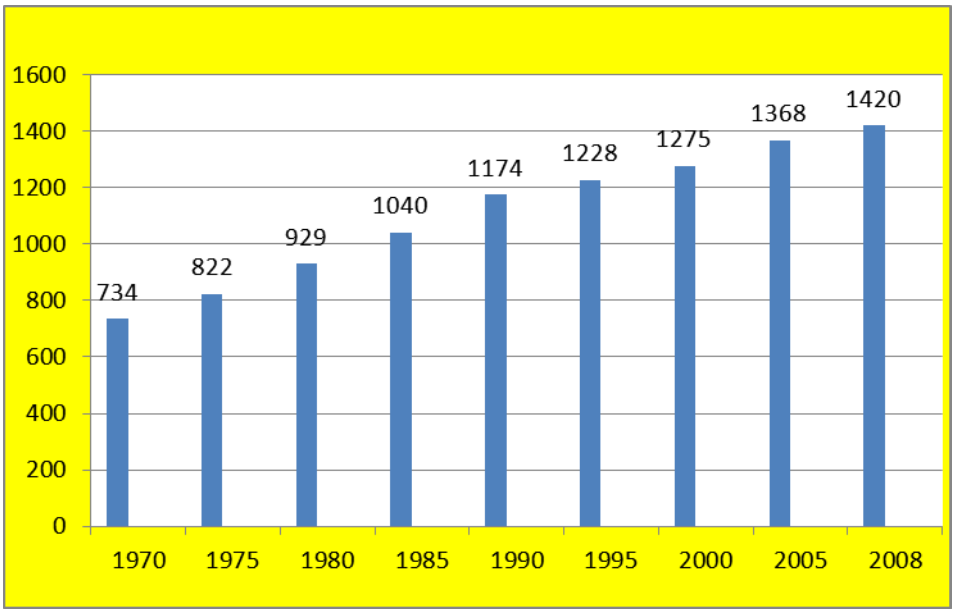

Figure 5.7.4. GHG emissions from waste of 1970-2008 in MtonCO2/year (Source: Gerlagh and van der Zwaan, 2012)

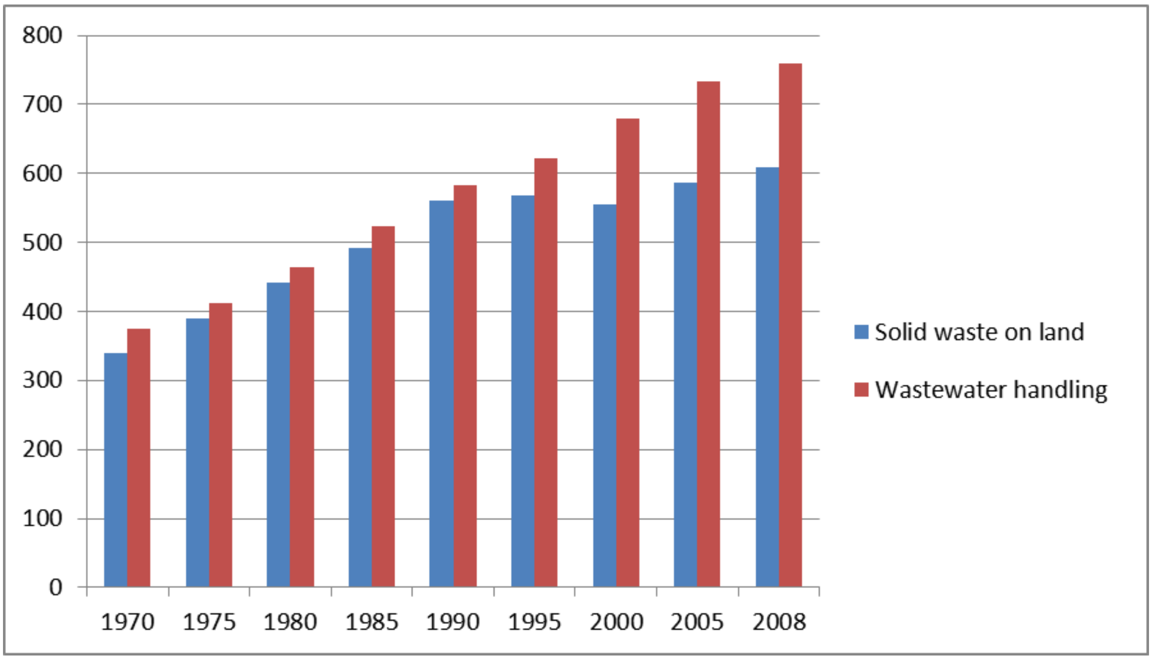

Figure 5.7.5. Evolution of GHG emissions from wastewater and solid wastes on land in the period 1970-2008 (M Tons CO2/year) (Source: Gerlagh and van der Zwaan, 2012)

The trends for GHG emissions from waste in 2010, 2015 and 2020 years are: 1460, 1585, and 1740 Mton CO2/year. The trends only for Landfill CH4 in 2030 and 2050 are: 1500 and 2900 M Ton CO2/year; and the trends for CO2 emissions in waste incineration from 31, 5 M ton CO2/year in 2008 are 60 for 2015 and 2020 years, and 70, 80 for 2030 and 2050 years. (Barker et al., 2008).[4]

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[4] **Solid waste disposal on land** represented in 1970 year 46.3% of total emissions in Waste Sector and in 2008 year 43%; while the GHG emissions were incremented from 1970-2008 by 179% in this subsector. In the case of **wastewater handling**represented in 1970 year 51% of total emissions in Waste Sector, and in 2008 year 53, 5%; while the GHG emissions were incremented from 1970-2008 by 203% in this subsector. In the case of **waste incineration** the main GHG emission is CO_2 that represented in 1970 19, 6 M ton CO_2 and for 2008 year 36 M ton CO_2 for an increment of 184 %.(Systematization of data from Gerlagh and van der Zwaan, 2012).

[1A] AR4 WG III-Chapter 10 Waste management, page 596 Table 10.3

Problems caused by the most visible sign of a lack of life cycle economy - the unsound management and disposal of waste - are well-known: pollution of air, water and soil, serious health risks for people caused by environmentally unsound management and disposal practices, GHG emissions, and increasing investments needed for solving immediate problems (WHO, Country Office for Maldives, 2010).

Municipal solid waste is a significant contributor to greenhouse gas emissions through decomposition and life-cycle activities processes, the majority of these emissions are a result of landfilling, which remains the primary waste disposal strategy internationally(Lou and Nair, 2009).

The enterprise Naanovo Energy Inc. of United Kingdom in the Caribbean islands, which has agreements with some countries of the Region, is installing plants in order to turn the garbage in electricity and drinkable water, and reducing the dependence with oil, through waste incineration with growing problem of electronic waste is a case in point. An estimated 50 million metric tons of e-waste replete with toxic materials are generated annually as consumers replace used electronics such as computers and mobile phones with the latest models, 2,3 million tons of electric and electronic waste are produced annually in China, and 3 million tons are produced in United States (UNEP, 2007); (Jacquet et al., 2010).

Countries have been incorporating alternative forms of waste management strategies for mitigation such as energy recovery from landfill gas capture(mainly CH4), aerobic landfilling (aerox landfills), pre-composting of waste prior to landfilling, landfill capping and composting of the organic fraction of municipal solid waste(Lou and Nair, 2009). Other technologies for mitigation are available, as, controlled wastewater treatment and recycling to minimize waste (Cohen et al., 2008), waste incineration with energy recovery; and biofilters to optimize CH4 oxidation to be commercialized before 2030 (IPCC, 2007).

Recycling is an effective means to reduce energy use, CO2, NH4, N2O emissions and waste at the source at the same time. The general trend throughout the last 25 years indicates an increase in recycling rates(UN, 2010).

5.8. Behavioural change

Energy intensity, which depends on behaviour, at the individual and economy-wide level, is one of the key determinants of emissions in the Kaya identity. Accordingly, the Kaya identity clearly places "behaviour" as an implicit and relevant driver of emissions. Clearly therefore, behaviour is equally a potential agent for change in emissions.

While many studies show individuals and households as being responsible for fuel use and related emissions, the industrial and commercial sector plays an important role as well in contributing to emissions. Companies and organizations through their activities have both a direct and indirect effect on the environment. Literature talks about emissions linked to behaviour in various ways – from the production perspective (wherein efficiency improvements can play a role in reducing emissions) and from the consumption side (whereby reduced consumption through behaviour changes especially in developed countries can reduce emissions).

Most studies indicate that behaviour plays a greater role on the consumption side, and that the level of consumption or the preference of goods and services that entail lower emissions are likely to

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[2] OECD – countries of Annex I Parties of UNFCCC, MAF – countries of Africa, REF – countries in transition included Russia, LAM – countries of Latin America and the Caribbean, Asia include all countries of this Region with main emitter China. (Table 1 - 1-mainly emissions from wastewater handling, 2-mainly from wastewater handling, 3- mainly from solid waste disposal on land, 4-mainly from wastewater handling, 5- mainly from waste incineration, 6- mainly from wastewater handling, 7- mainly from solid waste disposal on land, 8- mainly from wastewater handling).

2A From 1998 and forward GHG emissions from Waste in Asia is bigger than OECD countries (403.8 vs. 381.1 M ton CO_2), being already more and less similar in 1997 year (391,6 MtonCo$_2$ in Asia and 395,2 MtonCO$_2$ in OECD countries) affect the overall emissions. Recent research indicates that consumption patterns are shaped not only by economic forces, but also by technological, political, cultural, psychological and environmental factors. For example, domestic energy use and travel choices are intrinsically related to social identity, status and norms (Layton et al., 1993; Steg et al., 2001; Park, 2003, chap. 3, Exley and Christie).

Various studies indicate that 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. Therefore changing behaviours is not possible simply through information provision and economic measures(Jackson, 2005). The ipsative theory of behaviour (Frey and Heggli, 1989) holds that an individual’s behaviour may be constrained by a lack of real or imaginary opportunities, imposed by the individual’s internal as well as external conditions (Tanner, 1999). While non-action may be due to lack of motivation, it could also be 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.

Several studies indicate that variation exists in energy consumption across countries of similar incomes. Significant disparity prevails between the US (per capita CO_2 emissions of 20 metric tons) and the UK (per capita CO2 of 9.5 metric tons). While part of such variability may be attributed to population density, infrastructure etc., different social and cultural predispositions also affect the use of energy and materials (Tukker et al., 2010;Sovacool and Brown, 2010.

Moreover, not only current, but also past behaviour is seen as one of the most intractable barriers to changing energy behaviours (Pligt, 1985; Kollmuss and Agyeman, 2002)and Whitmarsh (2009)); (Mont and Plepys, 2008). Inherent behaviour in societies leads to large variations in consumption patterns and lifestyles. Empirical studies indicate that the link between material welfare and happiness is not omnipresent. Senses of security, clean environment, family ties and friendships are important factors in determining consumption patterns. Regions with a large proportion of vegetarian people, exhibit much lower emissions per unit of food as compared to other countries. Developing countries such as India that are inherently frugal in consumption behaviour also have very low levels of waste generation coupled with high levels of waste recycling and re-use.

Various policies and strategies are used across countries with varying degrees of success to bring about behaviour change. These may be antecedent strategies (involving commitment, goal setting, information or modelling) or consequence strategies (feedback or rewards) (Abrahamse et al., 2005). Some studies indicate that information tends to result in higher knowledge levels, but does not necessarily lead to behavioural changes or energy savings. Rewards are seen to have effectively encouraged energy conservation, though with rather short-lived effects. Feedback has also proven to be useful, particularly when given frequently. Many consumption oriented environmental studies also suggest that technological solutions directed at improving resource productivity are not 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. Policies dealing with changing consumption patterns deal with material substitution, pollution prevention, consumer information and optimization of end-of-life management practices.

Apart from individuals and households, companies and organizations also contribute to emissions, through both direct and indirect use of energy. Accordingly, literature also points towards the need of combining values and norms to account for climate policy support within public and private organizations as well (Biel and Lundqvist, 2012). Public and private sector organizations are expected to react differently to environmental policies – acceptance of policy measures in the private sector are more closely connected to economic costs and benefits than in case of public sector companies.

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. It is suggested that the energy saving potential of efficiency behaviours is greater than that of curtailment behaviours. However, there is also enough evidence which indicates that energy-efficient appliances do not necessarily result in a reduction of overall energy consumption when people use these appliances more often i.e. the “rebound effect” comes into play.

5.9. Technological change

This section will provide an update of the AR4 on the drivers for and barriers to technological change from a historical perspective. Distinguishing the “fingerprint” of technological change among other drivers of emissions is not straightforward; similarly, it is not easy to single out drivers of technological change. This section will discuss the policy-relevant system aspects of technological change that have emerged in the literature since the AR4, and technology issues in developing countries. Two particular topics will be discussed in technological change’s contribution to mitigation; the “rebound effect” as a mechanism how part of the technological change-induced mitigation can be annihilated, and infrastructure and lock-in, as an important enabling or inhibiting condition to technological change. How technological change is covered in scenario studies is discussed in chapter 6 of this volume.

5.9.1. 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, pp. 149–153; 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.

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). There are various ways of measuring the level of technology that control for these other factors. Top-down methods estimate the technical efficiency with which energy is used from observed production data. Alternatively, bottom-up, thermodynamic based engineering measurements of energy efficiency can be used, see energy efficiency above.

5.9.1.1. Technological change: a drive towards higher or lower emissions?

Previous assessment reports have focused on the question what the contribution of technological change can be to reducing emissions. With rising global emissions in emerging economies, and rapid technological change happening there, the question however arises what the impacts of technological change on rising emissions may be in developing economies. According to some studies, due to a combination of rebound effects (see section 5.9.2) and an energy savings bias in R&D, the result of technological change could be an increase in emissions (Fisher-Vanden and Ho, 2010). In addition, technological change may favour the one issue over the other. Compact cars in the 1930s have a similar fuel consumption to compact cars in the 1990s, but have far advanced in terms of speed, comfort, safety and air pollution (Azar and Dowlatabadi, 1999).

How are macro-economic factors affecting differences in energy efficiency between countries and changes over time? Using the 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). Strong correlations between the state of technology and the levels of other inputs can result in biased and inconsistent results (Eberhardt and Teal, 2011) and most existing estimates are, therefore, likely of low quality.(Newell et al., 1999) provide some information on the degree to which energy price increases induce improvements in the energy efficiency of consumer products. For room air conditioners, large reductions in cost, holding efficiency and cooling capacity constant, occurred from 1960 to 1980 in the United States. Also the cost of high efficiency air conditioners relative to inefficient ones was reduced. From 1980 to 1990 the former trend ended but the mix of air conditioners offered from those that were feasible to manufacture shifted sharply in favor of higher efficiency. 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. For gas water heaters the induced improvements were close to one half of the total, although much less cost reducing technical change occurred. Popp (2002) similarly finds that increased energy prices have a significant though quantitatively small effect on the rate of patenting in the energy sector.Cheon and Urpelainen(2012), using more recent data, find that through reinforcing the sectoral innovation system, high oil prices provide policymakers and entrepreneurs with an imperative to invest in alternatives.

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 optimal 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 behavioral 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)).

5.9.1.2. Historical patterns of technological change

There is ample evidence from historical studies, for instance in the United States, Germany and Japan, that technological change can affect energy use (Carley, 2011b);(Welsch and Ochsen, 2005); (Unruh, 2000). In Japan, it has also shown to be a driver for reduction of CO2 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) analyse functional performance metrics for energy transformation, storage and transport. They arrive at the conclusion that energy technology has annual progress rates of 3-13%, which is lower than the more extensively studied IT technologies (19-37%). They also report that data availability in energy is lower, and speculate that historic progress rates might have an element of self-fulfilling prophecy: if a field is not expected to develop fast, those involved will not feel urged to do so. 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.

Evidence also supports the conclusion that policy matters. For example, (Dechezleprêtre et al., 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, 2010)’s 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 (de la Tour et al., 2011).

5.9.1.3. System aspects of technological change

In the years since the AR4, and building on earlier literature on National Innovation Systems (Lundvall, 1992), the enabling conditions of technological change have been further systematised. Soete et al. (2010) highlights the role of learning and institutional and organisational factors, interaction between actors, and social capital. They also highlight the relevance of interactive learning and an associated dynamic rather than a static perspective – the innovation system and enabling conditions for technological change continuously. It is clear that R&D spending alone falls short as an explanatory factor for innovation. Such approaches seem to hold on the firm level too (Pinske and Kolk, 2010).

One method for defining and analysing enabling environments for technology is through the Technological Innovation System (TIS) approach (Bergek et al., 2008); (Hekkert et al., 2007). (Bergek et al., 2008) explains links between "structural components" of the TIS, such as actors, networks and institutions, to "functions", such as market formation and entrepreneurial experimentation. They specify key barriers and policy issues from a more systemic perspective. (Hekkert and Negro, 2009)illustrate how the functions work in different developed country cases. Many TIS studies have been used for comparative research on innovation success and mostly focused on technologies in industrialized countries (e.g., (van Alphen, 2011); (Hillman et al., 2008).

In developing countries, other frameworks are applied to analyse the factors contributing to technical change. (Hall et al., 2011) discuss technological, organisational, social and commercial uncertainties and argue on the basis of the biofuel case in Brazil, that although technological and commercial uncertainties are often well taken into account, social uncertainties also determine the outcome. (Wonglimpiyarat, 2010)discusses bioenergy in Thailand and emphasises the institutional aspects of technological innovation in this field. It is clear that innovation matters as much for developing countries as for developed countries ((Ockwell et al., 2010); (Altenberg, 2008) and that institutional factors possibly play an even more pronounced role (Altenberg, 2008).

Another example of the impact of enabling conditions concerns the acquisition of skills and technology for PV manufacturing in China. (de la Tour et al., 2011)find that Chinese producers have acquired the technologies through purchasing of manufacturing equipment in a competitive international market, but the skills with qualified individuals necessary to produce PV products through the Chinese diaspora. The pioneer PV firms were built up by the returning diaspora.

5.9.2. 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 microeconomic substitution (Khazzoom, 1980) and income effects (Lovins, 1988) or output effects as well as macro-economic effects. Increased real income also increases demand for all goods in the economy and, therefore, for the energy required to produce them (Berkhout et al., 2000). There also may be economy-wide changes such as adjustments in capital stocks that result in a further increased long-run demand response for energy (Howarth, 1997).

There is much debate on the size of the rebound effect. Rebound effects in production and in the macro-economy are likely to be larger than in micro-level consumption studies. (Brookes, 1990) suggested that, due to long-run growth effects, the rebound effect could be larger than the initial saving resulting in higher, not lower, energy consumption, or "backfire" also know as Jevons' paradox. Using a macro model with fixed energy prices, (Saunders, 1992) showed that this required that the elasticity of substitution between energy and other inputs is equal to or greater than unity, which is unlikely. (Howarth, 1997), however, argues persuasively that even if the elasticity of substitution is one or greater that, when a distinction is made between energy services and energy use, the macro-level energy rebound effect for a production innovation is less than the initial innovation induced reduction in energy use, so improvements in energy efficiency do, in fact, reduce total energy demand. However, backfire might be possible if the share of energy costs in total output was large and the share of energy costs in energy services was high. Both these conditions could have been true during the early industrial revolution so that Jevons' paradox (Madlener and Alcott, 2009) could have been valid then even if it no longer applies.

Extensive empirical studies have been conducted for both production and consumption. In an extensive survey of existing studies, Greening et al. (2000) find that micro-level rebound effects for consumption are typically in the range of 10-30% and may typically be even smaller for industry. This seems to be confirmed in subsequent studies in developed countries (e.g. (Bentzen, 2004); (Haas and Biermayr, 2000); (Berkhout et al., 2000); (Schipper and Grubb, 2000); (Sorrell et al., 2009)). 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)).

5.9.3. 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 (Ballesteros et al., 2010), such as transport infrastructure. 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, irrigation systems, and the like. Their choices include construction, maintenance and usage. Energy consumption and CO2 emissions vary greatly between different types of infrastructure. Long-term public investments provide commitment to current preferences, leading to investment biases in such assets (Gerlagh and Liski, 2011).

The 'lock-in' effects of infrastructure and technology choices made by industrialized countries in the post-World War II period at low energy prices are responsible for the major recent increase in world GHG emissions(IPCC, 2007). This approach is followed and copied by many new emerging economies in their process of urbanization and industrialization, such as the case in China and India, where physical infrastructure construction has been accelerating (Pan, 2010). For developing countries, the relative growth of services in GDP share, technological progress induced by higher oil prices and energy conservation efforts are crucial to avoid the lock-in effects. Although CCS might lead to "reinforced fossil fuel lock-in" by perpetuating a fossil fuel based energy provision system, a large-scale BECCS development could be feasible under certain conditions, thus largely avoiding the risk of reinforced fossil fuel lock-in (Vergragt et al., 2011).

The focus of climate mitigation is often on low carbon technologies and materials in policy making with regard to the construction of physical infrastructure. However, the choice of a specific type of physical asset carries more weight in carbon emissions. Take transport as one example. Air, rail and road transport systems are all applicable for distance with 1500km. Evidently, rail as a mass transport carrier can emit much less than air and road. In case of urban transport system, public transport requires much less fossil fuel to meet mobility demand.

Modern transport is almost totally dependent on oil, and 61.4% of all oil was used for transport in 2008(Banister, 2008). The growth in oil consumption between 1973 and 2008 has been more than 110% (IEA, 2009), and global CO2 emissions from transport have increased 44% in the period 1990-2007(IEA, 2009). Freight moved within and between countries accounts for roughly 50% of energy use in total world transport (Gilbert and Perl, 2008), especially for BRIC after the centre of gravity of global economy moved to Asia. The emerging megacities are associated with high population growth and relatively low levels of infrastructure supply. Whereas 20%-30% of all land is taken by roads in U.S. cities, the corresponding share for major cities in Asia is 10% to 12% (Banister and Thurstain-Goodwin, 2011; Banister, 2011a; b). Germany and Japan have been able to reduce transport CO2 emissions even as their economies grew(IEA/OECD, 2009). U.S. transportation is a major emitter on a global scale. Each year it produces more CO2 emissions than any other nation's entire economy, except China. Measures of reducing transport emission of U.S. considered include energy efficiency improvements, low-carbon alternative fuels, increasing the operating efficiency of the transportation system, and reducing travel. Highway vehicles should be the primary focus of policies to control GHG emissions. The decarbonisation of the world transport system requires a decoupling of economic growth from transport and emissions growth through creative combinations (including socioeconomic innovations) of new transport technologies and a reorganization of the ways in which travel and freight movements are undertaken.

Carley(2011) provides historical evidence from the US electricity sector indicating that crucial drivers – market, firm, government and consumer – work together normally in the right direction but the process can be slow. In order to lock out or escape from locked-in in such infrastructure, there is a need to reshape the technological-institutional complex to avoid ''persistent market and policy failures that can inhibit the diffusion of carbon-saving technologies despite their apparent environmental and economic advantages (Unruh, 2000, 2002).

Therefore a conclusion is drawn that avoidance of lock-in effect in physical infrastructure is highly important to reduce emissions not only in the short run but also far into the future. In absence of policy intervention there are significant consumption losses and welfare losses due to severe temporary lock-ins. Once built, it would be more difficult to retrofit. Actions must be taken in planning, choice of materials and construction using life cycle analysis.

5.10. Co-benefits and trade-offs of mitigation actions

As the preceding sections of this Chapter have demonstrated, greenhouse gas emissions and climate policies are intimately entangled with many of the energy, environmental, economic and social goals of society. 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 can provide significant "co-benefits" by helping achieve these other goals.

5.10.1. Co-benefits

5.10.1.1. Health co-benefits

Mitigation strategies can 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.For instance, 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), exceeding projections by 55% (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). Key categories of health co-benefits include:

Improved ambient air quality: Two principle paths for reducing greenhouse gas emissions are via improvements in energy efficiency and through reduced use of coal. Energy efficiency whether it is focused on improved end-use, transport or supply of energy, simply reduces the amount of energy needed to run the economy and consequently reduces air emissions (van Vliet et al., 2012). Improving energy efficiency and reducing coal use can provide 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-years or other physical measures. Others – by assuming dollar values for morbidity and premature mortality – provide monetary estimates which are compared to the cost of climate policy (Rao et al., 2012).

Ambient air quality may also be improved by the retrofit of technologies such as CCS to coal plants. For example, emissions of SO2 must be tightly controlled in order for many currently-conceived carbon capture processes to work. On the other hand, CCS will reduce a plant's net output of electricity substantially (today, reducing output by approximately 30%).The net impact on ambient air quality depends upon how this power is replaced.

Improved in-door air quality: To the extent that climate policy causes a move to commercial fuels for cooking and heating in developing countries, it can create substantial health benefits. Although the move to commercial cooking fuels, such as liquid propane have their own, negative environmental impacts, the net health benefits of moving away from cooking with biomass appear quite large (Haines and Dora, 2012).One study has suggested that in India around two million premature deaths, particularly in women and children, could be averted by introducing 150 million improved efficiency cook stoves over a decade, with a concomitant reduction of between 0.5 and 1.0 billion tonnes of CO2 equivalent greenhouse pollutants(Wilkinson et al., 2009).

Sulfur emissions reduction: Sulfur emissions have declined world-wide since the 1980s, after growing since the industrial revolution with the exceptions of the periods of the great depression and world wars, despite economic growth ((Stern, 2006); (Smith et al., 2011)). Emissions continued to increase strongly in developing East Asia through 2005 but since that year China has taken strong actions to reduce emissions ((Lu et al., 2010); (Xu et al., 2009)). Early policies to reduce urban air pollution tended to disperse emissions including to other countries. Japan was the first country to significantly reduce national emissions (Stern, 2005). It eventually followed by all developed countries apart from Australia especially after the LRTAP convention on acid rain in Europe. Emissions have been reduced by installing scrubbers, washing coal, switching to natural gas and other energy sources for electricity generation and using low sulfur coal.

5.10.1.2. Economic co-benefits

Energy security: Energy security is a primary goal of many countries even though it is not clearly or consistently defined. Nevertheless, it has been argued convincingly that several climate mitigation actions will improve energy security. Efficiency measures (end-use, transport or energy supply), increased deployment of renewable energy, and electrification of transportation will reduce the need for imported fuels in many countries, increasing their energy security. On the other hand, reductions in coal use – depending upon what replaces it – could lead to additional fuel imports for some countries.

Transport safety. In the transport sector, co-benefits may include not only the reduction of air pollution but also other social disturbances like noise, congestion and road surface damage. Major increases in greenhouse gas emissions are projected from the transport sector without decisive policies to address the growth in emissions. Motorised transport makes a substantial contribution to urban air pollution (also responsible for around 1.3 million deaths a year("WHO | Outdoor air pollution," 2012)).Increased active travel could reduce greenhouse gas emissions and the disease burden from ischaemic heart disease, cerebrovascular disease, depression, Alzheimers disease, diabetes, and breast and colon cancer(Woodcock et al., 2009).

5.10.1.3. Employment co-benefits

Stenborg and Honkatukia (2008) have evaluated the long-run employment effects in Finland of abatement of greenhouse gases, cutting emissions by 20 per cent would cause GDP to fall by as much as 3.4 per cent in the short run, leading to significant employment effects. In the long run, the labor market may recover, which shifts the burden of adjustment more on the capital markets. Employment, on the other hand may recover, if the labor markets are flexible enough in the long run.

5.10.1.4. Other qualitative co-benefit

Largely qualitative arguments are made regarding wide-ranging co-benefits of energy efficiency (GEA, 2012). For example, better insulated houses are more comfortable for the occupants, increasing quality of life and productivity.

5.10.2. Tradeoffs

While clearly producing a variety of positive co-benefits, climate policy will also likely produce a wide range of new technical and social challenges that could provide negative co-benefits or tradeoffs. Climate policy which targets stabilization of radiative forcing at levels under popular discussion will require dramatic changes in how we produce, transport, and consume energy. Effects – both positive and negative- will be felt at global, national, regional and local scales.

Co-benefits approach aims to reduce greenhouse gas emissions, prevent environmental pollution, and support sustainable development all at the same time. However, some “low-carbon” energy technologies will have negative impacts on air quality. To achieve +2 degree target, Carbon Capture and Storage (CCS) together with Combined Heat and Power (CHP) account for 77% of key technologies towards green growth(International Energy Agency, 2010). In CCS process, post-combustion capture from pulverized coal (PC) plants reduces SO2 significantly, but NOx and NH3 emission increase(Koornneef et al., 2012), at the same time the CCS will increase water consumption, which is unpractical in places where water resources are scarce(Zhai et al., 2011). For CHP process, global emissions decrease, but local emissions may increase, because CHP plants are installed near populated area (it has to be built near heat consumers) (Canova et al., 2008). When choose the mitigation way of specific area, the communication with local communities on “what is most important” is very crucial for local development.

The recent deployment of wind in Europe, for example, has displaced natural gas usage and lowered CO2 emissions, but has also created new technical and institutional challenges for maintaining system reliability in the short-term and providing incentives for building new capacity in the longer-term. As deployment of intermittent generation increases, additional challenges are expected. But these challenges can be overcome at a cost (Bilgili et al., 2011).

Widespread deployment of other emission reducing technologies can produce negative co-benefits that will require much more ingenuity to address. For example, a significant demand of bio-energy could lead to increased land competition, higher food prices (and stronger incentives for rapid increases in food productivity), loss of biodiversity if fuel plantations displace diverse ecosystems, and other negative impacts. The increased reliance upon grain commodities for both livestock feed and the increase in crops grown to make bio-fuels, along with shifting patterns of rainfall and drought, have contributed to sharp increases in commodity prices, threatening the nutrition of the world’s poorest populations(Lee et al., 2008; IEA/OECD, 2009).While a modest increase in the use of bio-energy could provide a number of co-benefits, a large-scale move to bio-energy could significantly increase the competition for land and modify local air pollution control needs. Also, some emission-control technologies reduce both air pollutants and greenhouse gases. But there are also examples where, at least in principle, emission-control technologies aimed at a certain pollutant could increase emissions of other pollutants.

1 **Table 5.10.1.** Co-benefits, positive (+) and negative (-)of mitigation options

Mitigation options	**Carbon efficiency (CO2/FE)**	**Energy efficiency (FE/Activity)**	**System/Infrastructure efficiency**	**Activity intensity (Activity/GDP)**
Options:	Biofuels (BF) Electricity of transportation(EL) Reduce coal use (RCU) Renewable energy (RE)	More fuel efficient vehicles Combined Heat and Power (CHP)	Modal shift (MS) Urban planning (UP) System optimization (SO) Carbon Capture and Storage (CCS)	Behavioral change (BC) Mobility service substitution (MSS) Active travel (AT)
Economic				
Productivity (Growth/ Income)	(+) BF, EL, RCU and RE will increase economic productivity.		(+) SO: More time for productive activity from improved mobility and time reduction spent in traffic	
Effects on long-lived capital stock/Lock-in		(+) CHP will reduce global emissions, but, (-)CHP may increase local emissions.		
Effects on energy security	(+) In some regions, BF production can contribute to increase energy security (+) RE will increase energy security by reducing oil import.	(+) Energy security gains through lower fuel consumption	(+) MS: Positive impacts through lower fuel consumption	
Social				
Employment effects (local)		(-) In the short run, the GHG reduction will affect employment.	(+) MS: Local employment gains for public transport	

Impacts on poverty & distributional effects	(-) BF use would contribute to sharp increases in commodity prices, threatening the nutrition of the world's poorest populations		(+) UP: Shift in focus from cars to public transport can largely benefit poorer households w/o access to cars	
Capacity building (incl. technology transfer)/ Knowledge				
Impacts on energy access & affordability	(+) Consumer spending savings		(+) SO: Better and more equitable access to mobility services	
Health impacts	(+) EL: reduction of noise and vibration	(+) Health benefits from lower emission vehicles (-) Weight reductions of vehicles may negatively impact on passenger safety	(+) MS: Health benefits through congestion reduction SO: Lower morbidity and mortality through reduction in accidents; reduction of noise, vibration	(+) BC: Health benefits through increase in active travel; reduction of motorized traffic can reduce incidence of accidents and injuries
Environmental				
Air quality	(+)RCU will improve the in-door air quality. (-) Emission-control technologies aimed at a certain pollutant could increase emissions of other pollutants.		(+) Air improvements through congestion reduction (+) CCS will reduce $SO2$ emission significantly (-) During CCS process, NOx and $NH3$ emission increase	
Water quality				
Water consumption			(-)CCS will increase water consumption	

Land use (incl ILUC)	(-) Bio-energy could lead to increased land competition, higher food prices		(+) MS: reduction of land used for parking areas	
Soil & other natural				
Biodiversity	(-) Bio-energy could lead to loss of biodiversity			
End of life of capital stock				
Quality of daily life				(+) AT will reduce social disturbances like noise,
Technological risks	(+) Lower risks for oil spills due to lower oil consumption and trade	(+) Lower risks for oil spills due to lower oil consumption and trade	(+) Lower risks for oil spills due to lower oil consumption and trade	(+) Lower risks for oil spills due to lower oil consumption and trade

5.10.3. Complex issues in using co-benefits to inform policy

Co-benefits of policy are often not estimated in policy analyses – consequently, they may overestimate or underestimate policy costs significantly. Recently, an increasing number of studies have included positive co-benefits and illustrated their value spreading of climate policy costs over a much wider range of potential benefits(Henriksen et al., 2011). Co-benefits estimates are particularly attractive to policymakers because many of the direct benefits of reducing greenhouse gas emissions will be realized decades into the future (IPCC, 2007), while many potential co-benefits, such as improvement in air quality, are realized immediately.

Analyzing co-benefits is often not straightforward. Key complexities include: choosing an appropriate baseline policy, understanding the importance of scale, and recognizing that net co-benefit calculations may hide critical details about winners and losers.

Cost and benefit. The Stern review (I) does discuss AQ co-benefits and even quantifies them in dollar terms as 'up to 1% of GDP' (Stern, 2006). (ÖSTBLOM and SAMAKOVLIS, 2007)include co-benefits in a CGE model for Sweden and find that the costs of climate policy are overstated if they are excluded. Bollen et al.,(2009) find the AQ co-benefits twice as large as climatic benefits. The benefit-cost ratio of replacing polluting and leaky biomass stoves with liquefied petroleum gas (LPG) stoves has been estimated at 4:1. These positive outcomes in terms of fuel, time, health, and climate are likely to be even greater with newer, more advanced biomass stove technologies that rely on renewable fuels and can greatly reduce the emissions of climate and health damaging pollutants. ("WHO | Outdoor air pollution," 2012). A systematic review of the economic benefits of cycling interventions, including economic benefits of health impacts from more physical activity, found a median benefit-cost ratio of 5:1, with a range of -0.4 to 32.5 (Cavill et al., 2008). 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, than in developed countries (IPCC, 2007).

The co-benefits from climate change mitigation in terms of reduced outdoor local air pollution might cover a significant part of the cost of action. Nonetheless, they alone may 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).

The benefits of GHG mitigation are global, long-term and uncertain, but the costs of GHG mitigation are local, near-term and certain, which requires that a good balance between global long-term benefits and local near-term costs.

[Note from TSU: caption for this Table (5.10.2) to be inserted by authors]

Dimension	Space	Time	Certainty
Mitigation Benefits	Global	Long-term	Uncertain
Mitigation costs	Local	Near-term	Certain
Development Benefits	Local	Near-term	Certain

Source: (Fukuda and Tamura, 2010)

Baseline: A critical step in estimating co-benefits of climate mitigation policy is to perform a thoughtful assessment of policies already in-place and to evaluate the likely evolution of future non-climate policies. For example, 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, dramatic reductions in air pollutant emissions have already occurred in the absence of climate policy and further tightening of air regulations is underway. If climate policy provides only small incremental reductions below this baseline, then the co-benefit is small. For countries and regions that do not have or do not enforce current air regulations, it is important to consider where future air pollution policies may go. If they are unlikely to adopt air pollution policies, the air quality co-benefits of climate policy could be large. On the other hand, rapidly developing countries such as China may follow the pattern of developed countries and adopt regulations to improve local air quality (and provide immediate local health and environmental benefits) before focusing upon climate policy (see earlier section in this chapter). If this is indeed the case, the co-benefits of climate policy will be much smaller.

Scale:For many mitigation actions it will be important to consider their scale of deployment. At small scale, the sustainable use of biomass may reduce greenhouse gas emissions and provide a number of co-benefits such as local energy supply (energy security) and local job creation. On the other hand, imagine how the world might change if 20% of global commercial energy were supplied by bio-energy. Competition for land between bio-fuels, food and forests would be greatly increased. Fuel conversion and transport would likely be big issues given the massive amount of biomass that would have to be harvested and moved, and new air emission issues would be created.

Winners and losers:While there may be significant positive net co-benefits from some emission-reduction actions, there may be distributional inequities with significant positive co-benefits for some and significant negative co-benefits for others. For example, replacing household use of biomass for cooking with liquid propane gas (LPG) can yield dramatic improvements in the households that make the switch, but create negative co-benefits for those involved in the production and transport of LPG.

In summary, good estimates of co-benefits can be important to the policy process, but much care must be taken to correctly frame the analysis and to understand important complexities for the mitigation actions chosen. Much co-benefits of mitigation turn out to be short-term effects, while the objective of climate change mitigation policies is, for obvious reasons, very long term. Integrated strategy assessments in a general equilibrium framework are in urgent need.

5.11. The system perspective: linking sectors, technologies and consumption patterns

CO2 continues to be the most important anthropogenic greenhouse gas; its increase is due primarily to the combustion of fossil fuels and in lesser extentto land use change. Between 1970 and 2008, global anthropogenic CO2 emissions increased by about 80%. Other GHG emissions also increased, but to a lesser extend; CH4 and N2O increased by about 45% and 40%, respectively, while fluorinated gases, which represented a minuscule amount in 1970, increased by about 650%. Specific contributions to the overall increase in GHG emissions from sectors like transport, buildings, industry, waste and agriculture, forestry, other land use (AFOLU) and fisheries and aquaculture have been estimated and analyzed.

The chapter identifies the main drivers for these trends by using the Kaya identity, which decomposes total greenhouse gas emissions into a series of factors: population size, output per person, energy per output, and emissions per energy. The factors involved in the decomposition have, in turn, other underlying drivers that influence their trends. These underlying drivers are not independent to each other; but despite this complexity, the use of the Kaya identity helps to organize the analysis.

With regard to population, the first factor in Kaya identity, the direct effect on emissions is a proportional increase, but the indirect effects of population on emissions are diverse. 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 has been stable at about a factor 50, though individual countries have changed their position in the ranking considerably. The population has been increasing mainly in Asia, Latin America and Africa; however, in Asia total emissions have been growing fastest due to other factors and drivers discussed below.

Other demographic trends such as urbanization, ageing and household size, have more subtleeffects on emissions. Migration from rural areas to urban areas tends to increase emissionsat its initial stage; while a further urbanization tends to decrease emissions. Ageing population seems to have an almost neutral effect on emissions, while the evidence on the effect of household size is not clear.

The second factor in the decomposition is GDP per capita, which is often used as a proxy for economic development, production and income. Worldwide income has gone up during the period assessed with much variation over time and regions. Economic growth was strong in Asia, the OECD also showed considerable growth levels, while Latin America showed lower growth over the entire period. Africa and the formerly centrally planned economies have seen setbacks in growth. Mainstream economic theory points to technological innovation as the key long-term driver of economic growth. The question whether innovations thereby also increase emissions (when not on purpose steered) remains controversial in the literature. The OECD countries have shown a remarkable income growth with more or less stable per capita emissions, but growth in developing countries seems more emission-intensive. The role of sector shifts, say from agriculture to industry to services, is probably less important for the development of emissions than improved energy efficiency within the sectors.

As a recent development in the literature, studies are undertaken to compare a structural decomposition for output with one for consumption, and to assess its consequences for the attribution of emissions over regions and countries. It is found that trade allowsdeveloped economies with a lower than global average emission-per-value intensity to import higher emission-per-value intensity goods from emerging economies, and vice versa. The growth in international trade results in significant variation between the territorial-based and consumption-based accountings of GHG emissions of countries. Consumption-based emissions are generally higher than territorial-based emissions for developed countries and lower for emerging economies, and that this gap between consumption-based and output-based emissions has increased over time. As trade serves as an instrument for exchange, in this respect, it is not a significant driver of global emissions per se, but it is an important driver for the regional distribution. Trade also implies transport, and in this respect it contributes increasingly to greenhouse gas emissions with a robust upward trend.

The third factor in Kaya identity is energy use per output. Energy intensity depends on a set of interrelated variables including demographics, technology and capital vintages, geography and climate, energy prices and taxes, lifestyles, and policies. 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 1% per year. Most regions show declining trends in energy intensity over the period 1970-2008. The change in energy intensity also depends on economic growth. Fast economic growth leads to a higher turnover of the capital stock, thus offering more opportunities to switch to more energy-efficient technologies.

The fourth factor in our identity is related to the carbon content in the energy resources. 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. The global rate of energy decarbonization has been on average about 0.3% annually, too low to offset the increase in global energy use of about 2% annually. The last decade shows a significant slowing of decarbonization, particularly due to rising carbon intensities in some developing regions, and to the slowed turnover of the energy system in developed countries.

The factors of the Kaya identity have various underlying drivers that are not independent to each other. As an example, consumption patterns are shaped not only by economic forces, but also by technological, geographical, political, sociological, and psychological factors. Large variations in consumption,energy use patterns,food choices, and lifestyles are observed between countries and regions, even between countries with similar levels of income. Behavioral change is an underlying driver of GHG emissions, dependent on the individual awareness and concern about climate change and the environment, the willingness to act, and the ability to change.

As already mentioned, technological change is also an important driver, for both overall economic growth and the energy intensity of growth. Some innovations directly increase or decrease emissions. Technical innovations that potentially decrease emissions are partly offset by the "rebound effect", the phenomenon that makes resources demand for resources to increase when due to innovation or efficiency improvements the final products becomes cheaper. The balance of evidence suggests that the "rebound effect"reduces the energy savings brought by energy efficiency measures by 10-30% from the reduction expected by the direct effect.

Finally we consider two particular issues of importance for developments in greenhouse gas emission in the coming decades: infrastructure and co-benefits or trade-offs. Infrastructural choices in the post World War II period are understood to still affect current emission levels, as they determined, for example, the fuel of choice for decades thereafter. Indirectly infrastructure also guides the choices in technological innovation, as greatest profits are expected for technologies that will remain in future demand due to the existence of complementary infrastructure. This is the so-called lock-in effect. The mechanism is reasonably understood, but there are few data with which to quantify its role in facilitating or impeding reductions in GHG emissions.

Co-benefits and other trade-offs have also influenced the implementation of mitigation policies and measures and, therefore, the GHG emissions. Co-benefits can be positive or negative. They may include improvement of ambient and in-door air quality, sulfur dioxide emissions reduction, energy security and transport safety, among others, but also can lead to undesirable outcomes, as in bioenergy production through increased land competition, higher food prices, and loss of biodiversity if fuel plantations affect diverse ecosystems.

To conclude, over the past 40 years global greenhouse gas emissions have considerably increased, therefore, the decreasing trends in energy efficiency and the almost stable trend in the carbon content of energy resources have not been sufficient to offset the increasing trends in population and economic growth. For the next decades, the past patterns suggest a continuous increase in global emissions due to continued increasing population, and energy-related emissions will form a major part.

At the same time, per capita emissions remained more or less stable. A major reason has been that the substantial income increase has been balanced by an equal increase in energy efficiency and slight decarbonisation of energy.

Though the territorial share of the OECD countries has decreased considerably, their average per capita emissions of approximately 16 tCO2 per year are still more than double the global average; for global emissions to go down, per capita emissions in the OECD countries must go down as well.

Reducing global emissions also requires the fast developing countries to change past trends. With a substantial part of the global population reaching middle and higher income levels, global emissions increasingly mirror the per capita emissions of these populations. Thus, a major shift in the energy system worldwide will be required to bend downwards the global trends. We have to reduce energy per output, or to decarbonise energy supply, or both.

We need to pay special attention to infrastructure, construction and technological choices as these affect future emissions for several decades. Recent insights in the dynamics of technological change could give guidance to policymakers about how to embark on innovation policies more effectively.

In view of this assessment, technological change and individual behavior becomes key aspects for future efforts on climate change mitigation. Chapter 6 will provide an in-depth study of future scenarios.

5.12. Frequently asked questions

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

Past trends indicate that GHG emissions are expected to increase in the future. The exact rate of increase cannot be predicted but there is little reason to expect it to be lower than the rate producing the 75% increase recorded between 1970 and 2008. The human population will increase at approximately the rate of recent decades, and on global scales economies will continue to grow, as well 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.

FAQ 5.2: **If society does wish to change the trajectory of GHG emissions, what options are available for doing so?**

Fundamentally, the options are to have fewer people, have individuals consume less, have the things consumed require less energy, and have the energy consumed result in lower GHG emissions. 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, then the choices 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).

FAQ 5.3: What factors constrain the range of choices available to society, and their willingness or ability to make choices that would contribute to lower GHG emissions?

Lower carbon energy sources need to be available and competitively priced, compared to fossil fuels. More low carbon energy sources are becoming available and their use is increasing at [section 5.6.1 and 5.6.2 still not available], but further technological development of both alternative energy generation methods and distribution systems will be required for the full potential of this option to be achieved. Infrastructure, including buildings, industry, and transportation systems, need to be energy efficient and not dependent on fossil fuels. Lower GHG technologies for infrastructure already are available and improving, but built infrastructure with multi-decadal lifespans can lock regions into high GHG emission options, particularly for transportation, where GHG emissions are projected to double from 1990 to 2030, and industry where CO2 emissions were without trend from the mid 1970s to 2000, but have increased by over 30% by 2008 and are projected to increase at that rate for the near future [from fig 7.5.2]. Agriculture accounts for 11.5% of global GHG emissions, with those emissions having increased by 25% since 1970. Technology has some scope to reduce the carbon footprint of food production, and substantial scope to reduce the carbon footprint of food distribution, however, consumer choice will play a large role in taking advantage of these food-related opportunities. All of these options are also dependent on the future effects of a changing climate, as weather conditions may affect alternative energy sources, demands on infrastructure for heating and cooling and movement of people and goods, and need for irrigation and choices of crops, livestock and fish for food. Society is not yet showing strong and consistent preferences for low GHG options, from the ranges of technological and behavioural choices available. Hence, above all, society needs to be well informed and motivated to make wise choices for products, services and activities that will reduce the GHG emissions for their chosen level of consumption.

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