Decoupling - past trends and prospects for the future

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Preface

The Environmental Advisory Council of the Swedish Government serves as a forum for discussions on environmental policies and sustainable development. Established in 1968, it has played an important role over the years as a platform for debate on strategic environmental issues.

Policy-makers need information from many sources for their decision-making. For issues related to sustainable development, the scientific community provides essential background information. The Council regularly invites researchers and other experts to its meetings to give input on the different themes addressed. The Council is also acting as a link to the scientific community during Sweden's preparations for the forthcoming World Summit on Sustainable Development (WSSD) in Johannesburg.

The Council also invites scientists to draw up synthesis reports on some of the themes addressed. There are widespread demands in society for a dematerialization or decoupling of environmental impact from economic growth. The ability to realize such a decoupling is crucial considering the likelihood of continued economic growth in developed countries and rapid economic growth in many developing countries with high populations. It is therefore of great interest to know how well we have succeeded so far and what potential there is for future decoupling. The present report Decoupling – past trends and prospects for the future summarizes some key trends of energy and material use over time in both developing and developed countries. The report was written by scientists involved in the analysis of how to generate sustainable energy and materials use. These researchers are connected to the international scientific network Alliance for Global Sustainability, consisting of research teams from Chalmers University of Technology, Massachusetts Institute of Technology, Swiss Federal Institute of Technology Zurich and the University of Tokyo, and are themselves entirely responsible for the contents of the report and any conclusions presented.

A short brochure with the main thoughts and some examples from the report has been published by the Swedish Environmental Advisory Council.

We hope that the report will be one of many contributions to a vivid and widespread discussion – before, during and after the WSSD in Johannesburg – on the necessary steps towards sustainable development.

Kjell Larsson
Minister for the Environment
Government of Sweden
Chairman of the Swedish Environmental Advisory Council

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Executive summary

There are widespread demands in society for a dematerialization or decoupling of economic growth from environmental impact. Calls are being made for eco-efficiency and/or an improvement of resource efficiency by a factor of 10. At the same time, some analysts claim there is an environmental Kuznets curve that supposedly implies a fall in environmental pressure, as we get richer. An improvement in the environmental situation has already been observed in many cases, but there are also many areas where the situation is deteriorating.

The purpose of this report is to summarize some key trends of energy and material use over time in both developing and developed countries. We have focused on Sweden, the EU, Japan and the USA as well as China, India and Brazil.

The main findings in this paper can be summarized as follows:

- Absolute emissions of CO_2 have been increasing in most countries and periods studied. For instance, emissions in the US in 1998 were 225 Mton C/yr higher than they were in 1990. This corresponds to the total emissions in Africa. Emissions in Brazil, China and India have increased by 325 Mton C/yr over the same period. Some countries have experienced periods with constant or even falling emissions, but this is the exception rather than the rule, and it has been triggered by oil crises or economic recessions. In order to stabilize atmospheric CO_2 concentrations, CO_2 emissions have to be decoupled much more rapidly than has been the case in the past, and it is extremely unlikely that this will happen by itself. Policies are required.
- There was some decoupling of CO_2 emissions from GDP in the major economies of the world from 1970 to 1998 in the EU (2.1 per cent/yr), Japan and the US (1.8 per cent/yr) as well as in some major developing countries such as China (3.2 per cent/yr),

although India actually increased its emissions over GDP by 1.4 per cent/yr over this period. The drop in CO_2 intensity has been prompted by some decoupling of energy from GDP (see next bullet) and CO_2 from energy, the latter being a consequence of an increased use of natural gas and nuclear power. In the South, fossil CO_2 per energy tends to increase from rather low levels. With industrialization, the proportion of biomass drops and the proportion of fossil energy rises in the energy supply mix.

- There has also been a decoupling of energy from GDP growth, at least in the EU (0.4 per cent/yr), Japan (0.2 per cent/yr) and the US (1.4 per cent/yr) over the past 40 years, although it should be noted that this decoupling was faster during the 70s and early 80s than during the 60s and the 90s. Clearly, higher energy prices and security-of-supply concerns during the oil crises triggered action to increase energy efficiency. Further, energy intensities are falling as a consequence of structural changes in many economies, with the service sector becoming increasingly important. On the other hand, this tends to be counteracted by rapid increases in transportation volumes and electricity use driven by continued income growth (and population growth, in particular in the US). As a result, primary energy supply in the OECD countries was roughly 50 per cent higher in 1999 than in 1971.
- Concerning materials, there is no clear tendency towards an increasing or decreasing intake in industrialized countries, which means that economic growth is roughly cancelled out by a decrease in materials intensity. For single groups of materials, the tendency varies substantially: plastics and aluminium have grown even faster than GDP for several decades, whereas other materials tend to grow in line with GDP (e.g., paper) or slower than GDP (e.g., iron and steel).
- The accumulated stock of materials in society is still increasing, mainly due to expansion in building volumes and infrastructure. A large proportion of the materials taken into society is, however, not added to the stock, but is used dissipatively. This is true for energy fuels and biomass in agriculture. In addition, many chemicals are not imbedded in durable goods.
- The flows to air and water of emissions detrimental to health and the environment, such as emissions of sulphur dioxide, particulates and CFCs, have in many cases been considerably

reduced in industrialized countries. In particular, emissions from the production system (factories, chemical plants, etc.) have decreased. Consumption emissions are, on the other hand, still increasing for many materials and can often be traced back to certain specific uses. An example of this is emissions of copper which predominantly emanate from brake linings and the tap water system.

- As regards hazardous chemicals and waste, we see no tendency towards decreasing volumes. The statistics and data on chemicals are insufficient or not available and it is also difficult to trace them indirectly. Chemicals are produced in society and are therefore not directly linked to the material intake. Furthermore, they are to a large extent used in processes without being incorporated in the produced products.

It should be noted that it is the absolute numbers – and not the relative – that matter. We point out that a general decoupling of materials and energy from economic development is less interesting than a decoupling of specific impacts that cause concern, e.g., emissions of metals and persistent chemicals foreign to nature, as well as CO_2 and acidifying substances. Thus policy-makers should focus on the key areas of concern and not primarily on overall indicators of dematerialization. Some general observations on the importance of interrelated material and energy flows for dematerialization are given in the final section.

1 Decoupling - Economic activity, industrial metabolism and the environment

Is the economy decoupling itself from environmental degradation? Some authors argue that decoupling is a “natural” process which takes place as economies mature. These same authors assume that environmental degradation increases at low incomes, reaches a peak, and then decreases as income continues to rise. This pattern is often described as an environmental Kuznets curve. Arguments supporting this view include: as incomes rise, consumer preferences shift towards less material intensive services; as economies mature, there is less demand for new infrastructure; as economies develop materials are used more efficiently (thinner car panels etc.), substitution occurs (e.g. plastics for metals and glass and fibre optics for copper) and there is more recycling of energy-intensive materials.

There has been an ongoing discussion on concepts related to decoupling (Carter 1966; Malenbaum 1978; Larson et al. 1986; Ayres 1989; Jänicke et al. 1989; Bernardini and Galli 1993; Grübler 1994; Schmidt-Bleek 1994; Seldon and Song 1994; WBCSB and UNEP 1996; Von Weiszäcker et al. 1997; Hinterberger et al. 1997; de Bruyn and Opschoor 1997; McDonough and Braungart 1998; Cleveland and Ruth 1999; Holmberg and Karlsson 1999).

Although some believe that decoupling happens almost automatically, others emphasize that political actions have been instrumental in bringing down emissions and environmental degradation in the past, and that this will also be required in the future. Over the past thirty years, we have seen that local air quality has improved in many developed countries (see figure 1.1). As income grows, people tend to demand better air quality and this has put pressure on the political system to regulate these emissions. Similarly, increasing income levels imply that people can afford sanitation and clean water, and begin to demand high water standards.

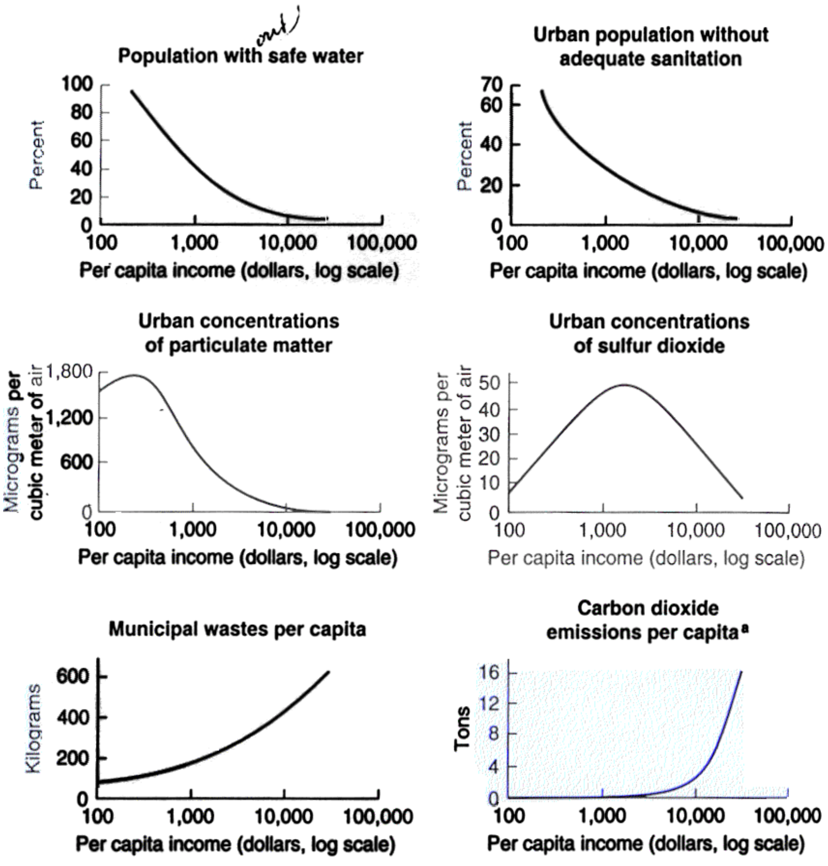
On the other hand, it seems that CO_2 emissions are much more difficult to decouple from income. One key reason for this is that the impacts of these emissions are distant (in time and space) and the political pressure to do something about them is much weaker. In addition, municipal waste production tends to increase with income.

The economic system is virtually indistinguishable from the industrial metabolism – the system of extraction, processing, transformation and dissipation or disposal of materials. Fuels are materials that carry useful energy. They are transformed into wastes – notably carbon dioxide and oxides of sulphur and nitrogen – by the combustion processes that convert chemical energy into electric output or useful mechanical or chemical power. Other materials from the earth are transformed after several stages of processing into chemicals, metals, inert construction materials – like concrete, bricks or glass – or consumption goods, everything from food and beverages to detergents, household chemicals, newspapers and plastic toys.

There are various possible limitations on the use of energy and materials related to environmental and resource requirements:

- The capacity of the ecosphere to assimilate different materials sets limits for the acceptable emissions of various pollutants.
- The availability of fertile land and requirements for ecosystem integrity will limit the management options, potential harvest and societal intake of various bio-resources.
- The limited availability of non-renewable geological resources implies restrictions on possible extraction scenarios for these resources.

Figure 1.1. Environment and economic development.



Note: **Estimates are based on cross-country regression analysis of data from the 1980s.**
[a] Emissions are from fossil fuels.
Source: **World Bank (1992).**

In this paper, we will analyze trends in energy and materials use in Sweden as well as some other major economies in the North and in the South. When analyzing and discussing decoupling, it is important to note that it is specific problems associated with these three restrictions that are of concern – not decoupling of materials in general. In addition, the specific properties of the societal metabolism will be crucial for any possible adaptation to sustainability – for instance, the dependence on various resources, the conversion characteristics of different processes and the dissipativeness of the use and possible recycling or discarding of various products when wasted. We will firstly look at the development of carbon dioxide emissions and the energy system in Chapter 2. Materials decoupling are discussed in Chapter 3 and in Chapter 4 we make some concluding remarks and recommendations.

Analysis of decoupling trends and futures

In our discussion of historical and ongoing trends in decoupling and future possibilities, we will make use of the equation given in Fig. 1.2, which in a highly aggregated way expresses the impact on nature (I) as a product of four anthropogenic factors, i.e., four factors that humans can influence.

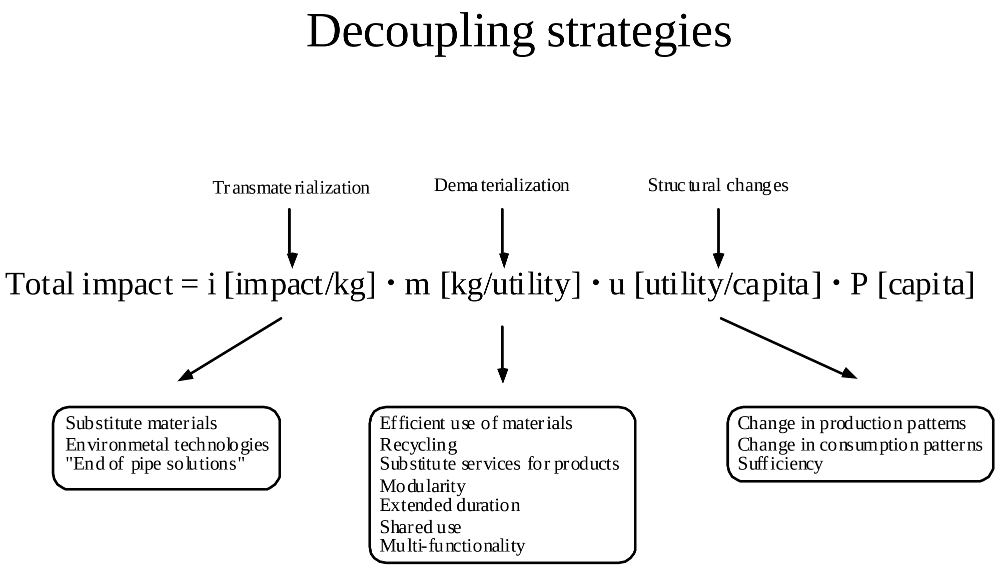
There have been various combinations of factors used in this type of equation, which (at least) goes back to Ehrlich & Holdren (1971, 1972). (A description or model of the real flows and impacts can of course be made at very different levels of aggregation. It is obvious that, in a more detailed modelling, the first three right-hand factors could be represented by vectors or matrices.) In the energy literature, this decomposition is sometimes referred to as the Kaya identity, and it reads

$$CO_2 = CO_2/\text{Energy} * \text{Energy}/\text{GDP} * \text{GDP}/\text{capita} * \text{Population}.$$

Applied on the global level, the equation illustrates the double challenge inherent in the concept of sustainable development: For a growing world population P, to develop and reach an acceptable quality of life by an increasing u, and, at the same time, to decrease society's harmful physical impact on nature I, by a decoupling of the societal materials/energy flows, that is a decreasing of i or m.

This decoupling can be achieved through various strategies as depicted in Fig. 1.2: reducing the environmental impact per kg of materials, dematerialization, structural changes. We will present data focusing on the two first factors, i and m, for major economies in the world and Sweden. We will also present data on overall indicators such as CO_2/GDP and CO_2 per capita trends, that is, on the joint result of all the different factors in the decomposition expression.

Figure 1.2. Various strategies to decouple environmental and resource impact from economic growth.



2 CO_2 and energy indicators

Climate change is often considered as one of the most serious environmental problems. This concern triggered the international negotiations that led to the United Nations Framework Convention on Climate Change (UNFCCC, UN 1992). The convention calls for a “stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.”

It should be kept in mind that the UNFCCC does not attempt to define the concept of dangerous interference with the climate system. Precise statements of what is "dangerous" are not possible, since (a) the degree of harm from any level of climate change is subject to a variety of uncertainties and (b) the extent to which any level of risk is "acceptable" or "dangerous" is a value judgement (Azar & Rodhe 1997; Azar & Schneider 2002). Science can provide estimates about expected climatic changes and associated ecological and societal impacts, but ultimately the question of what constitutes dangerous anthropogenic interference has to be settled in the political arena – given of course the best scientific assessments available about the likelihood of various potential outcomes.

Azar & Rodhe (1997) suggest a stabilization target below 400 ppm CO_2. The Swedish government suggest a 550 ppm stabilization target (CO_2 equivalent) which roughly corresponds to 450 ppm CO_2. If such targets are to be met, emissions have to drop to roughly 2-4 Gton C/year by the year 2100, or 0.2-0.4 ton C/cap/yr (assuming a global population of 10 billion people). For higher atmospheric stabilization targets, e.g. 550 ppm CO_2, world per capita emissions by 2100 would have to be approximately 0.7 ton C/cap/yr, but would over the subsequent centuries also have to drop to levels below 0.2 ton C/cap/yr.

Although the United Nations Framework Convention on Climate Change (UNFCCC, 1992) has been signed by 186 governments and the European Community, ten years of negotiations have produced very little in terms of bringing emissions down. Over recent years, emissions have gone up significantly in most regions of the world, with two major exceptions – the former Soviet Union (emissions dropped by some 40 per cent in the early 90s, mainly due to the collapse of its economy in the beginning of the 90s) and the EU (largely due to the UK, Germany and Sweden for reasons explained below).

In this section, we will present CO2 and energy indicators for the EU, Japan, Sweden and the US, as well as for developing countries such as Brazil, India and China. We will present trends in

- CO_2 emissions per capita.
- CO_2 emissions versus GDP
- CO_2 emissions per primary energy supply
- Energy intensity, i.e., primary energy supply divided by GDP
- Sectorial energy intensity, e.g., transportation, households, service and industry

We have relied on data from the International Energy Agency (IEA) on energy, population and GDP trends (IEA, World Energy Statistics and Balances, 2001) and on the Oak Ridge CO2 emissions data base (Marland et al, 2001) available on the net (http://cdiac.esd.ornl.gov/trends/emis/em_cont.htm). More details on carbon and energy intensities can be found in Schipper et al (2001), and references therein.

2.1 Per capita CO_2 emissions

There are perhaps three striking features concerning the numbers presented in this section:

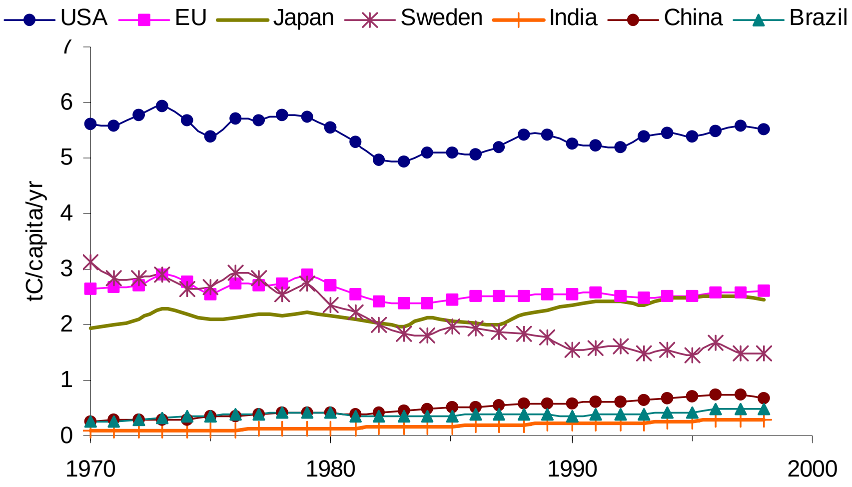
- *Emissions per capita in the North are substantially higher than emissions per capita in the South.* The U.S. per capita emissions exceed 5 tonC yr^{-1}, and Japan and Western European nations typically emit somewhere in the range 1.5 to 3 tonC $capita^{-1}$ yr^{-1}. In comparison, the per capita emissions are generally less than 0.7

tonC yr^{-1} in the developing world, and more than 50 countries emitted less than 0.2 tonC $capita^{-1}$ yr^{-1} by 1998. Today, global carbon emissions average about 1.1 tonC $capita^{-1}$ yr^{-1}.

- *Stabilizing the atmospheric concentration of CO_2 implies that carbon emissions per capita would eventually have to fall below levels that prevail in India and Africa today*. A 450 ppm target would for instance require that emissions by 2100 were equal to 0.2 ton C/cap/yr (assuming a global population of 10 billion people).
- *Emissions per capita in many countries in the North have remained stable over the past thirty years.* In the US and EU, per capita emissions today are below the level that prevailed in 1973. In Sweden, per capita emissions have dropped even more significantly. In Japan per capita emissions have increased.

Clearly, the reason for the much higher per capita emissions in the North than in the South is the higher level of per capita income. The reason for the stabilized per capita emission levels in the US and the EU is (from 1970-1990) the impact of the oil crises, which led to much stronger incentives (price and regulatory) to save energy. Automotive fuel efficiency in the USA improved substantially (from very inefficient values). However, since 1990, emissions in the US have increased on a per capita basis by 5 per cent, following low energy prices and little talk of and even less action on climate change. In Japan, energy efficiency in cars was already high and with a rapid per capita income growth, emissions continued to increase throughout the entire period 1970-1998.

Figure 2.1. Trends in per capita carbon dioxide emissions from the combustion of fossil fuels in some countries. Long-term sustainable levels (by 2100) are 0.2-0.7 ton C/cap/yr for a 400 ppm and 550 ppm target, respectively. Beyond 2100, further reductions in emissions would have to take place.



Source: Based on data from Marland et al (2001).

Per capita emissions in Sweden are lower than in most other OECD countries, and this is largely due to the large proportion of biomass, hydro and nuclear power in the primary energy supply mix.

2.2 Carbon intensity I: CO_2 emission versus GDP

A very important factor driving changes in CO_2 emissions is the amount of emissions per unit of GDP. Sometimes this ratio is referred to as "carbon intensity", but carbon intensity might also refer to the ratio of carbon emissions to energy supply (see section 2.3).

Below, we report national emission trends and compare them with GDP growth, in order to analyze whether any decoupling has taken place (in absolute or relative terms). Starting with the EU, Japan, Sweden and the US, it can be seen that all countries have experienced a drop in CO_2 emissions compared to GDP over the entire period. This drop was faster over the period 1973 to 1988 than during subsequent years .[1]

The European Union has managed to roughly stabilize its emissions, despite a growth in GDP by 15 per cent since 1990. This has been achieved through some climate policies (as voluntary energy reduction agreements between industrial associations and the government, increased oil taxes, and market restructuring of the power sector) but primarily through the incorporation of eastern Germany in the EU and the “dash for gas” policy in the UK, which resulted in a rapid reduction in coal.

Sweden is one of very few countries that has an active climate policy. The carbon tax, introduced in 1990, and levied only on the transportation sector, residential fuel use and parts of industry, has led to an increased use of biomass, and managed to keep emissions at roughly the same level as in 1990. The reduction in emissions during the 70s and 80s, was largely due to an expansion of nuclear power and energy efficiency improvements.

In the US, emissions grew by 13.1 per cent over the years 1990-1998 while GDP rose by 26.8 per cent. The carbon to GDP ratio thus dropped by 1.4 per cent/yr. It is interesting to note that Bush's alternative to Kyoto implies a "voluntary" target for the US economy to drop the carbon to GDP ratio by around 2 per cent/yr, i.e., a slight increase over current trends, but roughly the same as those that prevailed in the 1970s.

In absolute numbers, US emissions in 1998 were about 225 MtonC/yr higher than they were in 1990. This can be compared to the total emissions of CO_2 from India and Africa, which are approximately 290 and 225 MtonC/yr, respectively. Thus, the US has increased its annual emissions by as much as the *total* emissions in Africa. The growth in the US depends largely on increasing per capita income (by 17 per cent over the period 1990-1998) and a growing population (8 per cent over the same period, or 20 million people in absolute terms).

In Japan, CO_2 emissions increased by 6 per cent between 1990 and 1998, which is much lower than the growth in previous periods (e.g., a 22 per cent growth over the years 1982-1990). The decline in the CO_2 growth rate depends mainly on the much lower GDP

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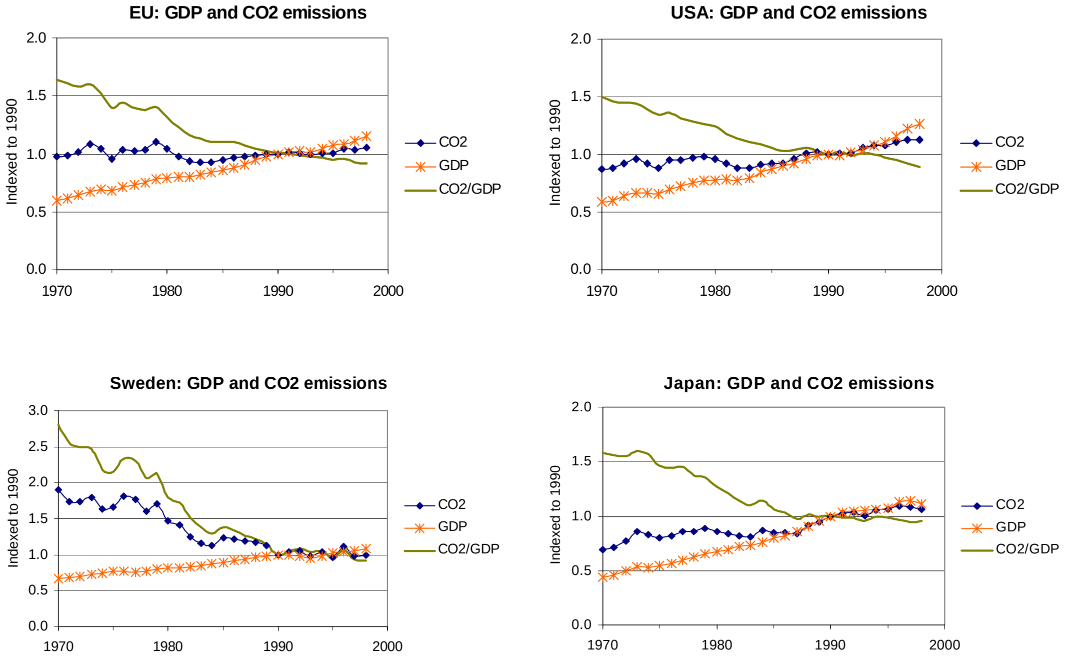
[1] For the US the drop was 1.9 per cent/yr on average between 1973 and 1988, and 1.5 per cent/yr between 1988 and 1998, for the EU we have 2.7 per cent/yr vs 1.2 per cent/yr , Japan 2.8 per cent/yr vs 0.6 per cent/yr and Sweden 4.4 per cent/yr vs 2.5 per cent/yr)

growth rate during the last 10 years. Over the years 1982-1990 GDP increased by almost 40 per cent while the GDP grew by 11 per cent during 1990-1998.

Figure 2.2. GDP and carbon emissions in the EU, Sweden, the US and Japan. Indexed to 1990.



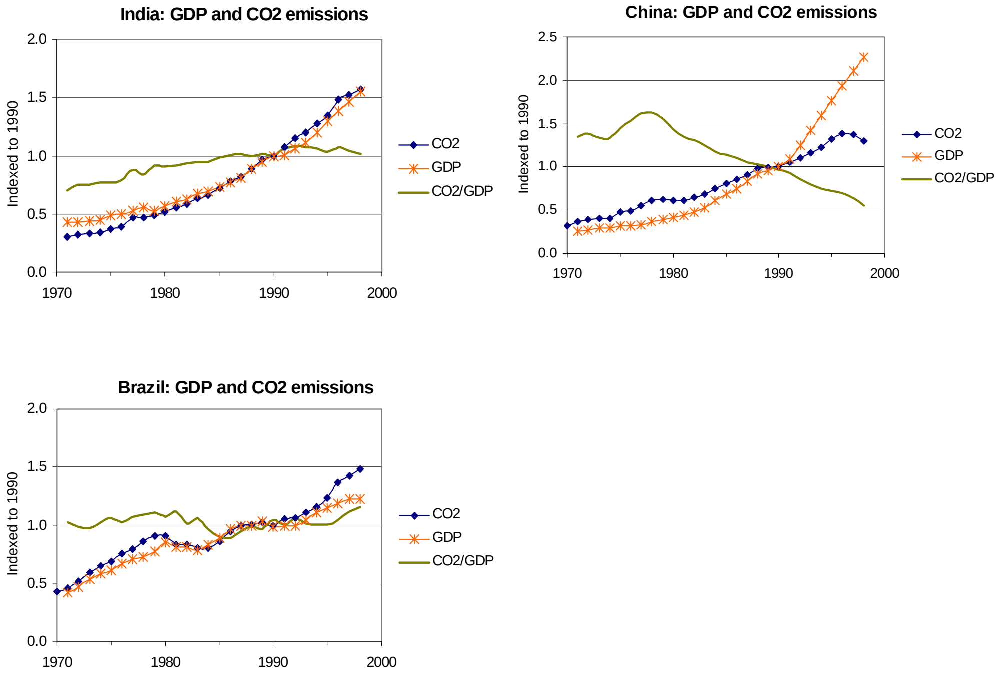
Source: Based on data from IEA (2001) and Marland et al (2001).

In developing countries, essentially all countries that experience economic growth also report rising CO_2 emissions. All countries that we focus on have experienced significant growth in emissions over the past thirty years (see figure 2.3).

Emissions grew by 48 per cent in Brazil, 29 per cent in China and 57 per cent in India over the years 1990-1998. Record growth numbers can be found in Chile (75 per cent) and Botswana (70 per cent) over this period of time. In absolute terms the emissions in Brazil, China and India combined are now 325 Mton C/yr higher than they were in 1990 – this increase corresponds to 33 per cent of the emissions in the European Union. These numbers point to the fact that although emissions per capita are low, any reasonable climate policy would eventually have to include developing countries.

It should also be observed that CO$_2$ emissions have grown in line or faster than GDP in India and Brazil over the past 30 years. In China, the CO$_2$ emissions to GDP ratio has dropped by a factor of three over the past 20 years, but several analysts express concern over the reliability of GDP data in China. It may also be noted that CO$_2$ emissions in China have actually dropped in absolute terms as well over the past couple of years (although some doubt the magnitude of this drop).

Figure 2.3. GDP and carbon emissions in India, Brazil and China. Indexed to 1990.



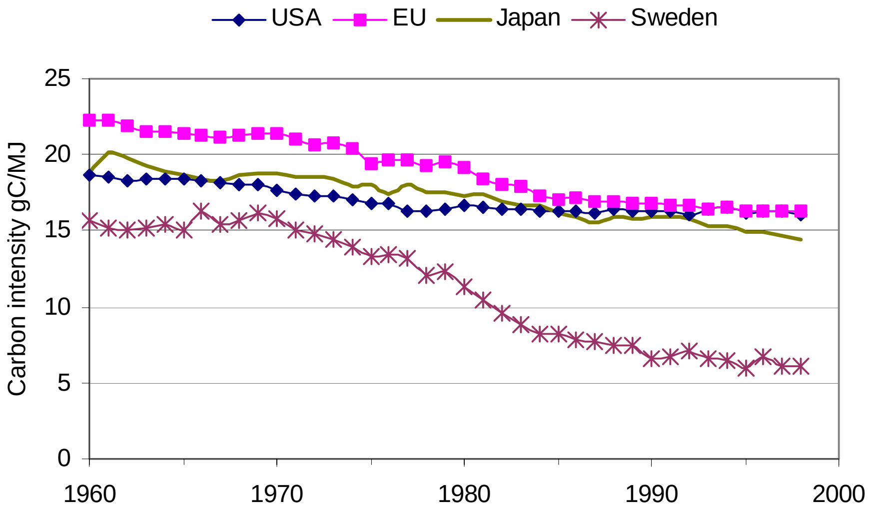
Source: Based on data from IEA (2001) and Marland et al (2001).

2.3 Carbon intensity II: CO_2 emissions per primary energy supply

Coal is the "dirtiest" fossil fuel, and natural gas the cleanest. Many OECD countries have experienced a drop in the CO_2 to energy supply ratio following an expansion of nuclear power and natural gas.

In figure 2.4, we have displayed this trend in several developed countries. The change in carbon intensity has been roughly 0.4 per cent/yr in the USA over the last 40 years. In the EU, it has been twice as fast. It may be noted that the rapid drop in Sweden in the 80s was largely a result of nuclear expansion, and the fact that nuclear-based electricity replaced oil in the heating sector (the carbon intensity declined by 4.1 per cent yr^{-1} in Sweden between 1970 and 1990). IEA data on total primary energy supply include conversion losses in nuclear power plants, and the fact that nuclear-based electricity is a rather inefficient way of generating heat for residential heating, implies somewhat paradoxically that the carbon to total primary energy supply ratio dropped even further (actual carbon emissions in the country are “diluted” into a larger supply of total primary energy).

Figure 2.4. Carbon emissions divided by primary energy supply in the EU, Japan, Sweden and the US.

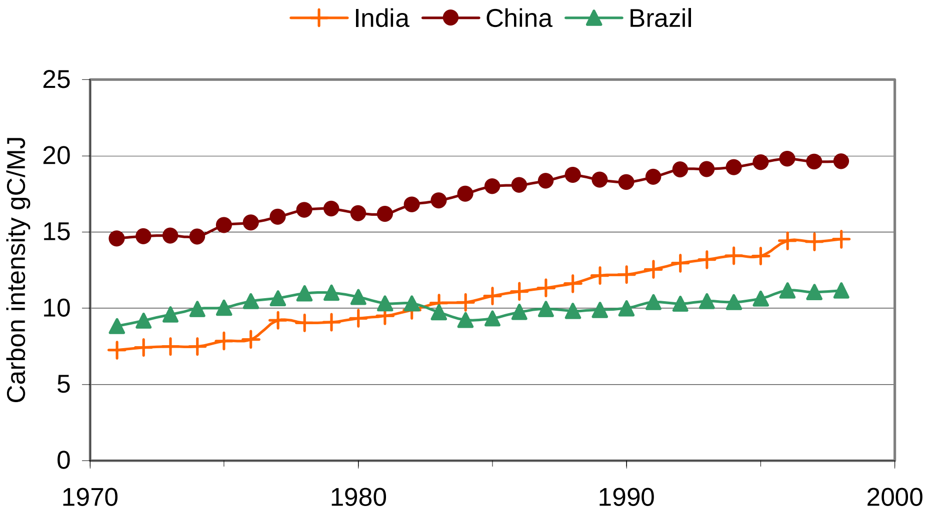


Source: Based on data from IEA (2001) and Marland et al (2001).

In developing countries, the trend has sometimes been the reverse. The reason for this is that the proportion of non-commercial fuel (biomass, which is considered CO_2 neutral) has dropped over time as a result of an expansion of modern energy carriers. These trends are evident in the case of Brazil, China and India (see figure 2.5). Between 1971 and 1998, the carbon intensity increased by 1.1 per cent yr^{-1} in China and by 2.6 per cent yr^{-1} in India.

It should also be noted that although emissions per MJ are increasing in developing countries, they are still lower than in many developed countries (because of the extensive use of biomass).

Figure 2.5. Fossil carbon emissions divided by primary energy supply in Brazil, India and China. Note that the low carbon intensity is a result of the large proportion of traditional biomass energy. Although not fossil, parts of this bioenergy use may be associated with deforestation, and such land use related emissions are not included in the graph.



Source: Based on data from IEA (2001) and Marland et al (2001).

Finally, it should be noted that it is not possible to suggest a specific carbon intensity rate that is sustainable or desirable. It is total global emissions that count, and they depend not only on the carbon to energy ratio, but also on energy use which is a function of income and population.

However, we may make some illustrative calculations in order to estimate rough numbers of what we may have to achieve in order to meet specific climate targets. At present, primary energy supply per capita in the EU Japan and the US is 160 GJ/cap/yr, 170 GJ/cap/yr, 348 GJ/cap/yr, respectively (1 G=Giga=109). Let us assume a primary energy supply equal to 100 GJ/cap/yr by the year 2100.

However, with a global population of 10 billion people, we end up with a total primary energy supply equal to 1000 EJ/yr (1 EJ =

1018J). This is roughly 2.5 times higher than the current global energy supply.

Let us further assume that we should stabilize atmospheric concentrations of CO_2 at 450 ppm (which is consistent with the Swedish government's target). This would require global emissions to drop to 4 Gton C/yr by the year 2100. Under these assumptions, carbon emissions would have to fall to 4 gC/MJ primary energy supply.

2.4 Energy intensity trends

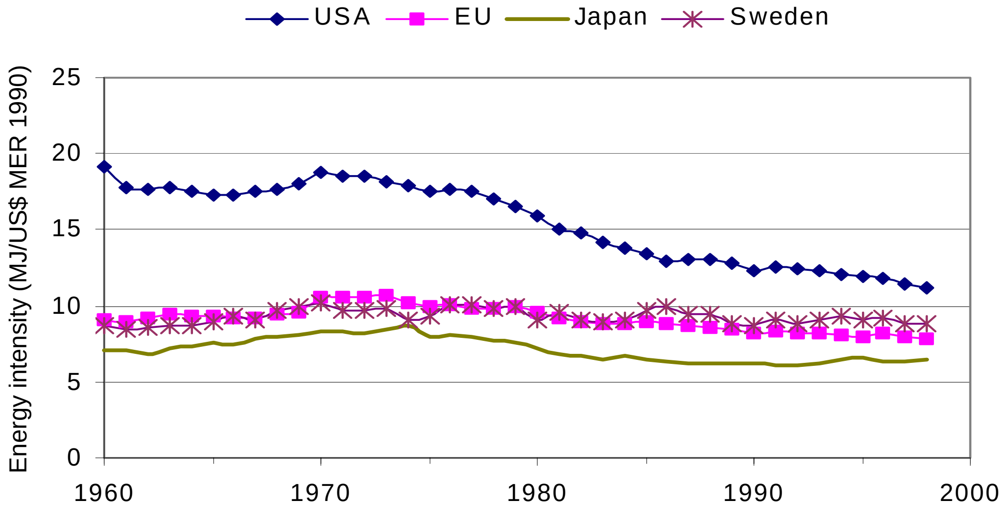
In this section, we present trends in energy intensities. Energy intensity measures energy supply divided by GDP (in real terms) and is not a direct measure of energy efficiency since the economic structure of a country also affects the rate of energy intensity. For instance, a country with a high dependence on heavy industries may be very efficient but yet have a high energy intensity rating. Thus, energy intensity may decline over time, not only as a result of improved energy efficiency in technical terms, but also as a result of structural changes.

Over the past forty years, energy intensity has declined in most developing countries. Overall, energy intensity declined in the US, EU, Japan and Sweden by 1.4 per cent/yr, 0.4 per cent/yr, 0.2 per cent/yr and 0.0 per cent/yr on average over this period. The drop in energy intensity was more pronounced during the 70s and early 80s, than during the 60s (when energy intensity actually increased in most regions) and 90s (when it actually increased in Japan).

In absolute terms, the drop in energy intensities has been cancelled out by rising GDP levels. It is important to note that the contribution of nuclear power is counted as the thermal energy required to produce the electricity (average 33 per cent thermal efficiency). This is not what is normally done in Swedish statistics and the energy intensity decline in Sweden in the graph below (over the years 1970-1998) is therefore less pronounced than what some Swedish readers may expect. On the other hand, if the traditional Swedish way of reporting total primary energy supply had been used, the drop in the carbon to energy ratio would have been substantially slower.

The drop in energy intensity during the 70s and 80s was largely due to the oil crises. Concerns over oil availability and its geopolitical implications, as well as rising energy prices, both contributed to energy efficiency improvements.

Figure 2.6. Energy intensity trends measured as energy divided by GDP in market exchange rates (fixed at the 1990 level).



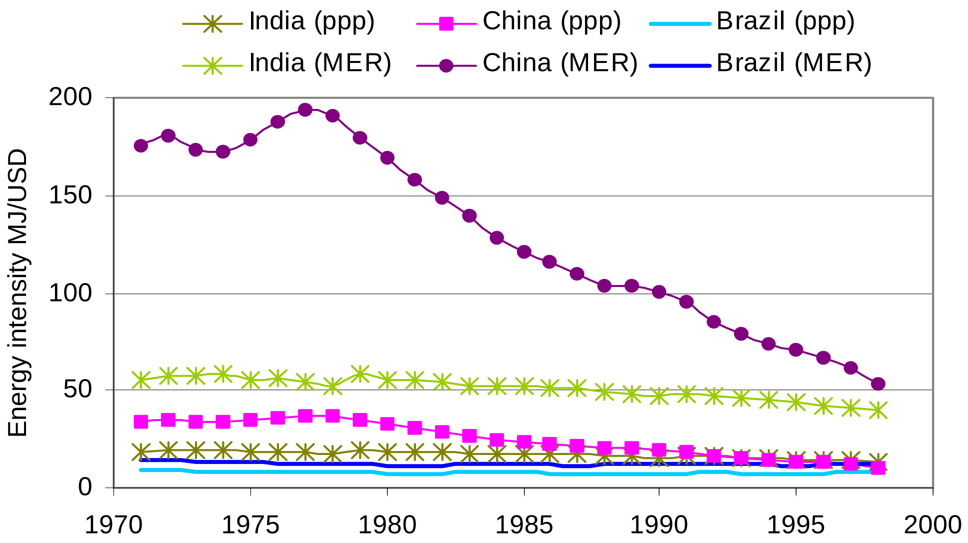
Source: Based on data from IEA (2001).

It is also interesting to analyze trends in energy intensities in developing countries. Here, it becomes particularly important to distinguish between market exchange rates (MER) and purchasing power-based exchange rates (PPP). PPP rates are developed to reflect the fact that various goods and services are less expensive in the South than in the North. Thus, MERs tend to underestimate actual income levels in the South, and consequently overestimate energy intensities. We note for instance in the graph below that the PPP-based energy intensity rate for Brazil is roughly in line with corresponding numbers for OECD countries, but the MER based measure is much higher.

We also note that energy intensity in Brazil and India does not fall as rapidly as in the above-mentioned OECD countries/regions. The reason for this may be that developing countries go through a phase of industrialization where heavy industries, infrastructure expansion and so on play – in relative terms – a more important role.

Note that the very high intensity levels in China (in market exchange rates) are largely due to exchange rate levels. It may be interesting to observe that the energy intensity of gasoline, net of taxes, is around 150 MJ/USD.

Figure 2.7. Energy intensity trends in developing countries.



Source: Based on data from IEA (2001).

2.5 Sectorial energy and transportation trends

Finally, we conclude this section on energy and CO_2 trends with a somewhat more disaggregated view. In figure 2.8, we display energy intensity trends in four sectors; transportation, industry, residential sector and households. The intensity is measured as energy use in the sector divided by national GDP.

The following key observations can be made from figure 2.8:

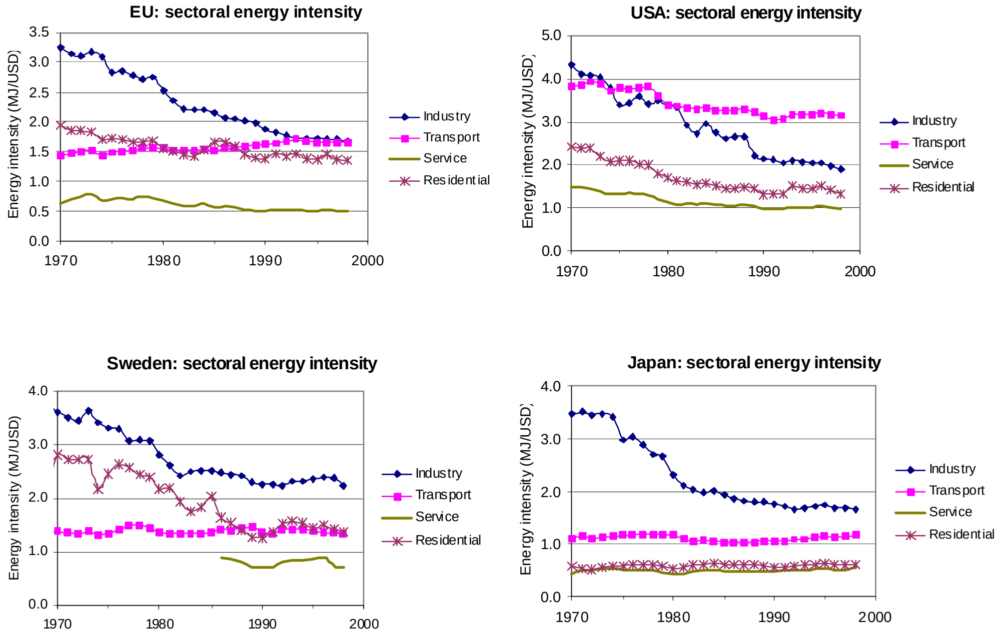
- Industrial energy intensity has declined in all regions rapidly and is currently often at a lower value in absolute terms than in 1970.
- Transport energy intensity has increased in all regions but the US where it fell by some 25 per cent over the years 1970 to 1990. The transportation sector typically grows in line with GDP or even

faster, and technical fuel efficiency improvements are cancelled out by increasing vehicle weight and power ratings.

- Service energy intensity is typically constant or growing.
- Residential energy intensities have typically declined but not as rapidly as manufacturing energy intensities.
- The US has substantially higher intensities than all other countries in all sectors.

Thus, a key observation is that drops in energy intensity that have been observed economy wide, have been prompted by reductions in energy intensities primarily in industry, but in some cases in the residential sector (USA and Sweden) and in the transportation sector (only the US). Unless changes also start to occur in the other sectors, we cannot expect any rapid intensity declines since the relative importance of industry drops over time. It can also be noted that the drop in energy intensity in industry in essentially all countries was much faster during the 70s and 80s than during the 90s.

Figure 2.8. Energy use in different sectors divided by GDP in the EU, Sweden, the US and Japan.



Source: Based on data from IEA (2001).

3 Historical and recent trends in materials decoupling

The previous section focused on one of the most important materials to decouple from economic growth. But CO_2 is only one of hundreds of thousands of different materials that are used today and it is not the only one closely interlinked with the use of energy. Some other emissions like SO_2 and NO_X are also strongly connected to the use of the energy, and some materials like aluminium are related to the energy system since a great deal of energy is needed to process them. Many other materials are not strongly related to the use of energy but it is still very important to decouple them from economic growth, e.g., CFCs. While fuels for energy are used directly and cause immediate emissions, many other materials accumulate in society. Any ambition to appropriately measure material decoupling trends must therefore include a selection of materials and indicators at different points of the materials flow. Therefore we begin this section with a short discussion of the characteristics of the societal turnover of materials before we present the decoupling trends.

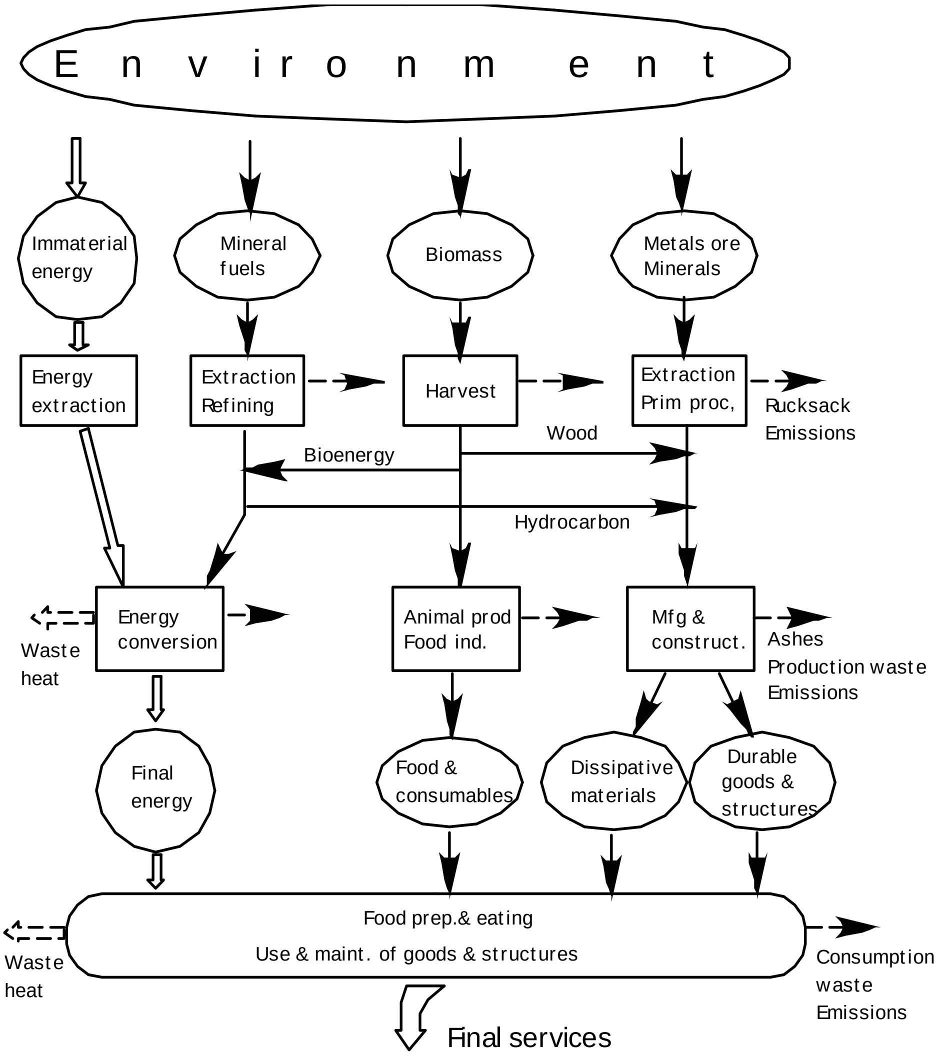
3.1 Materials turnover

In Fig. 3.1 the principal energy and materials resources, processes and products and their interconnections in the technosphere are depicted schematically. The principal intakes of materials are fossil fuels, biomass for food, but also for materials and energy, and minerals and metals for the production of various products. Table 3.1 gives an example of the relative proportions of these flows in today’s industrial society. (Due to the relatively low weight of international trade in the US economy, US data on relative materials use are fairly representative for an industrial country.) The input is dominated by non-renewable resources for energy and constructions.

Table 3.1. Materials intake in the US 1990. Data from Wernick & Ausubel (1995).

Materials	Intake Tg/year	per cent
Energy (fossil fuels, fissile materials)	1961	37.2
Construction minerals	1921	36.5
Industrial minerals	249	4.7
Metals	112	2.1
Biomass, agriculture	757	14.4
Biomass, forestry	260	4.9

Figure 3.1. Schematic illustration of the main categories of materials and energy resources and flows through the economy.



There is in general a big difference between the use of energy and the use of materials. The use of energy is *immediate* and *dissipative*. Energy dissipation means energy quality degradation and less scope for reuse, though there are instances where waste heat is utilized. Concerning the materials balance of energy use, for hydrocarbons or wood burned as fuels, the entire original mass is ultimately dissipated as combustion products or ash. Some energy flows are also immaterial: certain energy supply sources do not involve any materials transformation and translocations, for instance, wind and solar electricity, which implies a considerable decoupling opportunity. (The build-up of the system for extraction and distribution does require both energy and materials, though.)

Concerning materials use, it is the qualities of the materials, be they physical or chemical, that are used and deliver the service. Often this means a *lasting* and *non-dissipative* use, for instance, for materials in buildings and infrastructure and consumer durable goods with decades, centuries, or sometimes even millennia of use. A large proportion of the intake of metals and minerals is used to produce various durable goods. The materials in use are accumulated in stocks of artefacts and in many cases they can be recycled after use due to the non-dissipative character of the use.

Not all the goods produced are long lasting. A considerable proportion of the materials production in society is used either dissipatively or contained in short-lived products. The chemicals produced are to a large extent not embodied in consumer durables but used dissipatively in the production processes, for instance, cooking and bleaching chemicals in the paper industry. In addition, modern agriculture involves large dissipative flows of supplied chemical compounds, for instance, fertilizers and pesticides. Packaging materials represent another important category. These materials are used within a short time span and then wasted.

Food is also used immediately and dissipatively. In energy terms, and given the requirement of a decent, healthy and active life, the need for food is strongly connected to the number of people. The use of resources, i.e., the necessary primary biomass harvest, is, however, strongly dependent on the specific diet composition and the efficiency of the agricultural system constituting the food supply.

If one reflects on the fate of all the materials extracted from the environment, it is easy to see that only a small fraction is actually embodied in durable goods such as buildings or vehicles. A very large fraction of the mass of materials taken from mines, as coal or metal ores, is discarded immediately as overburden or subsequently as concentration waste in the first stage of processing. In the case of metals, a further fraction of the original mass is discarded as slag – a mixture of oxides of light metals – or lost to the atmosphere as oxides of carbon or sulphur during the reduction process. This part of societal metabolism has been named the rucksack or hidden flows. This category also includes excavations and dredgings, and flows due to erosion from biomass production and harvest (Schmidt-Bleek, 1994).

For materials use, therefore, not only the flows and emissions, but also stocks and waste, are of interest. This means that it is important to have different indicators for the decoupling of these materials, e.g., the material intake, the growth of the stock of materials, emissions and waste.

We will next highlight some trends from intake to waste in the materials turnover in society. The focus is on industrialized countries.

3.2 Materials intake

The trends in the total *intake* of materials within the EU-15 countries in recent years are shown in Fig 3.2. Although a slight decrease can be noted in the materials intake per capita (i.e., $m*u$ in Fig. 1.2) on the aggregated EU-15 level, there is more divergence in the different countries. An increase is seen in the countries with the lowest GDP per capita. This near constancy in materials intake means that the increase in economic activity (u) has been more or less cancelled out by an equal decoupling or decrease in materials intensity (m).

Figure 3.2. The development of the direct materials intake (DMI) and GDP per capita for different countries within the EU-15 between 1988 (left) and 1997 (right). (After Bringezu and Schütz 2001). In the DMI measure, the hidden flows are excluded.

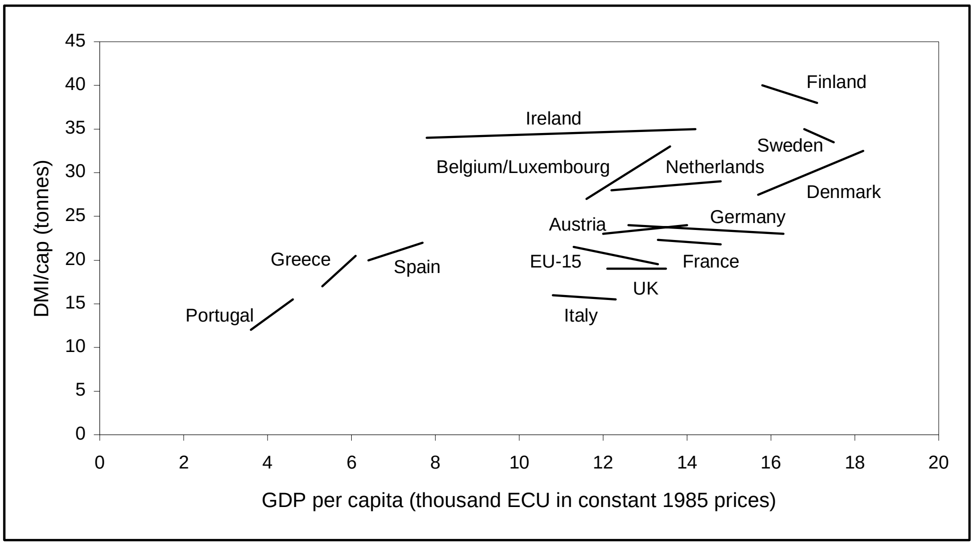
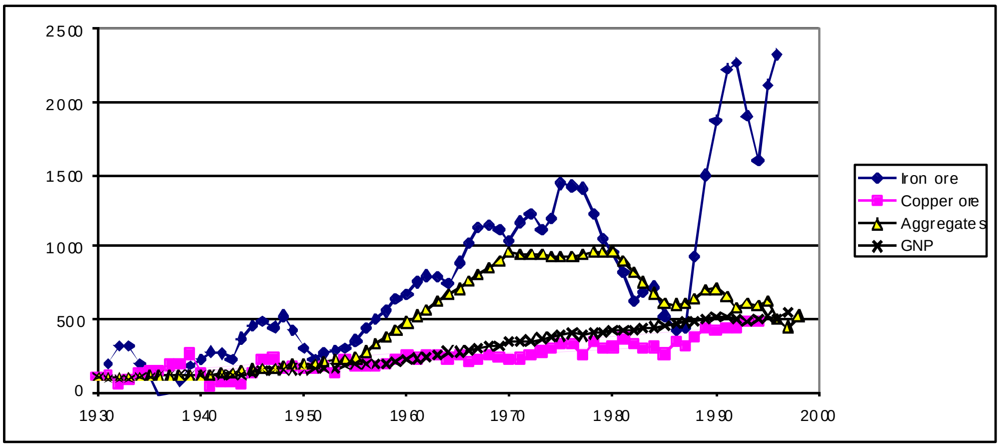


Figure 3.3 gives the extraction of some raw materials in Sweden over the years 1930 to 1997. For aggregates (sand, gravel and crushed stone) there is a clear maximum in the total intake, or $M = m * u * P$, in the seventies and then a decline, clearly corresponding to phases of the expansion and investments in infrastructure and housing. The materials intensity, *m*, thus grew until 1970, and has thereafter deceased. The Swedish mining of some metal ores, which is also given in the figure shows no sign of a general decline. It should be noted that for mining of metal ores in small countries, the country-specific situation and the trade balance are of very considerable importance.

Figure 3.3. The extraction of some primary minerals in Sweden 1930 to 1997. Index 1930 = 100.



For the use of single materials, there are different trends, as shown in Fig. 3.4, which depict the situation in the US. The materials intensity *m* of "older" materials such as many of the well-known metals tends to stagnate or even decrease. The use of new materials such as plastics (from fossil fuels) and the modern metal aluminium increases faster, even faster than GDP (for Al only up to 1970), that is, the materials intensity *m* increases.

Figure 3.4. The intensity of materials use *m* in the United States from 1900 to 1990. Production data (kg) divided by GDP in constant dollars. Index 1940 = 1. After Wernick et al. (1996).

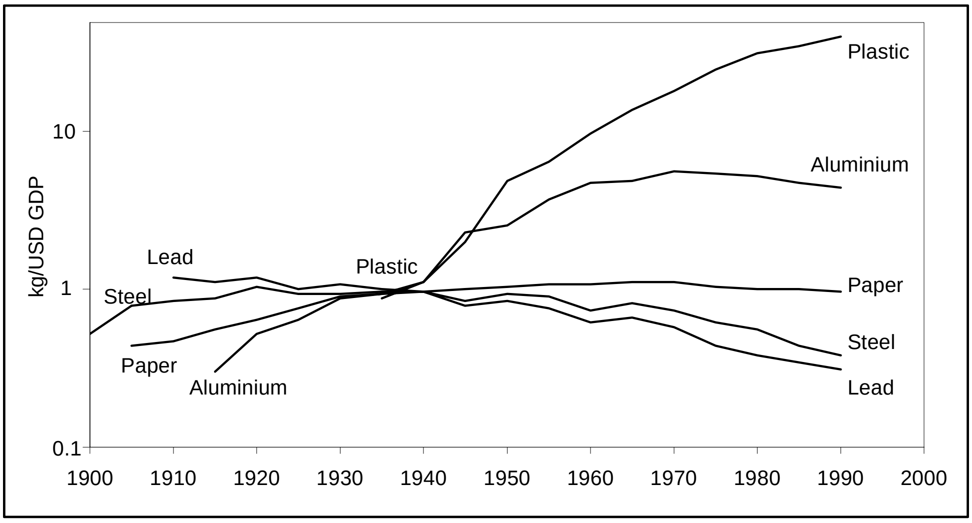
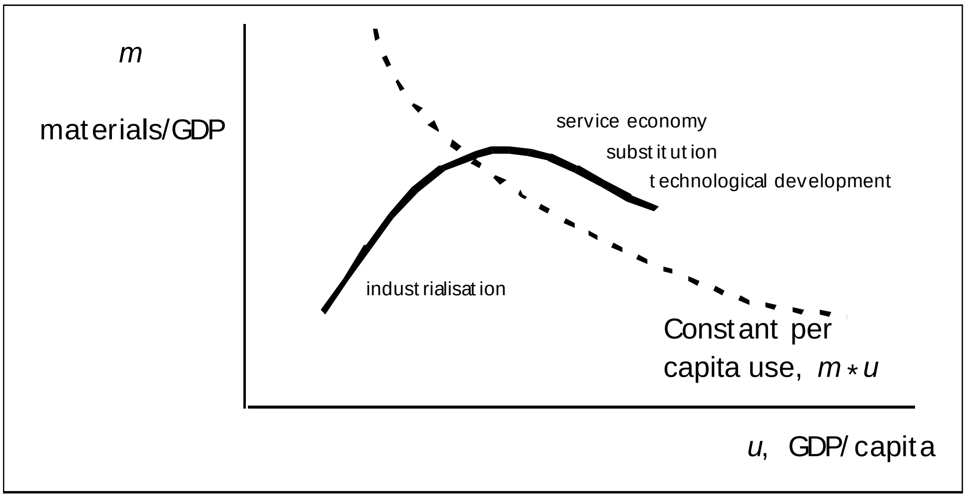


Figure 3.5. Schematic representation of the intensity of use for both iron/steel and non-iron metals. Materials use (bold line) tends to increase with rising income and then level off towards a constant per capita use (dashed line). After van Vuuren et al (1999).

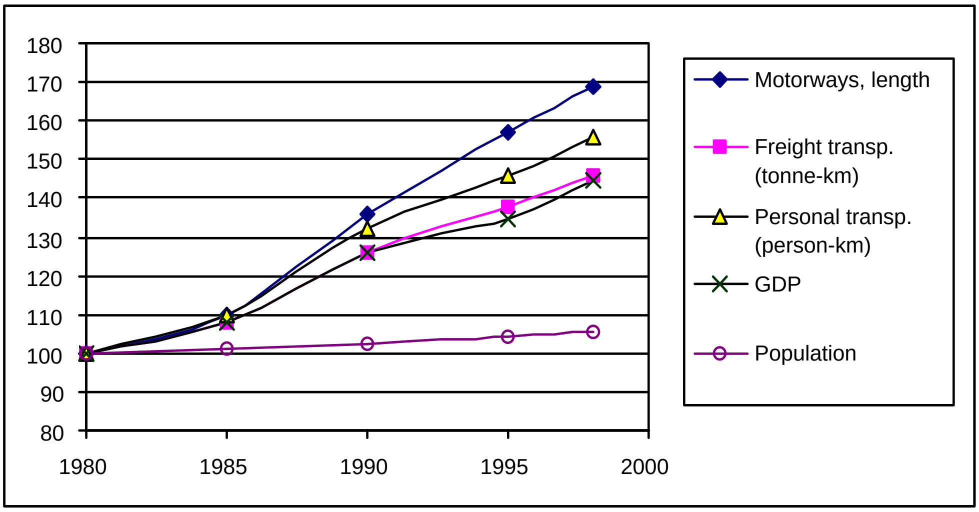


The long-term trends in the consumption of different common metals in different regions and countries of the world have been analyzed by van Vuuren et al. 1999. For iron, the dominating metal in societal use, they identified a consumption pattern tending towards a constant per capita consumption (constant $m*u$) as income increases, see Fig. 3.5. They also found a similar pattern in an aggregated measure of non-iron metals.

There are several suggestions for the cause of the levelling off of the demand: structural changes in demand in industrial society as incomes increase; substitution of other materials; and technical and materials development leading to more service produced with less materials. Concerning the last suggestion, there has been a continuous development in Swedish steel production towards higher *quality* of the produced steel in the last few decades. This development has allowed the amount of produced “steel service”, measured as steel quantity times a steel quality factor, to increase, while the produced quantity (tons of steel per year) has stagnated (Wackinger 2001). A natural question is whether this tendency towards higher quality materials, counteracting increases in quantity, can continue for long. The plausibility of a future revival of quantitative growth in demand, when the scope for qualitative improvements has been exhausted, has been put forward (McSweeney & Hirosaka 1991). This would suggest an N-shaped pattern in growth of demand over time, that is, increase – levelling off – increase.

Where are all the extracted materials going? As was shown in Table 3.1, the dominating input in industrialized countries is materials for buildings and infrastructure and fuels for energy purposes together with the biological harvest in agriculture and forestry. As already noted, the organic material in fuels and harvested biomass is to large extent used and dissipated immediately or within a short time span and therefore the main mass of these flows is quickly emitted as water and carbon dioxide.

Figure 3.6. Indicators for the development within the transportation sector in EU-15 over the last 20 years. Index 1980 = 100. Data from EEA (2001).



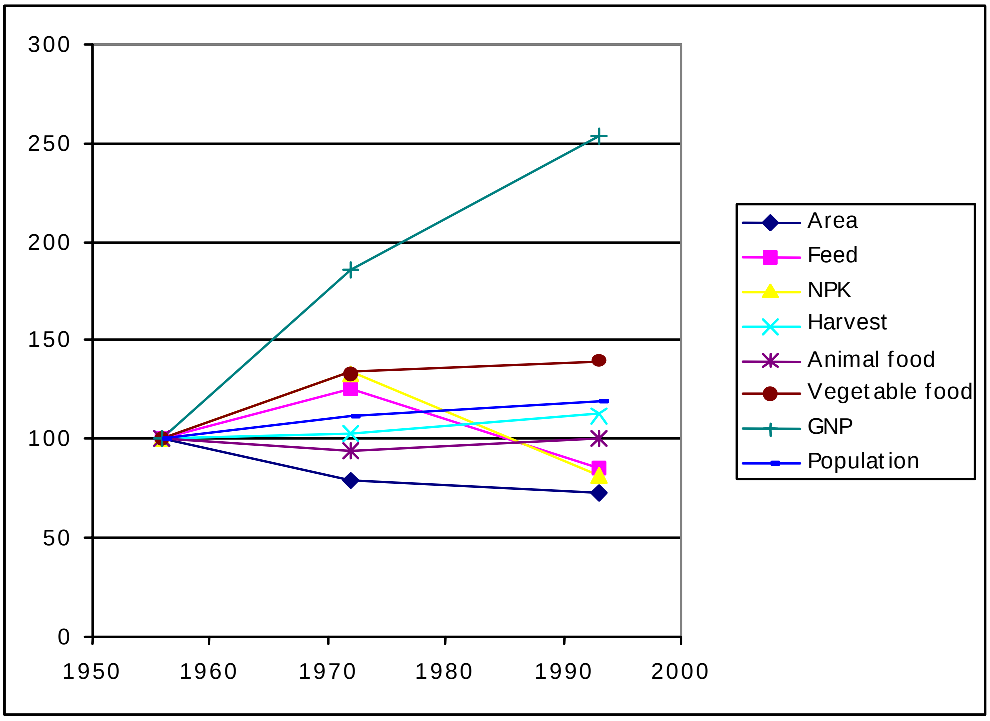
Infrastructure and buildings have a long life-span and the materials input to these sectors is to a large extent still *accumulating*. According to Bringezu (2002), the net additions to the societal materials stock in EU-15 are about eight times larger than the outflow from the societal stock in the form of landfilled waste. Various measures of the trends in activity in these sectors as well as the changes of the stock itself also point to a "necessity" for increased stocks. For instance, transportation activity, measured as total person-kilometres and ton-kilometres per year, as well as the stock of motorways, has increased within EU-15 at the same rate as GDP or faster in the last 20 years (Fig 3.6). The number of persons per households has simultaneously continued to decrease implying an increased demand for housing (EEA 2001).

The recent structural shifts in consumption in EU-15 have led to increased shares of less basic consumption such as transportation and tourism and a substitution for basic needs such as food and housing (EEA 2001). The overall implications for materials decoupling of these shifts in consumption are not clear though. New consumption can be both more intensive and less intensive in materials intensity in comparison to total consumption.

3.3 Biomass intake

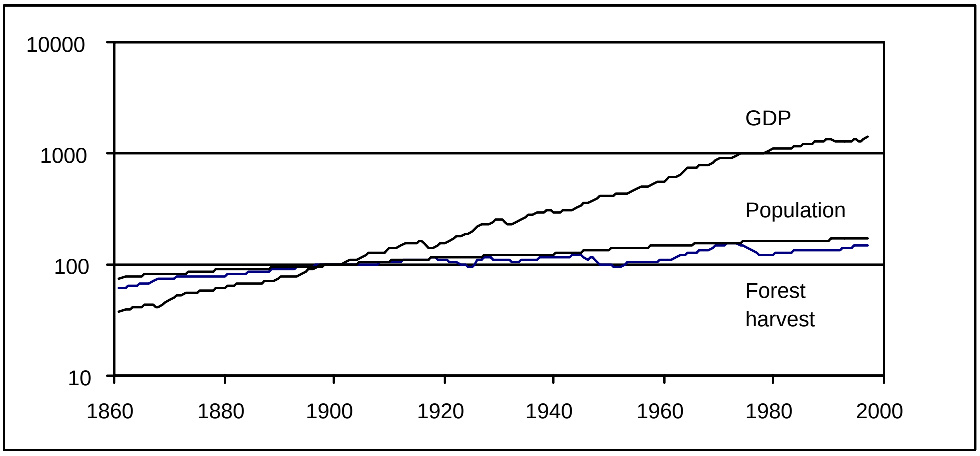
The main harvest of biomass occurs in agriculture and forestry. Figure 3.7 illustrates the decoupling trends in the Swedish agricultural system between 1956 and 1993. During this period, the input of cultivated land area, fertilizers, and imported feed, has decreased in absolute terms, and therefore was strongly decoupled from economic growth. The output in the form of total harvest, animal food and vegetable food has been constant or increased, but not as much as GDP. It should also be noted that during the period there was a trend shift for the input of fertilizers and imported feed to the Swedish agricultural system. These inputs increased between 1953 and 1972, but then decreased more between 1972 and 1993.

Figure 3.7. Indicators of the Swedish agriculture system 1956, 1972 and 1993. Index 1956 = 100. Data from Uhlin (1999).



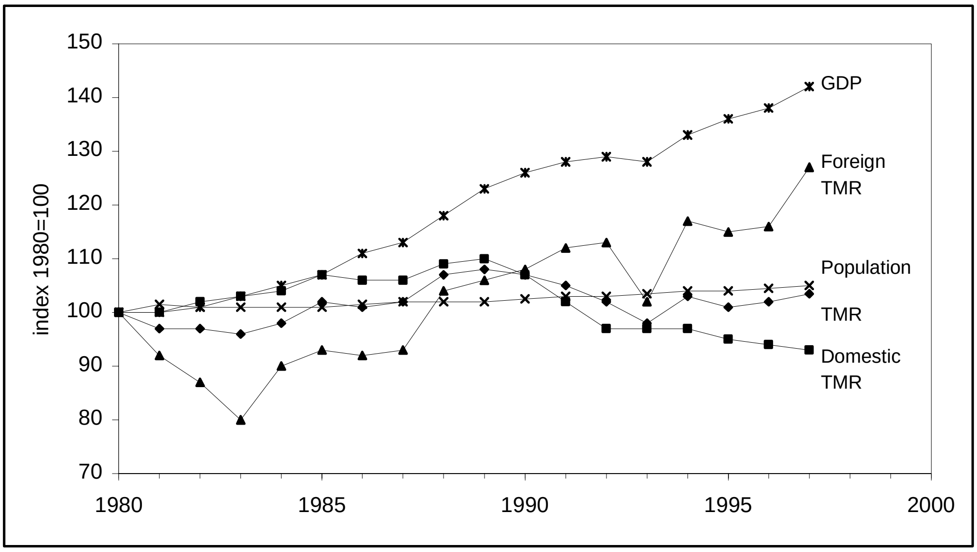
The per capita harvest of forest products in Sweden has been relatively constant since the latter half of the nineteenth century, see Fig. 3.8. Consequently, the harvest has not followed the dramatic increase in GDP during this period.

Figure 3.8. The materials intake in the form of forest harvest in Sweden 1861 to 1997. Index 1900 = 100.



3.4 Rucksack

Figure 3.9. The development of the domestic and foreign total materials requirements (TMR) in the European Union 1980 to 1997. Index 1980 = 100. Foreign TMR is the total materials requirement abroad due to import of materials. Adapted form Bringezu (2002).

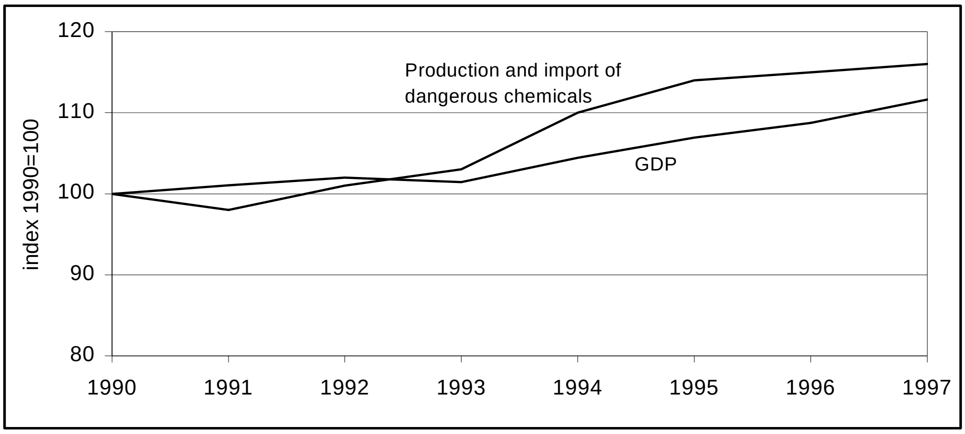


The extraction of materials induces materials flows that are not part of the intake of (useful) materials. This rucksack is mainly connected to extraction of fossil coal, low grade metals and some important minerals like phosphorus. The total materials requirement, defined as the direct materials intake plus the rucksack, has recently been investigated for a number of industrialized countries, for instance Adriaanse et al, 1997. The results show no clear trend of changes in the absolute measure. Thus, decreases in total materials intensity *m* have been more or less out-weighted by increases in the service produced, *u*. This is illustrated in Fig. 3.9, which concerns the recent development in the European Union. However, the figure also shows that in later years there has been a tendency for increased “outsourcing” of the rucksack to countries outside the EU.

3.5 Chemicals

An important fraction of the materials taken into society is transformed into various chemicals. The use of hazardous chemicals (fuels excluded) is about 8 kg per capita each day in Sweden. This is equivalent to around 2.8 tonnes per capita per year. The use of hazardous chemicals per capita in Sweden has been roughly constant in recent years. The growth of production and import of dangerous chemicals in EU-15 is about the same as or higher than economic growth, see Fig. 3.10.

Figure 3.10. Trends in production and import of dangerous chemicals within EU-15, 1990-1997. Adapted from EEA (2001).



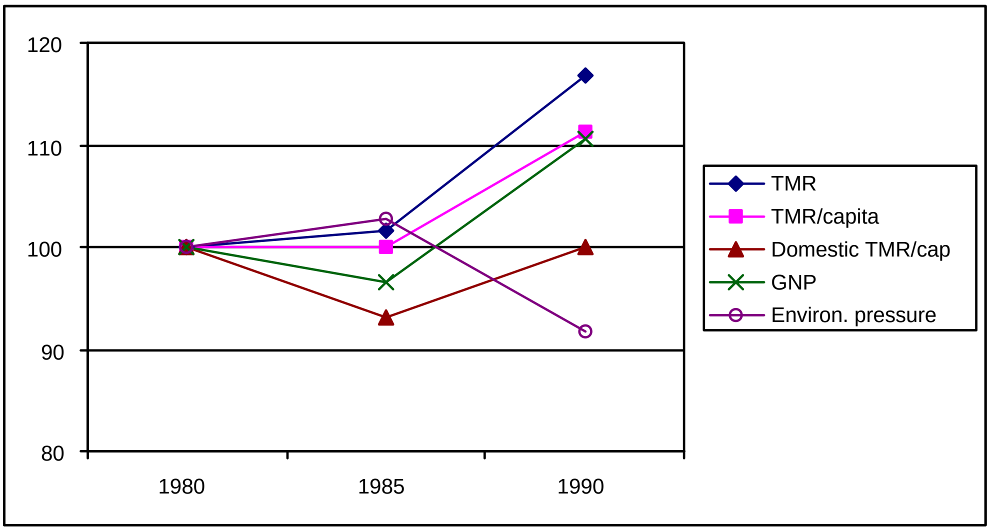
Chemicals can be embedded in products, e.g., softener in plastics, but large amounts of them meet another fate. They are used in various production processes without being incorporated in the product, e.g., solvents, or they are used in a dissipative way, for instance as pesticides in agriculture.

For example, sulphur is a major industrial input, mainly in the form of sulphuric acid. Yet virtually no sulphur is incorporated in any durable good, and very little is embodied in any consumer product. One exception, which accounts for a very small fraction of all industrial sulphur, ends up in the form of sulfonates, in certain detergents and pesticides. Another is sulphur in tyres. Virtually all the rest is discarded in some sort of industrial waste. Chlorine is another case in point. Less than half of all the chlorine produced each year is embodied in any finished goods – mostly in the form of the plastic PVC, and to a lesser extent in the form of chlorinated solvents.

3.6 Emissions

Trends in the materials intake to society, though more or less directly an indicator of the resource use, are often not good indicators of what comes out in the form of detrimental emissions to air and water. Figure 3.11 illustrates this by showing some recent trends in The Netherlands. While the intake plus rucksack has increased, an indicator for the aggregated emissions has decreased during the actual time period.

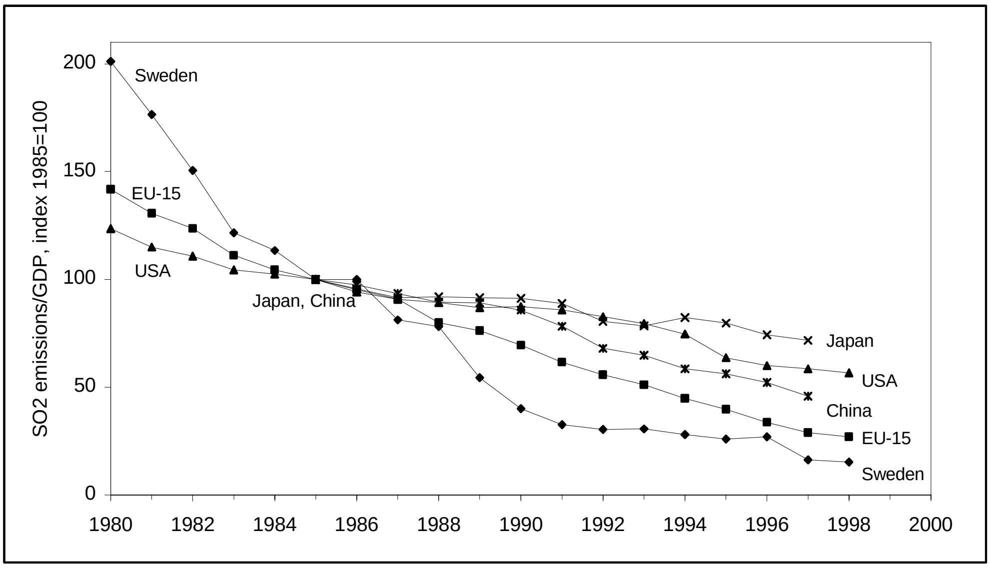
Figure 3.11. Total Materials Requirement (TMR) (exclusive of water) and Environmental Pressure weighted by sustainability levels for The Netherlands (1980 = 100). From Holmberg and Karlsson (2001). Data from Adriaanse (1993), Adriaanse et al. (1997).



While the materials intake in developed countries has continued on a high level, many production processes have been subject to regulation and equipped with end-of-pipe technologies. This has led to reduced emissions in the production of many goods in the developed countries, that is, referring again to Figure 1.2, factor i has decreased.

The emission of acidic substances is a good example. Figure 3.12 depicts the development for sulphur dioxide emissions in various countries and regions. In addition, global emissions of sulphur dioxide have stagnated since the 1980s (Smith et al. 2001). The reduction has been large in Europe and less in the US. Currently, per capita emissions in the EU-15 are less than a third of those in the US.

Figure 3.12. Trends in the emissions of sulphur dioxide in some countries and regions 1980-1998, a) emissions per GDP (Index 1985 = 100), b) annual emissions per capita.
The emission data for USA, EU-15 and Sweden come from EMEP (www.emep.int). The emissions from Japan and China are estimations by Streets et al (2000), using IEA energy-use data.



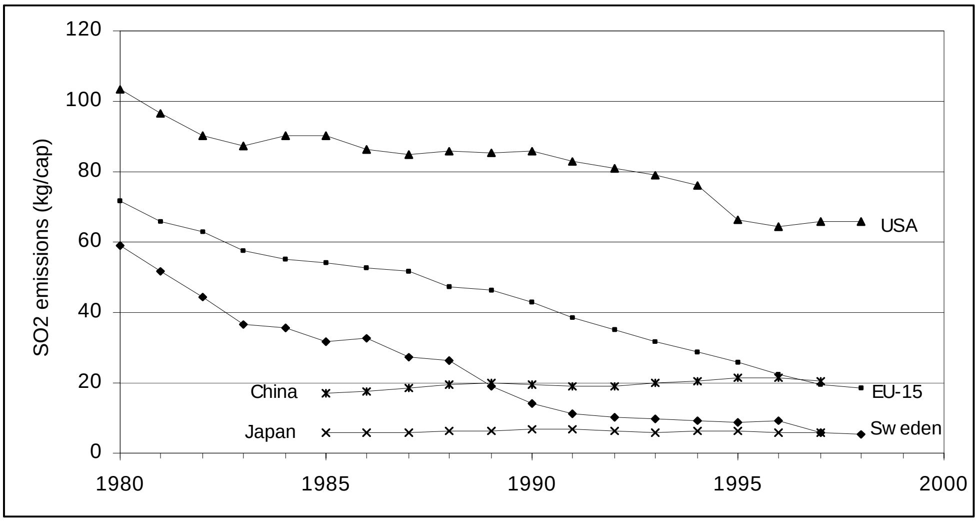
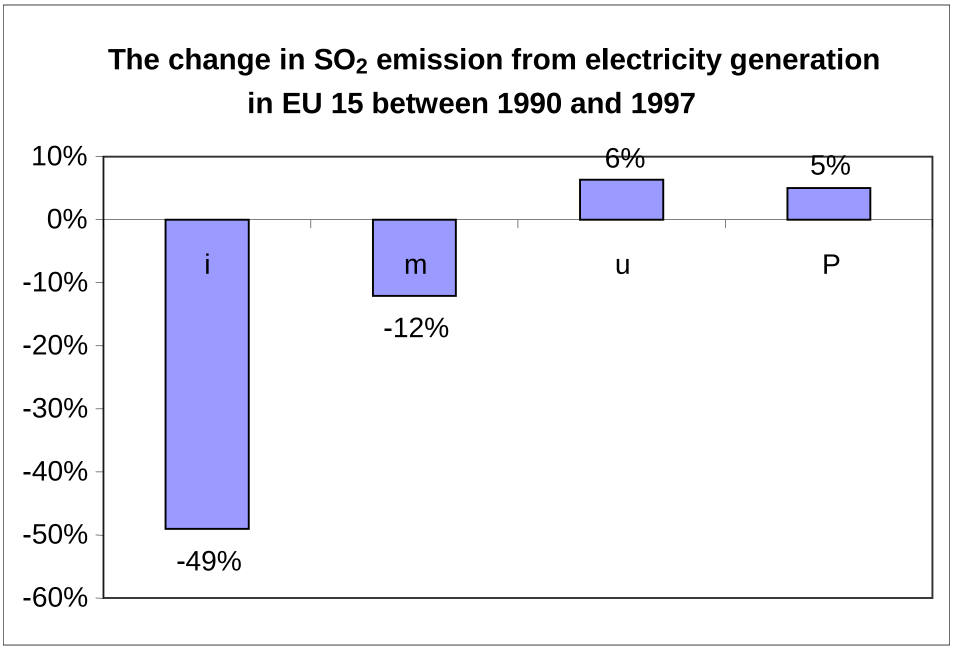


Figure 3.13 shows a decomposition of the decrease of SO_2 emission from electricity generation in Europe. During the period 1990 to 1997, the population *P* has increased by 5 per cent, and the GDP per capita, *u*, has increased by 6 per cent. Factor *m*, measured as fossil fuels for electricity generation over GDP, has decreased by 12 per cent. This factor includes aspects such as increased use of electricity, increased efficiency in the electricity generation and substitution of fossil fuel with renewable and nuclear energy. The main change though, a 49 per-cent decrease, has occurred in factor *i*, which represents SO_2 emissions from fossil fuels for electricity generation. The main reason is that there has been a switch towards fossil fuels containing less sulphur per energy unit and increased implementation of fuel gas desulphurization. It is clear from the figure that the policy measures directed at decreasing SO_2 emissions per fossil fuel input have had the greatest impact for the total decoupling of SO_2 emissions from economic growth.

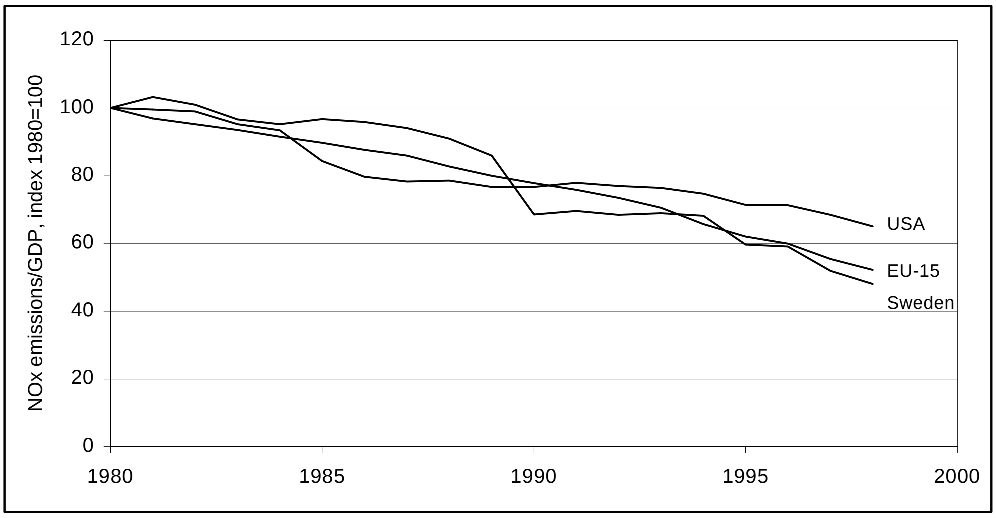
Figure 3.13. The change in SO_2 emission from electricity generation in EU-15 between 1990 and 1997. The total change of –50 per cent is decomposed into the four factors in the *imup*-equation, described in Section 1.

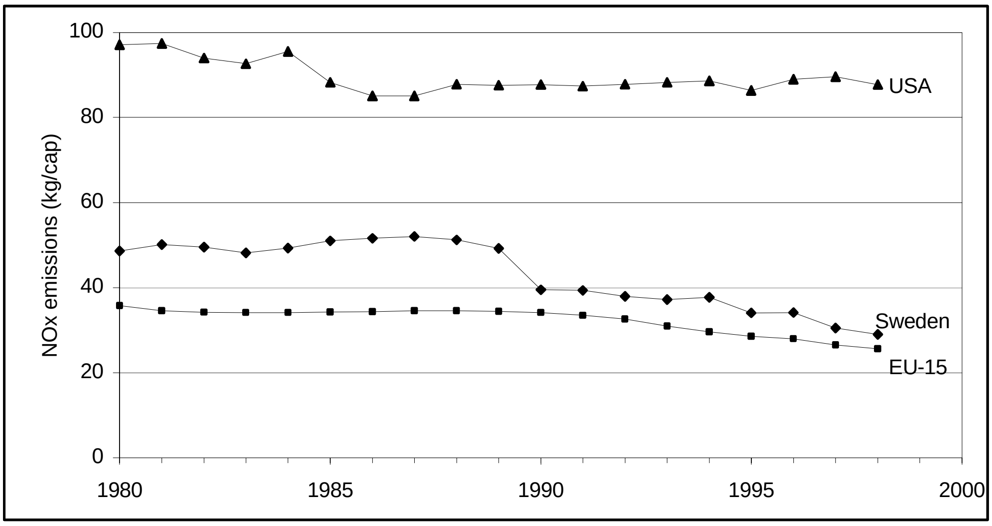


Also the emission of nitrogen oxides has decreased in industrialized countries in the last two decades, see Fig. 3.14. The decrease has generally been considerably smaller than for sulphur dioxide.

Though the production emissions in many cases have been successfully decreased, the intake of materials into society is continuing. A proportion of the materials taken into society are built into different consumed products, which possibly gives rise to emissions in the consumption phase. In general, these consumption emissions have not shown a similar trend of large decreases as emissions from production facilities, see Fig 3.15 for the example of chromium in Sweden.

Figure 3.14. Trends in the emissions of nitrogen oxides in some countries and regions 1980-1998, a) emissions per GDP (Index 1980 = 100), b) annual emissions per capita.
The emission data come from EMEP (www.emep.int).





Depending on the specific products and their use, there may be huge differences in emission patterns and environmental impact in the consumption phase. Table 3.2 shows an estimate of the stock of copper in Stockholm and the emissions from this stock. Many durable products, and thus a large share of the societal stock of materials, are however sheltered from degrading in the use phase. Some uses are inherently dissipative in that they are such that materials losses are a part of the functioning of the product. Emissions in the consumption phase may also be due to wear and corrosion of the stock and accidents. These emissions are basically proportional to the actual stock and not the through-flow of the material. Decreasing the intake through recycling of the used products will then not change this relation and thus not necessarily lead to any decoupling of the emissions.

Figure 3.15. Emissions of chromium from the production and the consumption of goods containing chromium, inclusive of emissions from incineration and leakage from waste deposits. Adapted from Anderberg et al. (1989).

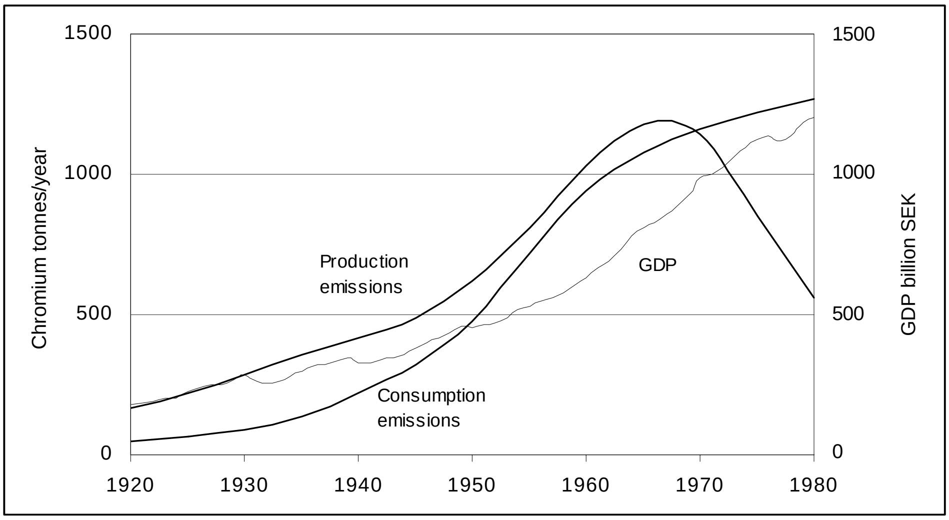


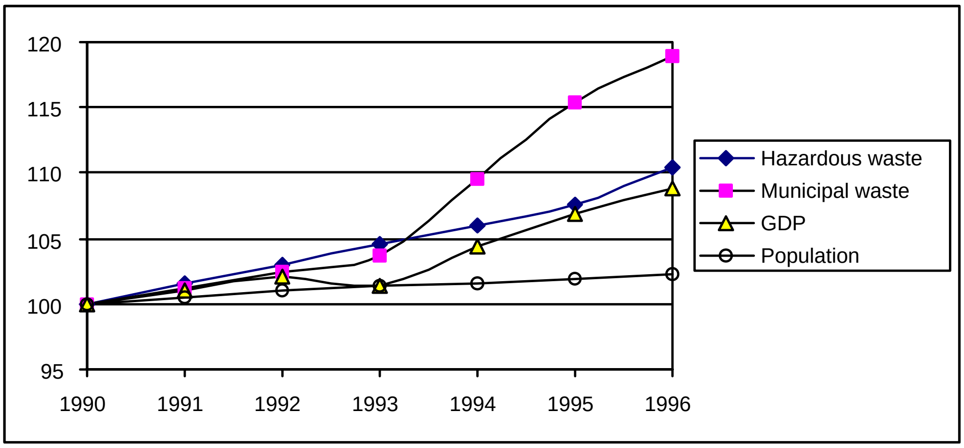
Table 3.2. Emissions of copper from Cu-containing goods in Stockholm. From Sörme et al. (2001).

Goods containing copper	Stock of copper (ton)	Exposed part of the stock (ton)	Emission of copper (kg yr^{-1})
Heavy electrical equipment	50,000	Negligible	Negligible
Power cable, buildings, public and industry	28,000	Negligible	Negligible
Brass	22,000	14,000	Potential
Tap water system	6,500	6,500	4,300
Telephone cables	4,200	Negligible	Negligible
Roofs	4,200	4,200	1,200
Cars	3,100	1,200	Potential
Consumer electronics	2,700	Negligible	Negligible
Electronics, TVs, VCRs, PCs	970	Negligible	Negligible
Wood preservative	570	570	Potential
Telephone stations	500	Negligible	Negligible
Electrical grounding	430	430	40-900
Aerial lines	200	200	1,200
Protection painting, boats	16	16	700
Asphalt wear	?		400
Brake linings	?		3,900
Tyres	?		200

3.7 Waste and recycling

Municipal waste as well as hazardous waste generated within the EU-15 has increased in recent years, as shown in Fig. 3.16. The growth has been larger than the increase in population, leading to an increased waste generation per person ($m*u$). It has also been higher than economic growth. Landfilling has however been more or less constant or has slowly decreased in absolute measures (EEA 2001).

Figure 3.16. Trends in the generation of municipal and hazardous waste in the EU 1990-1997. (Index 1990 = 100.) Data from EEA (2001).



4 Policy recommendation and some reflections on decoupling

This report has presented and analyzed various decoupling trends in Sweden, the EU, Japan, US, Brazil, China and India over the past 10-40 years. Sometimes an even longer time perspective has been taken. Here we present some concluding remarks and policy recommendations.

4.1 Some reflections on decoupling

Absolute versus relative decoupling

Decoupling is a multifaceted concept: it is sometimes measured as total materials flows and sometimes the focus is put on specific compounds; sometimes it is measured in absolute terms (in kg) sometimes in relative terms (e.g., in relation to GDP, value added or kg per capita).

All too often, it is claimed that progress is being made on the basis of emissions of specific compounds falling in relation to GDP. However, it is the actual emissions that matter, and they will increase as GDP grows faster than the emissions-to-GDP ratio drops. Therefore focus should be on trends in absolute terms. This was also the main conclusion in the Swedish official report "Efficient use of natural resources" (SOU 2001).

This latter observation is particularly important when it is observed that significant decoupling has taken place in certain sectors: although such trends are positive, one should be careful not to extrapolate this into a belief that an overall decoupling has taken place.

Similarly, what happens to overall material flows is less relevant than what happens to specific material flows, or even specific emissions. Rather than stating that total material flows are increasing or decreasing, we should ask ourselves what happens to specific flows that cause concern: are CO_2 emissions, dioxin releases, or Cu releases on the rise or are they under control? Overall measures of decoupling may conceal rather than highlight critical trends in the societal use of energy and materials.

Decoupling has taken place in some sectors (e.g., CFC emissions), whereas progress has been sluggish in others – most noticeably CO_2 emissions. Thus, it is not possible to offer a general answer to whether decoupling takes place or not, and since it is specific environmental problems that are cause for concern, focus should be on them rather than on decoupling in general.

Increased decoupling of CO_2 required

Currently, CO_2 emissions are increasing in most countries of the world. The increase is primarily driven by an increase in income per capita and population. Counteracting factors include an ongoing reduction in energy use per unit of economic output and emissions per unit of energy, although it should be recognized that these are also operating at too slow a rate in most countries of the world. In many countries these factors even work in the wrong direction.

In order to bring down emissions, we need primarily to reduce energy supplies (by improving efficiency, structural changes and limiting population growth) and to reduce CO_2 emissions per unit of energy. This could be achieved through the use of CO_2-neutral energy technologies or through carbon sequestration from the combustion of fossil fuels, or biomass, which would actually lead to negative emissions, see Obersteiner et al. (2001). See World Energy Agency for a detailed analysis of current and future options to curtail the emissions (WEA 2002).

The rates of change that we have seen in most countries over the past forty years are far too low to make it possible to meet the climate targets set by the Swedish government. However, such targets are technically and economically feasible to meet, as has been shown by several modelling groups (see e.g., work by Azar et al 2002, and Azar & Schneider, 2002, and references therein).

Dynamics in societal materials use

The discussion on decoupling of material flows is more complicated than the discussion on energy and CO_2. Many materials accumulate in society, which means that it is possible to have different indicators for the decoupling of these materials, e.g., the materials intake, the growth of the stock of materials, emissions and waste. Another important issue is that there are many different types materials used in society and they have different characteristics.

When analyzing decoupling trends, focus is often on the intake (or extraction) of materials. We have noted that intake is on the increase in most cases. However, if the intake leads to an increase in the valuable stock of materials in society, this is not necessarily a problem. It is not the stock of resources in society *per se* that is a problem, it is the leakage of materials from specific uses to the environment that is the key cause for concern, e.g., copper emissions from brake linings. This does not imply that the rate of intake is unimportant but that more focus should be on dissipative uses. One implication of this might be that an "acupunctural strategy" focusing on specific measures and uses rather than general measures against whole classes of materials is required.

Another interesting observation is that although the use of many materials is still increasing, it is reasonable to assume that societies will be more saturated with materials in the future. What will happen when this increase levels off? One important aspect is that the share of recycled materials will increase. If we take the Swedish aluminium system as an example, we have shown that the share of recycled aluminium in production will increase from today’s 41 per cent to 63 per cent if the annual growth of production decreases from today’s 5 per cent/yr to 1 per cent/yr and if there is no adaptation as a result of changes in export and import. This will happen without any increase of collection of scrap, etc. It is just due to the decreased growth (Holmberg 2002).

What will happen if a greater proportion of the societal intake of materials comes from recycled materials? Will these recycled materials be of a sufficiently high quality to replace primary materials? This is an important question for the future. How can the material flow quality of recycled materials be safeguarded? We have studied that question for the Swedish aluminium system (Holmberg et al. 2001a). In our study, we found that the material flow quality of the recycled aluminium, measured as the necessary dilution with primary aluminium to produce new alloys, tends to decrease when the material quality (for instance the tensile strength) increases. There is an ongoing ambition to increase the material quality by developing new aluminium alloys. This means that the material flow quality will decrease over time in the aluminium system, i.e., the resmelted aluminium will be more difficult to recycle into valuable products. If we combine this fact with the prediction that there will be relatively more recycled aluminium available in the future, we can conclude that there will be an increased demand for *material flow quality management*. Even if this example is for aluminium, it is reasonable to believe that the conclusion also holds for many other materials. In order to prepare for this future situation, it is important to introduce well-functioning material labelling systems and standards, which can help to avoid unwanted mixing and therefore facilitate the management of the material flow quality.

Interlinked material flows

When trying to increase the sustainability of materials use, it is important to note that certain materials are mined as by-products. This means that an increased use of a certain product might make certain scarce and potentially harmful elements more available, which in turn might make them less expensive and therefore used in wasteful forms. For this reason, the aim should not always be to phase out specific elements, but to phase out their use in specific applications.

We may consider cadmium as an example. The current objective is to heavily regulate, or even phase out the use of cadmium. But cadmium is mined as a by-product of zinc, and if OECD countries phase out cadmium, the price of it will drop and this might result in dissipative uses in non-OECD countries. However, if cadmium to a large extent is used in solar cells made of cadmium telluride, its value would increase and more wasteful uses would decrease. This could be referred to as a soak-up strategy, and it could also be applied to other flows. From an environmental perspective, this could be beneficial since it could provide an incentive to reduce the leakage to nature of a toxic metal. Cadmium-telluride solar cells and/or large nickel-cadmium batteries could thus sequester cadmium that is extracted from zinc ore and that otherwise would have been emitted, left on a waste dump or used in short-lived and non-recyclable products.

It may also be noted in this context that a decision to phase out Cd-Te cells for environmental reasons could have the opposite effect on Cd flows to nature. This could happen if the preferred choice of solar cells were to be copper-indium/gallium-diselenide cells. In order to recover indium for a one watt copper-indium-diselenide cell, one would have to mine an amount of zinc ore that contains about hundred times more cadmium than what would be used in a comparable cadmium-telluride solar cell, the so-called cadmium paradox (Andersson 2001).

The example above highlights the importance of studying how material flows are nested, as well as the importance of analyzing links between energy and materials systems.

It may also be interesting in this context to note that while the use of some materials may have to decrease in the future, a reasonable strategy might be to increase the use of other types of materials, e.g., biomass for energy, silicon for solar cells, light metals in vehicles. Kram et al. (2001) has analyzed the economics of materials substitution as a way of reducing CO_2 emissions.

Bioproductive areas for food, materials and energy

When analyzing decoupling trends, the use of land is all too often neglected. However, there are two strong reasons to believe that bioproductive areas will become more scarce during the course of this century.

First, the demand for food is increasing because of rising incomes and growing populations. Currently, this increased demand has largely been satisfied by increasing yields, e.g., in India, agricultural crop land has remained stable over the past thirty years. In the debate on how to feed a growing population, most focus is put on an expansion of agricultural production, but it is equally important to analyze and understand how to reduce the demand for primary production. There are two main factors that determine this demand: (i) the share of animal food in the diet, and (ii) the efficiency and composition of animal food production. Wirsenius (2000) has shown that there is a potential for substantial improvements in both these factors.

Second, biomass for energy can be expected to play an important role in meeting stringent climate targets. We have already noted how the use of biomass has increased in response to the introduction of a carbon tax in Sweden. A global carbon tax would increase the price of energy and thus the profitability of biomass.

Biomass would largely come from energy plantations, and these are land intensive. An increased profitability for biomass energy might increase competition with food production. Land values, and consequently the price of food, can be expected to increase. Azar & Berndes (1999) have shown that the price of food might more than double if ambitious carbon policies are adopted. This might increase hunger in third world cities, but it might also trigger development in rural areas if they get better paid for their products.

These examples highlight the interrelationship between energy, materials and land, and that equity and land use policies might be required as part of a policy package to deal with climate change. It also shows that more precise measures of environmental impact and economic development than simply an overall dematerialization are required.

4.2 Policies are required

In the literature on economic development and the environment, it is sometimes observed that emissions are reduced in line with economic development – this is referred to as the Environmental Kuznets curve.

However, the existence of such improvements is sometimes misunderstood to imply that economic growth automatically leads to reductions in emissions. In reality, improvements in local air quality or in CFC emissions have generally been brought about as a consequence of specific environmental policies, rather than as a result of general economic development. Similarly, technical solutions to environmental problems are most often triggered by societal debates and eventually regulation. A key example is the strong interest in fuel cells that existing and foreseen legislation in California has prompted.

This implies that we can not expect technology or economic growth to automatically solve present and future environmental problems. This will generally not happen when there are market failures, when property rights are not fully allocated, when there are externalities, public goods or other factors that hinder the market from operating optimally. Rather, policies are required, and these should at least include:

- price incentives (higher prices on emissions via taxes or permit trade systems)
- technology development incentives (R&D and niche markets)
- regulatory measures (e.g., energy efficiency, emissions standards).

Clearly, an exhaustive discussion on environmental policies is beyond the scope of this paper, and more details can be found in Sterner (2002).

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