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ANALYSIS

Projection of energy-intensive material production for bottom–up scenario building

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Abstract

The production growth of energy-intensive commodities in physical terms is an important component of bottom–up emission scenarios and a relevant national circumstance to be incorporated in schemes for differentiating greenhouse gas emission allowances. In this study, average future growth rates of physical production are estimated for various branches of the energy-intensive industry in a wide range of countries.

To this end, historic patterns of growth were analysed on a per capita basis from the 1980s onwards. Per capita production levels of steel, cement, and refinery products tend to level off for all countries as per capita income increases. These stabilisation levels, however, differ by a factor of 10 from country to country. Petrochemical and total paper and board production per capita, on the contrary, keeps on increasing with increasing income, and per capita aluminium production shows a rather weak relationship to income. Aggregated annual growth of physical production of energy-intensive commodities in this time period amounted to 5.9% in low, 1.1% in middle, and 0.8% in high-income countries. Assuming that a country experiences declining growth rates of physical production as its income increases, these aggregated figures may be used to estimate future growth rates. Projections thus based on recent growth trends suggest that earlier estimates may be improved.

Keywords: Greenhouse gas emissions scenarios; Heavy industry; Commodities; Dematerialization; Income; Developing countries

1. Introduction

Recently, the International Panel on Climate Change published its Special Report on Emission Scenarios (Nakicenovic et al., 2000). The scenarios provide a basis for future assessment of climate change and possible response strategies. Covering a wide range of possible demographic, economic, and technological developments, they provide insight into the main driving forces of greenhouse gas and aerosol emissions, which are population and economic growth. These forces are rough indicators of CO_2 emission growth. Driven largely by population and

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economic growth, the SRES scenarios may be characterised as top–down scenarios.

As opposed to top–down, a bottom–up scenario would comprise varying national circumstances that are more directly linked causally to the emission level than population and economic growth. These comprise, for instance, growth of passenger and freight transport, physical production growth in industry, the growth of household appliances, and the growth of power consumption in all sectors of the economy.

Insight in these developments gives a better founded insight in emission trends than insight in population and economic growth alone. In addition, scenarios for the physical production of energy-intensive commodities, on which we focus in this study, may well be more robust than economic scenarios. Economic scenarios span a wide range of possible futures, and uncertainty on future economic growth may be larger than on growth in physical production. This is because the large-scale production of energy-intensive commodities requires substantial investments, which makes it unattractive for a producer to close down part of the production capacity in case of (minor) economic setbacks. Therefore, production in the energy-intensive industry will not fluctuate as the economy as a whole.

In this article, we will address the growth of industrial production in physical terms as an important national circumstance affecting the growth of greenhouse gas emissions. As global industry accounts for over 20% of the total fossil fuel-related CO_2 emissions (IEA, 1997), it is obvious that developments in the growth of the industrial sector, in particular, the energy-intensive subsectors, are highly relevant for evaluating climate policy. These developments may vary substantially over the different world regions and industrial subsectors. In the light of the aspiration to contribute to scenario building in a bottom–up way, our main question may be formulated as follows:

What development trajectories can be projected for the energy-intensive industry in various regions of the world in the coming decades?

Seeking an answer to this question, an obvious source of information would be the wide range of literature that exists on historical material consumption trends. Some of these studies point to a trend of so-called dematerialization for many materials, in particular, steel and nonferrous materials. In the following, we will give an overview of the literature on dematerialization. Next, we will present a method for projecting future production levels of key commodities. We present historical growth rates of per capita production growth of key commodities and use these to estimate future growth rates. As an application, we will compare these with projections for physical production by the World Energy Council. The article ends with a discussion and a number of conclusions.

2. An overview of the dematerialization literature

Over the last few decades, a large body of research has the addressed consumption patterns of main commodities. On the one hand, there are economic analyses, in particular, of metal flows, using either demand or production functions or input–output analysis. On the other hand, a wide range of dematerialization literature exists that analyses material flows as a function of income.

2.1. Economic analyses

Radetzki and Tilton (1990) reviewed several economic approaches to analyse historic metal demand. Economic demand functions, for instance, give demand as a function of price, the price of a substitute, and, possibly, other determinants, such as gross domestic product (GDP). They argue, however, that establishing the relationship between demand and its determinants may be difficult. Moreover, the relationship may not be stationary over time. Considine (1991) models apparent consumption of a number of materials in a perfectly competitive market, as well as their material intensity (the ratio of consumption to GNP). He uses the Divisia index of apparent material consumption, which is measured in value terms and thus allows an estimate of aggregated material consumption. While the Divisia index is a good means to relate products with different economic values, it does not allow adding the environmental impacts of products. Therefore, in studies with environmental focuses, a detailed specification of material flows and subsequent addition thereof using

Divisia aggregation may not provide the right answers to the research question.

One may also specify a production function to study material flows. Studies based on this type of function assess the extent to which they may substitute labour, capital, or other factor inputs. Again, findings depend largely on the specification of the function and on how technological change is accounted for. A third approach (see, e.g., Leontief et al., 1983) involves the use of input–output analysis, in which metal or mineral flows to intermediate and final uses are identified. This method is very suited to obtain a better insight in the mutual interdependencies between different sectors of an economy. Supported by a number of assumptions, it may also be applied to forecast total production of a commodity in an economy.

2.2. The dematerialization hypothesis

Cleveland and Ruth (1999) give an overview of major empirical analyses of dematerialization of national economies as a function of GDP per capita. Many of these studies address intensity of use (I-U). I-U is defined as the consumption of a commodity divided by the gross domestic product. In various studies, the relationship between the I-U and income has been investigated (e.g., IISI, 1972; Malenbaum, 1978; De Bruyn and Opschoor, 1997). Most analyses find support for the hypothesis that I-U, in relation to a country's GDP, increases in the initial stages of development of a country but then tend to fall as income rises, producing an inverted U-shaped function. Malenbaum (1978) did further pioneering work with his study on the intensity of use of metals in a number of major world regions. He found that the intensity of use of most materials in world regions where most of each material is used has been declining over recent decades. Aluminium was the only exception, showing increasing I-U rates. Williams et al. (1987) also came with an influential study in which they empirically demonstrated an inverted-U shape for U.S. consumption over time of steel, cement, paper, ammonia, chlorine, aluminium, and ethylene, although the timing of the curves varied.

Malenbaum (1978) did not claim that I-U should be linked directly to income. Instead, he stated that the relation between income and I-U should be understood from three underlying explanatory factors.

First, the materials demanded by an economy through successive stages of development vary. In the early stages of development, when incomes are low, material requirements are also low, particularly for metals and building materials, because such economies are based largely on unmechanised agriculture. Industrialisation drives an increase in materials demand to build basic infrastructure: roads, railways, bridges, factories, cities, pipelines, power grids, etc. As development continues, the need for basic infrastructure declines, and consumer demand shifts increasingly toward services, which usually are less materials intensive.

Next, technological developments may alter the efficiency with which raw materials are discovered, extracted, processed, distributed, and utilised in production of final goods. This is likely to result in a decrease of the consumption of raw materials over time, although these efficiency gains may act to raise material consumption, following lower prices. Such lower prices for one material following efficiency improvements in production may lead to a substitution for other materials. Therefore, efficiency improvements for one or a limited number of commodities will not necessarily decrease aggregate material production.

Finally, substitutions among raw materials may occur if new alternative materials are introduced that are superior to traditional material in, e.g., price, strength, or weight.

Malenbaum not only came up with the recognition of the inverted-U shape of the curves representing intensity of use as a function of income, he also suggested that these curves might repeat one another in a similar way for different national economies, independent of the period in time. However, changes in the intensity-of-use pattern may occur in a shorter time interval because of technological developments. Larson (1991) elaborated on these repeating patterns. He stated that developing countries might not need to reach the same levels of per capita consumption to achieve an equivalent or higher standard of living.

Note that Malenbaum only addressed the I-U of an economy. He did not make any statements on total material consumption in a growing economy. In this respect, it is good to take note of the distinction made by De Bruyn and Opschoor (1997). They distinguished between 'weak' and 'strong' dematerialisation. A so-called weak dematerialization would entail a drop in material intensity. A strong dematerialization would mean that total material use drops over time in absolute terms.

Bernardini and Galli (1993) summarise the findings in literature as the 'theory of dematerialization'. It comprises two elements:

- The intensity of use of a given material follows the same pattern for all economies, at first increasing with per capita GDP, reaching a maximum at about the same per capita GDP, and eventually declining.
- The maximum intensity of use declines the later in time it is attained by a given economy.

Since these elements have not been derived from first principles, but are based on empirics, we prefer to refer to the hypothesis of dematerialization instead of the theory of dematerialization. The two elements of the hypothesis are illustrated in a figurative way in Fig. 1. It must be stressed that the hypothesis applies to single materials only. It should not be used to explain the overall material intensity of GDP. There is abundant evidence of dematerialization trends in single products, especially metals, but this effect may well be counterbalanced by a substitution of alternative materials or by an increase in the number of products consumed. Indeed, Considine (1991) distinguished between an aggregate material trend and trends for single materials in the United States

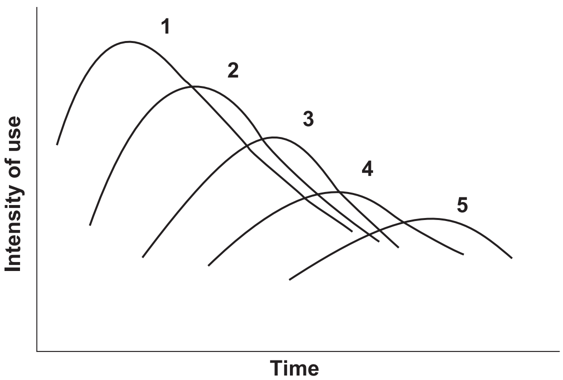

Fig. 1. Figurative description of the theory of dematerialization (Bernardini and Galli, 1993). Reprinted from Futures, May 1993 (p. 436), with permission from Elsevier Science.

from 1960 to 1985. While the aggregated materials I-U showed no overall trend, the I-U for steel and aluminium declined. At the same time, the I-U for plastics and copper increased. Additional opposing arguments to the theory of dematerialization were collected by Cleveland and Ruth (1999), who designate it as a tentative hypothesis about the relation between income and material (and energy) throughput, for which the quality and quantity of evidence fall short, as thorough statistical testing is lacking.

2.3. Application of the hypothesis of dematerialization for projections

The hypothesis of dematerialization provides an attractive framework to describe long-term trends in the intensity of use of material consumption, its main appeal being its simplicity. We wish to proceed along the line of considering income in the study of material flows. An example of the application of the hypothesis applied for a better estimation of future trends is given by van Vuuren et al. (1999). In their model study on future metal consumption, the authors assume that current low-income regions will follow a more or less similar path in terms of intensity of use to what high-income regions followed earlier. In this study, the authors, however, also pointed at some empirical evidence that contradicts the hypothesis. The historical trend of metal consumption in the United States and most other regions follow an inverted-U shape quite well. However, they found that a number of regions deviated from this pattern. In Eastern Europe and the former Soviet Union, no initial upward trend in the intensity of use could be distinguished. In these regions, heavy industry played an important role, resulting in a high metal consumption that collapsed as soon as economic restructuring began around 1990. In the Middle East, the intensity of use has always been much lower than in other parts of the world, which can be explained by the high national income accumulated by the oil exports. In Latin America, the intensity of use has been low as well. Here, monetary data were distorted by high inflation rates, whereas the high foreign debt may have prevented the development of (heavy) industries.

There is another indication that the insights offered by the hypothesis are mostly of a qualitative nature. Bernardini and Galli (1993) state that Malenbaum's

(1978) intensity-of-use forecasts of the world demand for 12 metals turned out to be an overestimate by, on average, 54% in 1985.

It is also good to take note of the findings of De Bruyn and Opschoor (1997). They constructed a throughput indicator, in which they combined the aggregated throughput of material, energy, and the volume of transport. After a long period in which this indicator turned out to delink from GDP, several Western European countries now find their aggregate material consumption again increasing faster than GDP. This resulted in an N-shaped rather than an inverted-U shaped curve. This is another indication that the inverted U describing intensity of use cannot be used as a generic trajectory for material throughput.

3. Method for the analysis of historical growth patterns

The hypothesis of dematerialization offers qualitative insights in the material intensity of an economy as a function of income. We wish to join the line of considering (per capita) income in the study of material flows in the national economies of countries in varying development stages. We will use income to distinguish different country groups that are each in different development stages. However, analysing the hypothesis of dematerialization five points may be formulated that render its application for our purpose, as a quantitative forecasting tool, somewhat problematic.

First, the hypothesis of dematerialization focuses on the consumption of materials, which decreases its applicability for answering our research question. A bottom–up approach of building emission scenarios requires insight into production levels, since production has a direct link to domestic emissions as in the prevailing UNFCCC emission accounting system.[1] Studying production rather than consumption has two additional advantages apart from its direct link to emissions. Contrary to consumption studies, no correction needs to be made for inventory behaviour. Consumption is calculated as domestic production plus imports minus export minus inventory additions. As stock changes are mostly invisible and poorly documented, they may obscure intensity-of-use trends. Furthermore, studying production makes corrections for indirect consumption (i.e., incorporated in final goods) redundant. Consumption studies in general just focus on apparent consumption, which does not include material use in final products. This means that, for example, metal consumption in an automobile-exporting country may well be overestimated in such countries. In production-based studies, this problem is obviously avoided.

A second problem arises when applying the hypothesis of dematerialization as a forecasting tool is the fact that material flows are predicted on a GDP basis. To make the insights into historic growth thus obtained applicable to the estimation of future growth rates, we need an economic scenario. However, economic projections vary widely. Therefore, it seems preferable to study material flows on a somewhat more robust basis, such as population. This means that the indicator considered is not the materials produced per unit of GDP, but materials produced per capita. If we obtain insight in material production per capita, we may combine these with a population projection. The agreement on future demographic developments in a medium-growth future makes population a more attractive parameter to link material flows to than size of the economy. Medium variants of major world population projections issued by the UN, World Bank, U.S. Census Bureau, and IIASA show “excellent” agreement with respect to many features of future world population growth (Gaffin, 1998). It must be noted that this agreement reflects the use of similar methodologies and databases, including assumptions of fertility and mortality, rather than implying accuracy.

An additional argument for studying material flows on a per capita basis is that per capita commodity production, particularly in developing countries, is quite well correlated to per capita income. Per capita income is a frequently used (be it one-dimensional) indicator for development, and it seems natural to incorporate it in global material flow studies.

Now, since per capita production levels are, to some extent, correlated to this obvious indicator,

[1] It may be argued that national greenhouse gas emission balances should contain emissions related to consumption instead of production, i.e., emissions corrected for imported or exported goods. This would enhance equal treatment of countries with different economic structures, but greatly decrease transparency.

studying production levels on a per capita basis becomes self-evident. The correlation between the two is presented in Table 1. It lists the square root of the Pearson correlation coefficient (R^2) of per capita commodity production and per capita income for six energy-intensive commodities.

Obviously, per capita production levels and income are highly correlated in maturing economies, although we found that, in individual cases, correlations may be weak, such as for aluminium in Indonesia and Mexico or crude oil input in Mexico. In the OECD, correlation does not stand out that clearly for most commodities. This can be explained by the fact that, for most of these countries, saturation levels may have been reached, which means that the correlation between material production per capita and per capita income vanishes. This applies to a lesser extent for per capita production of petrochemicals and not at all for per capita paper and board production in the OECD. The latter is even strongly correlated to per capita income. In our view, overall correlation coefficients, in particular, in developing countries, offer sufficient support to justify a study of generic trends in material flows on a per capita basis, in which economic development, indicated by per capita income, is considered simultaneously.

Continuing our discussion of the hypothesis of dematerialization as a basis for projections, we raise a third problem. Evidence for the hypothesis of dematerialization is limited to a small number of mineral ores, fuels, and metals (Bernardini and Galli, 1993). Indeed, although a decrease of intensity of use was reported for steel, lumber, and cement, Ross and Purcell (1981) report an increase in the intensity of use for a number of chemicals.

Fourth, the geographical scope that the hypothesis has been used in hitherto is limited. So far, most studies have focused on OECD countries, in particular, the United States. The inclusion of a wider range of countries, including transition economies and developing countries, would be desirable.

A fifth problem regards the long time series used in intensity-of-use studies. Long time series may be distorted by nonrepresentative past events. In particular, the 1973 OPEC crisis and the accompanying boost in energy prices restrained material throughputs (see, e.g., Williams et al., 1987). In addition, production levels in developing countries may deviate from those in economies with comparable per capita income levels at the beginning of or halfway the last century. For instance, steel flows may be lower in current maturing economies due to trends of dematerialization and material substitution. On the other hand, throughput of plastics is probably much higher in current developing economies than they were decades ago in economies with similar income levels. It seems, therefore, that extending time series too far into the past is of limited value.

Following from the five problems addressed above, it seems preferable to leave the intensity-of-use scheme to address our research question on medium-term growth rates of production levels. Five characteristics may be formulated for our study on materials in society:

1. We will focus on historic production levels rather than consumption levels.
2. We will study material flows in proportion to the size of the population rather than to the size of the economy, as in previous studies on intensity of use.

Table 1
Square root of the Pearson correlation coefficient (R^2) between per capita production of several commodities (UN, 1998) and per capita income (1995 US$, PPP; World Bank, 1999) in the 1980s and the first half of the 1990s[a]

	Crude steel	Cement	Total aluminium	Total paper and board	Key petrochemicals[b]	Crude oil input[c]
Developing countries	0.97	0.98	0.90	0.99	0.95	0.94
OECD	0.32	0.31	0.36	0.91	0.51	0.24
All	0.71	0.90	0.56	0.97	0.65	0.30

The countries included are listed in Table A1 in Appendix A, but transition economies have been excluded.
[a] Time series vary: crude steel (1985–1994), cement (1987–1995), total aluminium (1987–1995), total paper and board (1980–1995), key petrochemicals (1987–1995), and crude oil input (1980–1995).
[b] Ethylene, propylene, butylenes and benzene.
[c] Crude oil input was used as a proxy for production in the refining industry, since output from this subsector consists of a wide variety of products.

GDP will still be in the analysis, but mainly as a criterion to distinguish between countries in different development stages.
3. We will include a varied range of commodities, not only materials that are being used for building up an infrastructure, but also those used for consumer goods (plastics, aluminium).
4. We will include a wide range of countries, both in the developed and in the developing world.
5. We will focus on recent history to prevent that too generic conclusions are drawn from historic developments in industrialised countries that may have taken place in earlier innovation waves. In particular, distortions in production trends due to the 1973 oil crisis can be avoided this way.

Note that our use of per capita income as an indication for countries' development is in line with most dematerialization literature. The basic presumption that countries follow certain patterns of material flows on their way to economic maturation is the same. However, we will use another graphical presentation of the information. We will come back to this later.

We will focus on the production levels of five commodities: crude steel, cement, aluminium, total paper, and board and the sum of four key petrochemicals. To study historic growth rates in the refining industry, we focused on crude oil input rather than on production levels. The output of refineries consists of a wide range of products, which makes it difficult to pick one as an indicator for growth. Note that natural gas and natural gas liquids are additional (but minor) inputs in the refining industry.

We will include a wide range of both industrialised and developing countries to track down possible patterns in the changes in production over time. Groups of countries can be distinguished based on their per capita income: low-income countries with a per capita income of less than US$5000 (based on purchasing power parities), middle-income countries (US$ 5000–12 500), and high-income countries (over US$ 12,500). We placed economies in transition in Eastern Europe and the former Soviet Union in a separate group.

The start year for the analysis of each industry's production ranges from 1980 to 1987.[2] The start years for total paper and board and crude oil input are earlier than those for the other commodities, and only for these industries, the recession in the early 1980s has been included. This may reduce the comparability of these time series somewhat, as a matter of fact, less so for total paper and board than for crude oil input in refineries since paper and board production growth in the early 1980s does not deviate that much from growth later on.[3]

For this study, we have used UNDP (1999) data on population and World Bank figures of the gross domestic product based on purchasing power parities (World Bank, 1999). Production figures for crude steel have been derived from both the International Iron and Steel Institute (1996), for paper and board, from Pulp and Paper International (PPI, 1997), and for other commodities, from the UN (1998).

4. Patterns of per capita production levels worldwide

In the following, we present an overview of per capita production growth patterns worldwide. Figs. 3–7 show per capita production levels for, respectively, crude steel, cement, total aluminium, total paper, and board and the sum of the production levels of four key petrochemicals: ethylene, propylene, butylenes, and benzene. Crude oil input in refineries per capita is shown in Fig. 8. Production levels are presented both on normal and logarithmic scales. Labels are listed in Table 2. Each line in the figures represents a per capita production level plotted against per capita income over a specific period (as given in Table 5) for one specific country.

Before making some general observations on the varying growth patterns of the different commodities, we will discuss the figures in more detail.

Fig. 2 shows *crude steel* production per capita plotted as a function of income per capita. For each

[2] Exact time ranges are given in Table 2.

[3] Total paper and board production growth in low- and mid-income countries was the same in the first and the second half of the 1980s (on average respectively 8% and 5% per year). In high-income countries, average annual growth was 2% until 1985 and 4% thereafter. As for crude oil input in refineries in high-income countries, the recession resulted in a negative growth (on average, −3% between 1980 and 1985).

Table 2
Countries included in this study and their abbreviation according to ISO (ISO, 2001)

AR	Argentina	ES	Spain	KR	South Korea	RU	Russia
AT	Austria	FI	Finland	KZ	Kazakhstan	SA	Saudi Arabia
AU	Australia	FR	France	LT	Lithuania	SE	Sweden
BE	Belgium	GR	Greece	LV	Latvia	SG	Singapore
BG	Bulgaria	HU	Hungary	MX	Mexico	SK	Slovakia
BR	Brazil	ID	Indonesia	MY	Malaysia	TH	Thailand
CA	Canada	IE	Ireland	NL	Netherlands	TR	Turkey
CH	Switzerland	IN	India	NO	Norway	UA	Ukraine
CN	China	IR	Iran	NZ	New Zealand	UK	United Kingdom
CZ	Czech Republic	IS	Iceland	PL	Poland	US	United States
DK	Denmark	IT	Italy	PT	Portugal	ZA	South Africa
EE	Estonia	JP	Japan	RO	Romania		

country, the development from 1985 until 1994[4] is plotted.

In the lower left part of the figure, the least developed countries are located. India, Indonesia, and China have experienced growing economies and also extended their crude steel production from 1985 until 1994. The size of Iran's income per head has not increased very much, but crude steel production did increase. All transition economies experienced a decline in production since the beginning of the 1990s. Higher incomes and higher crude steel production are encountered in Brazil, South Africa, and Turkey, and also in Mexico and Argentina, which have even higher incomes. In the figure, they constitute a bridge to the industrialised world, which is characterised by more or less constant production levels and increasing income. These constant production levels per capita may vary by a factor of up to 10 in developed countries—compare, for instance, Belgium and Ireland. This may be related to different sizes of the infrastructure, different lifestyles, and specialisation. Note that the level of geographical aggregation is an important issue in this respect. Steel production within the United States is concentrated geographically just as well as it is in Europe.

Cement production per capita and income from 1987 until 1995[5] are plotted in Fig. 3. In the left part of the figure, the low-income countries are situated, with a drop of production in the former Soviet Union and Eastern Europe and increasing per capita production levels in China, India, and Indonesia. The Asian tigers in the middle-income group exhibit increasing per capita production levels, whereas per capita levels in OECD countries are fairly constant.

Total aluminium production (including secondary aluminium) and income from 1987 until 1996, both in per capita terms, are depicted in Fig. 4a, b, and c. In general, per capita production levels are somewhat higher in high-income countries. Yet, the pattern is not very pronounced. An important reason for this may be that the presence of cheap electricity is a more important explaining variable than the income level in a country.

Total paper and board production per capita from 1980 until 1995 is plotted as a function of per capita income in Fig. 5a, b, and c.[6] In both developing and mature economies, production levels in per capita terms increase. Production levels are particularly high in forested countries in which production is very much export oriented: Canada and the three northernmost Scandinavian countries, followed by New Zealand and Austria. In most other countries, per capita production levels seem to increase more or less linearly with income, with varying growth rates in each income group.

The sum of the per capita productions of the *key petrochemicals* ethylene, propylene, butylenes, and benzene from 1987 until 1995 has been plotted as a function of income in Fig. 6.[7] Per capita petrochemicals production shows a rather dispersed pattern.

[4] Except Czech, Kazachstan, Russia, Slovakia, and Slovenia (from 1992 onwards).

[5] Except Czech, Kazachstan, Latvia, Lithuania, Russia, Slovakia, and Ukraine (from 1992 onwards).

[6] Czech and Slovakia form 1992 onwards, Estonia, Latvia, Lithuania from 1991.

[7] Kazachstan, Ukraine, Russia from 1991 onwards, Czech from 1992, Slovakia from 1993.

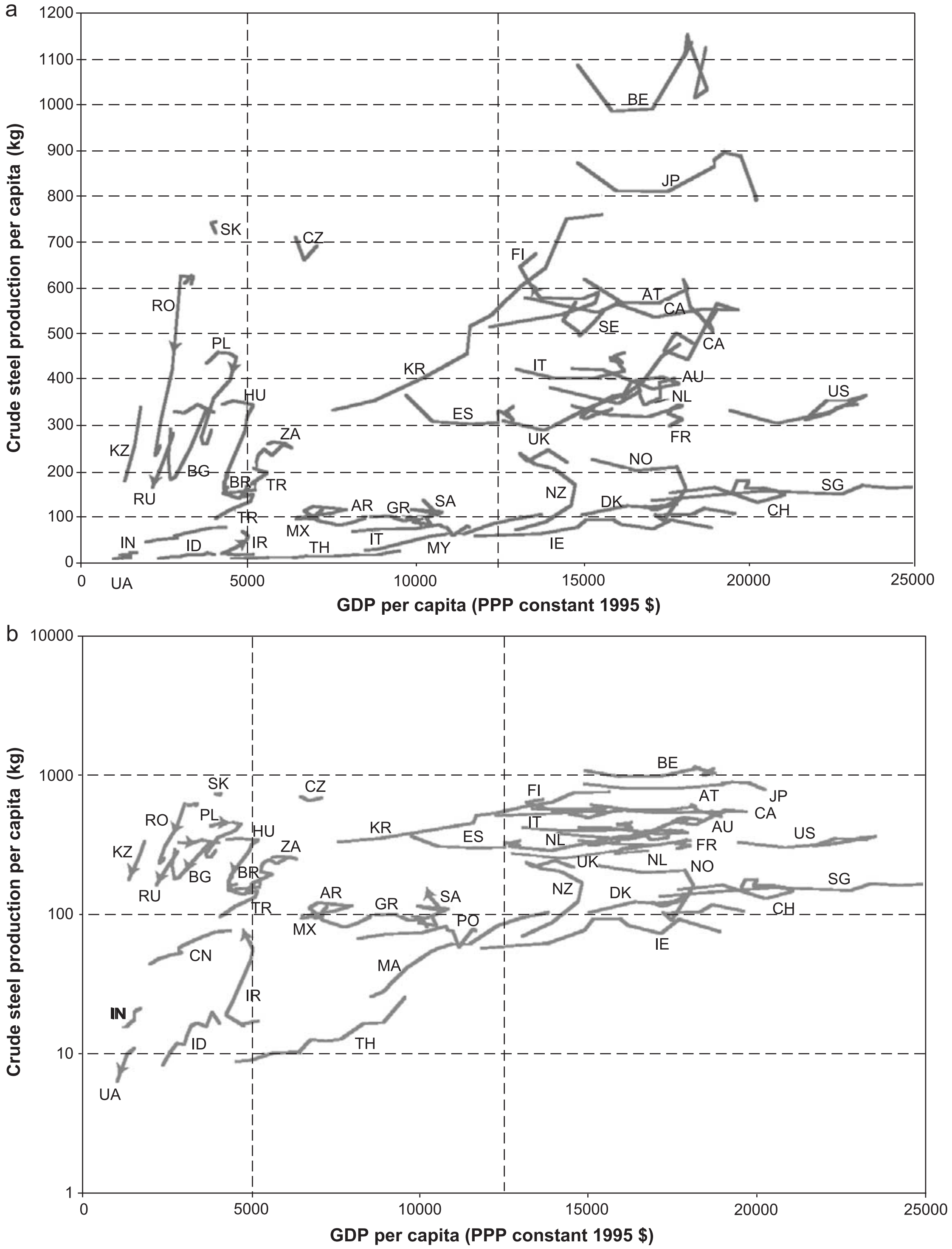

Fig. 2. Crude steel production per capita, on a normal (a) and a logarithmic (b) scale, vs. per capita income (based on purchasing power parity) for industrialised and developing countries from 1985 until 1994. Lines are from left to right, unless indicated otherwise by arrows.

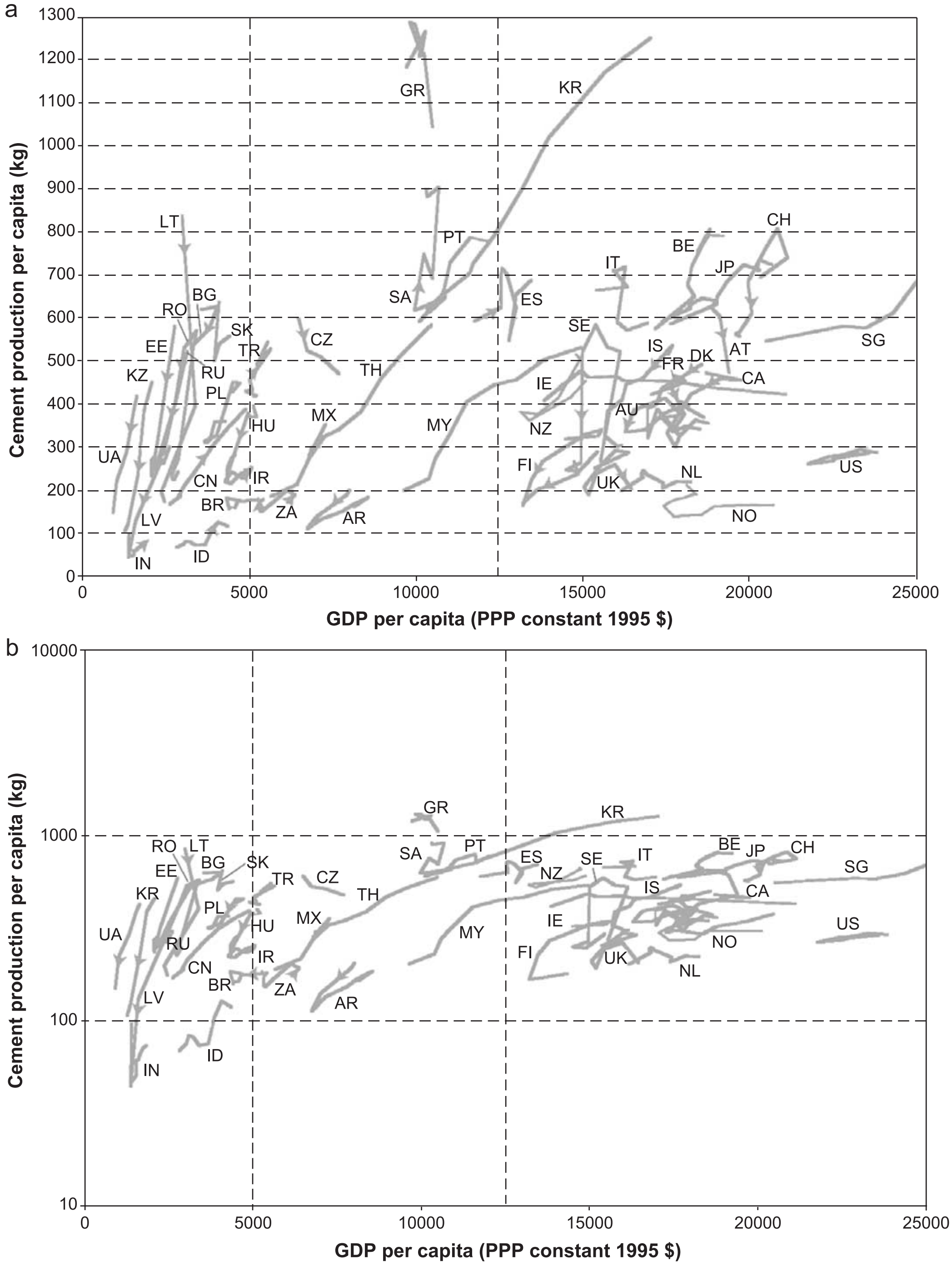

Fig. 3. Cement production per capita, on a normal (a) and a logarithmic (b) scale, vs. per capita income (based on purchasing power parity) for industrialised and developing countries from 1987 until 1995. Lines are from left to right, unless indicated otherwise by arrows.

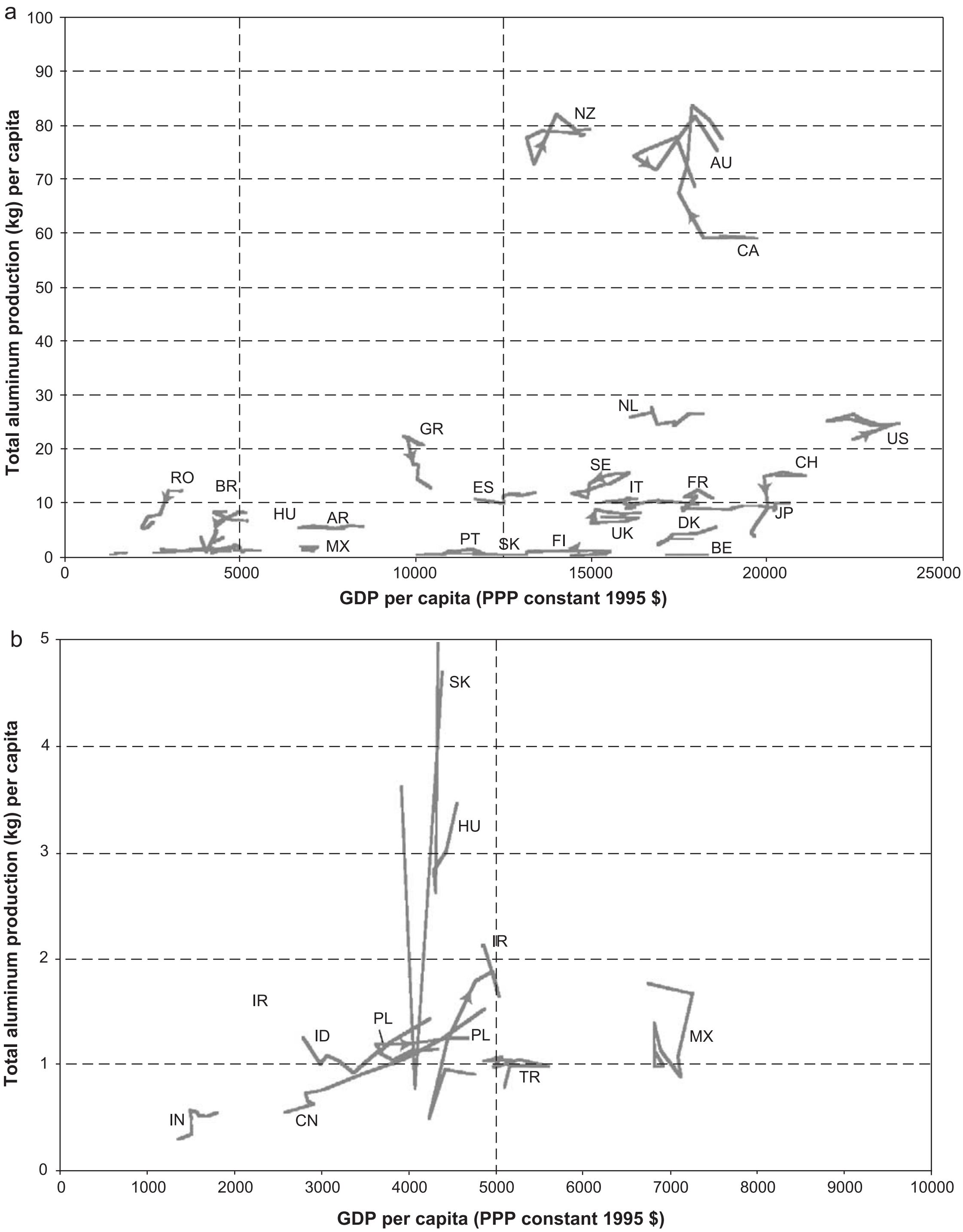

Fig. 4. Aluminium production per capita, on a normal (a and b) and a logarithmic (c) scale, vs. per capita income (based on purchasing power parity) for industrialised and developing countries from 1987 until 1995. Lines are from left to right, unless indicated otherwise by arrows.

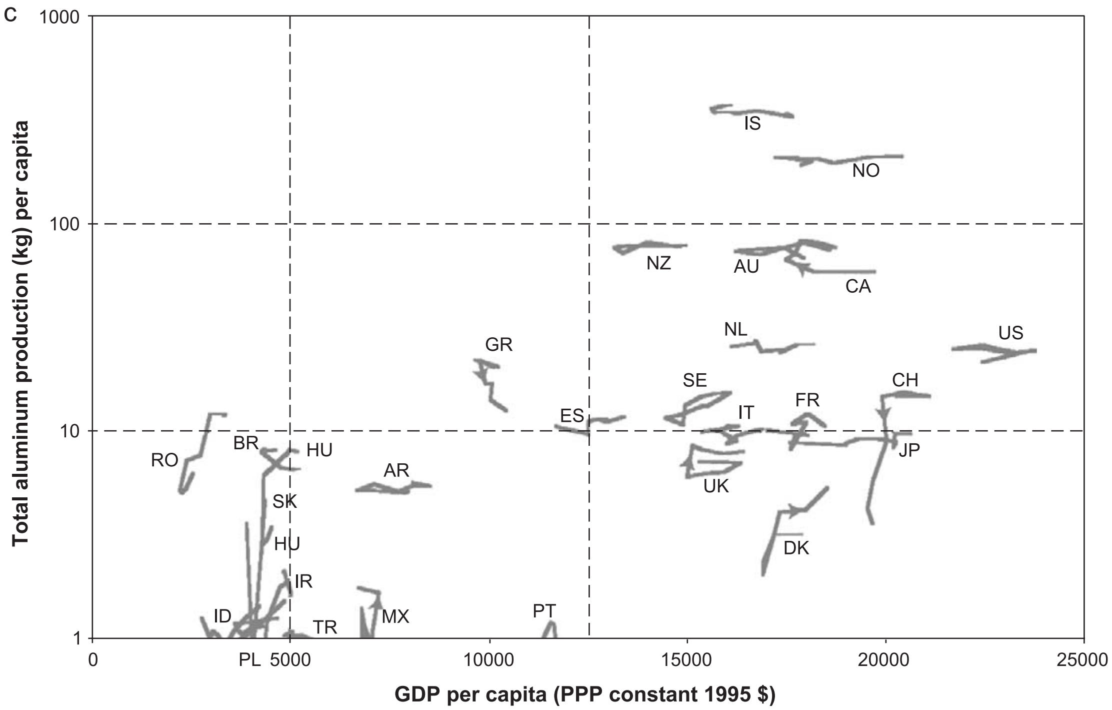

Fig. 4 (*continued*).

Production levels in the transition economies are low, showing a decrease in the first half of the 1990s. Per capita production levels in India, Indonesia, and China are virtually zero, whereas South Korea went through a boost in its production during the time period studied. Per capita production levels in Canada and the United states are higher than those in Japan and even further surpass European levels.

In Fig. 7, we plotted the *input of crude oil* on a per capita basis versus income over the period 1980–1995. Many high-income countries show a more or less stable per capita production level, most often below 100 kg per capita. The Netherlands, Canada, France, Italy, The United States, Singapore, and Saudi Arabia put in 100 and 250 kg per capita annually, and also, Norway rose over the 100 kg over recent years. Singapore put in most, over 500 kg per capita.

We conclude that different types of commodities with diverging growth patterns exist:

- Commodities for which per capita production levels increase with increasing per capita income, with stabilising production levels in countries that have per capita incomes over a certain level. These include steel, cement, and the input of crude oil in refineries;
- Commodities for which per capita production levels continue growing with increasing per capita income. These are mainly paper and board and the petrochemicals;
- Aluminium, which has a less pronounced growth pattern and does not show explicitly stabilising or growing production levels.

Note that our representation in Figs. 3–8 can be considered as a transformation from the most representations in the dematerialization literature. In many studies, the horizontal axis depicts per capita income, and the vertical axis depicts material consumption per unit of GDP. In our figures, the horizontal axis is the same, whereas the vertical axis represents material production per capita. Apart from the distinction between production and consumption, this is not more than a simple transformation. Intensity-of-use patterns (material flow per GDP) may be multiplied with per capita income to obtain patterns in terms of material

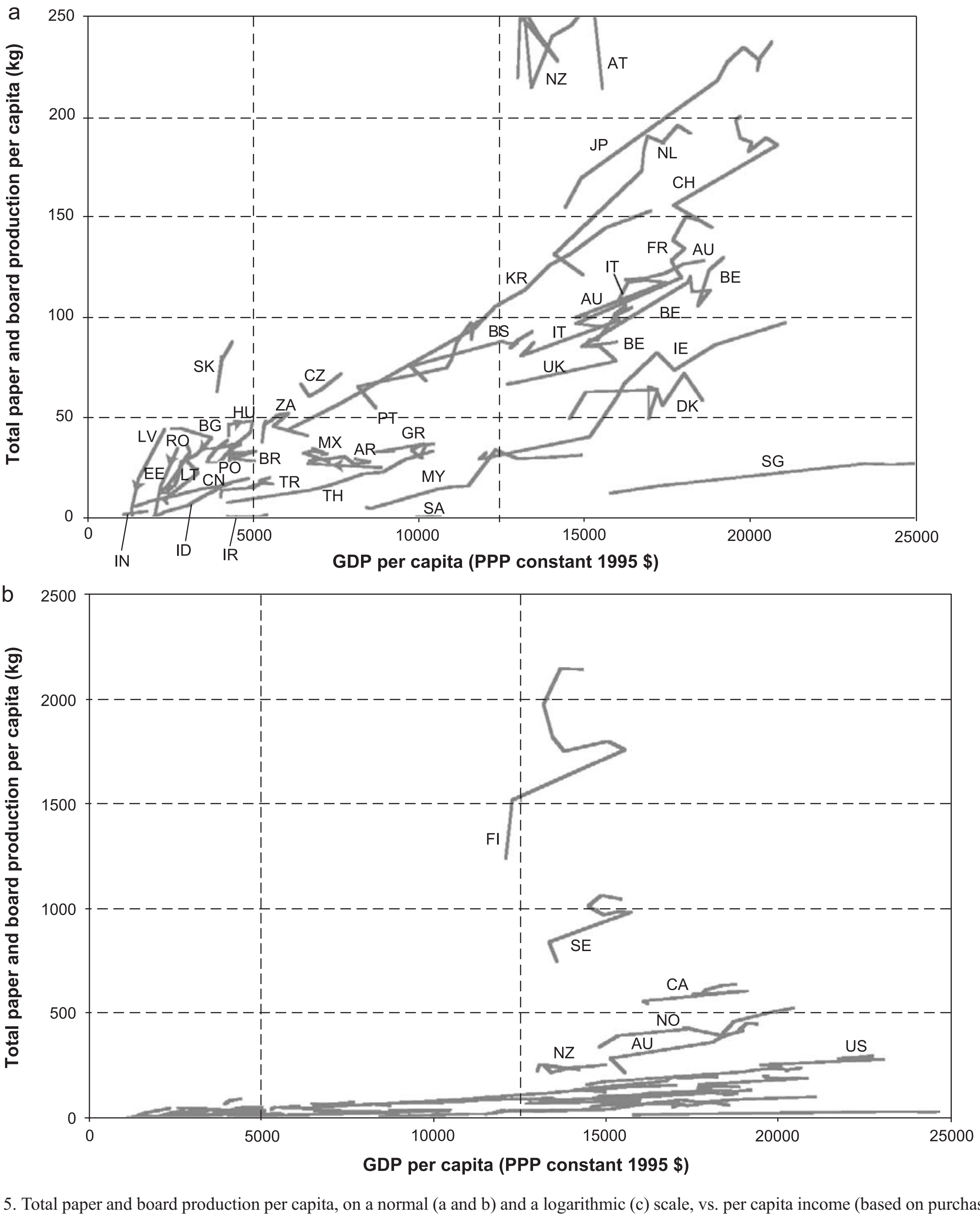

Fig. 5. Total paper and board production per capita, on a normal (a and b) and a logarithmic (c) scale, vs. per capita income (based on purchasing power parity) for industrialised and developing countries from 1980 until 1995. Lines are from left to right, unless indicated otherwise by arrows.

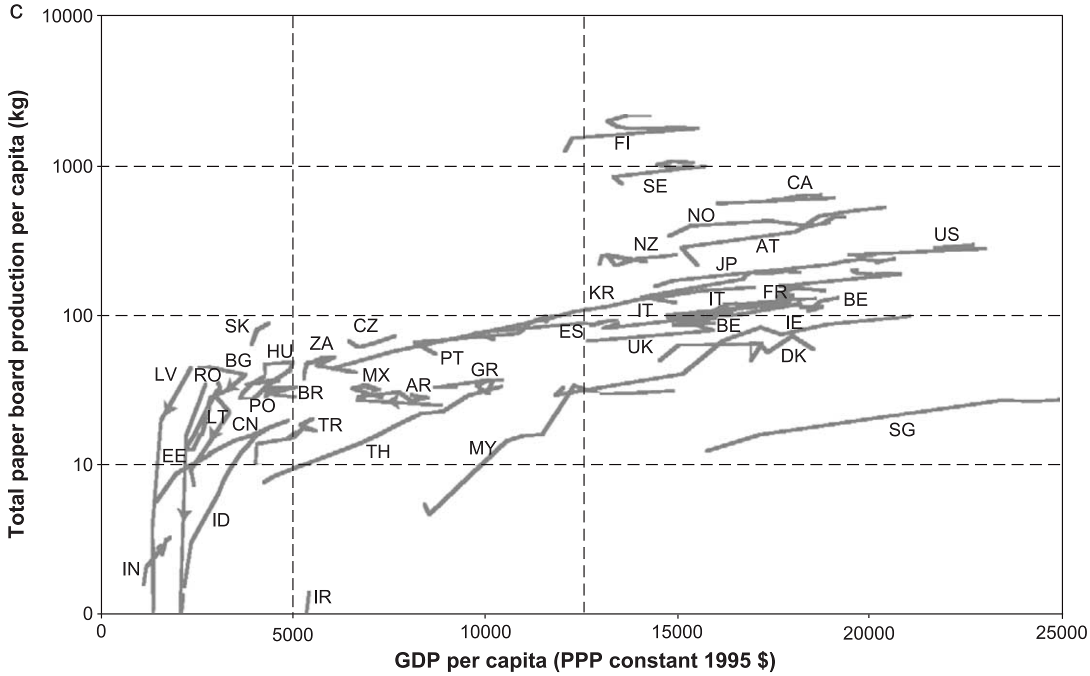

Fig. 5 (*continued*).

flows per capita. Besides the production–consumption difference, both representations contain exactly the same information. However, our representation has the advantage that it reveals stabilisation patterns for a number of commodities.

Stabilisation levels for steel, cement, and the input of crude oil in refineries differ for the various developed countries. These differences might be caused for instance by the size of an infrastructure, including varying travel distances. The larger an infrastructure is relative to the size of a population, the higher the replacement requirements will be. Another important determinant of per capita stabilisation levels is specialisation. The production of commodities for consumption abroad involves that production levels per head of the domestic population become higher.

Per capita production of total paper and board and petrochemicals continues, growing with increasing income. Aluminium differs from the other commodities. This is not because per capita production would not level off, but rather because production is concentrated in a limited number of countries. The reason for the latter is that the presence of cheap (hydro) electricity is the main explaining variable for the location of the electricity-intensive aluminium industry. Hence, countries that dispose of hydropower have high per capita production levels, Canada and New Zealand being forerunners, which is also explained partly by their relatively low population numbers. Austria, which also has a large availability of hydropower, experienced a sharp decrease in aluminium production, following the closure of a large aluminium plant, which made up nearly the entire Austrian production capacity.

The observed growth patterns, in particular for stabilising commodities, lead us to the notion that countries may be classified into groups based on their degree of development that their infrastructures and economies are in. In the following, we will make such a classification using per capita income as an indicator for the development of a country.

Based on the observed growth patterns for, especially, the stabilising commodities, we chose US$ 5000 and 12,500 as classification limits (constant 1995 US$ and based on purchasing power parities). These limits were suggested by the figures and have been indicated there. The countries with per capita incomes below US$5000 comprise the low-income countries

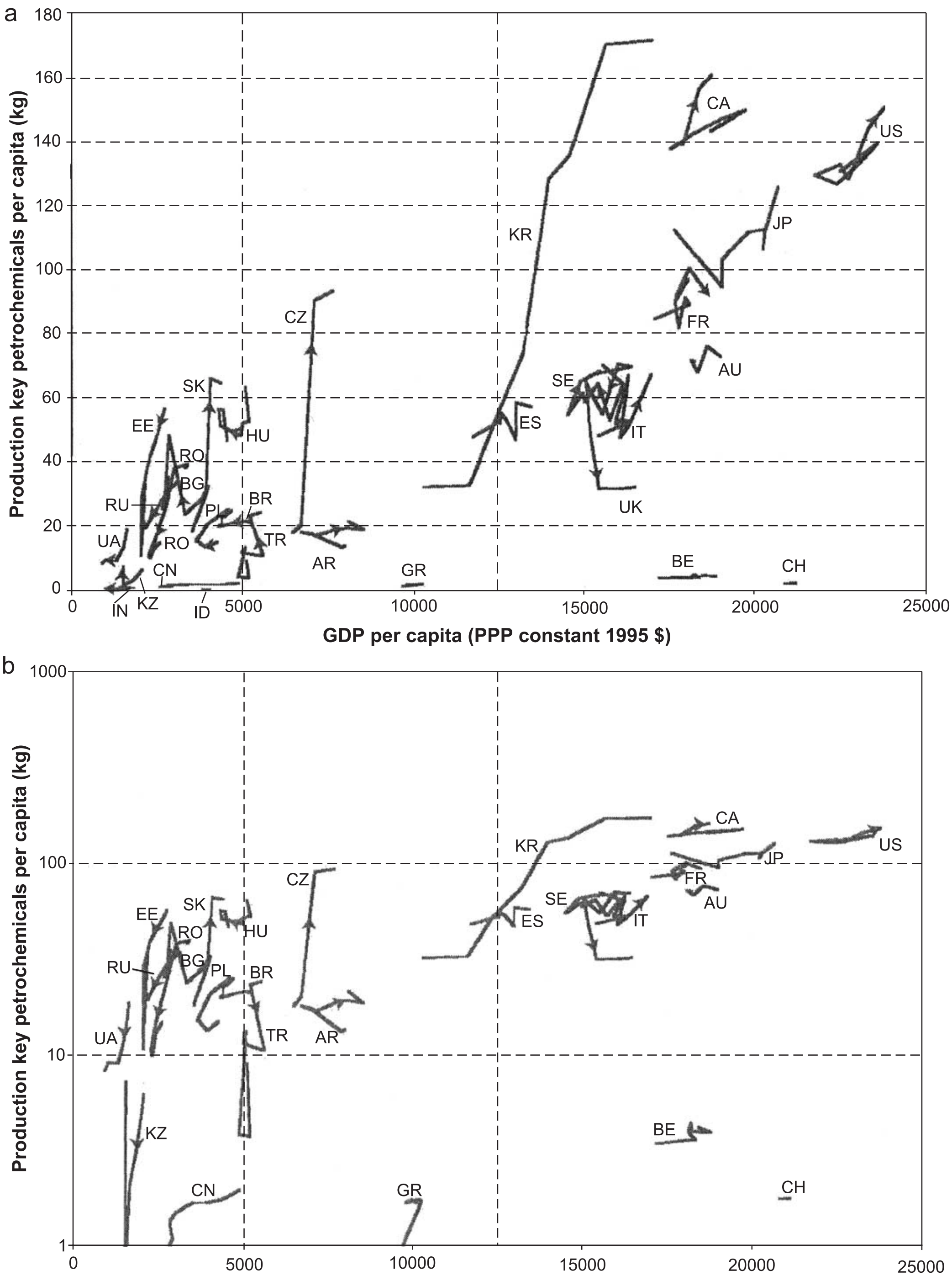

Fig. 6. Total production of four important petrochemicals (ethylene, propylene, butylene, and benzene) per capita, on a normal (a) and a logarithmic (b) scale, vs. per capita income (based on purchasing power parity) for industrialised and developing countries from 1987 until 1995. Lines are from left to right, unless indicated otherwise by arrows.

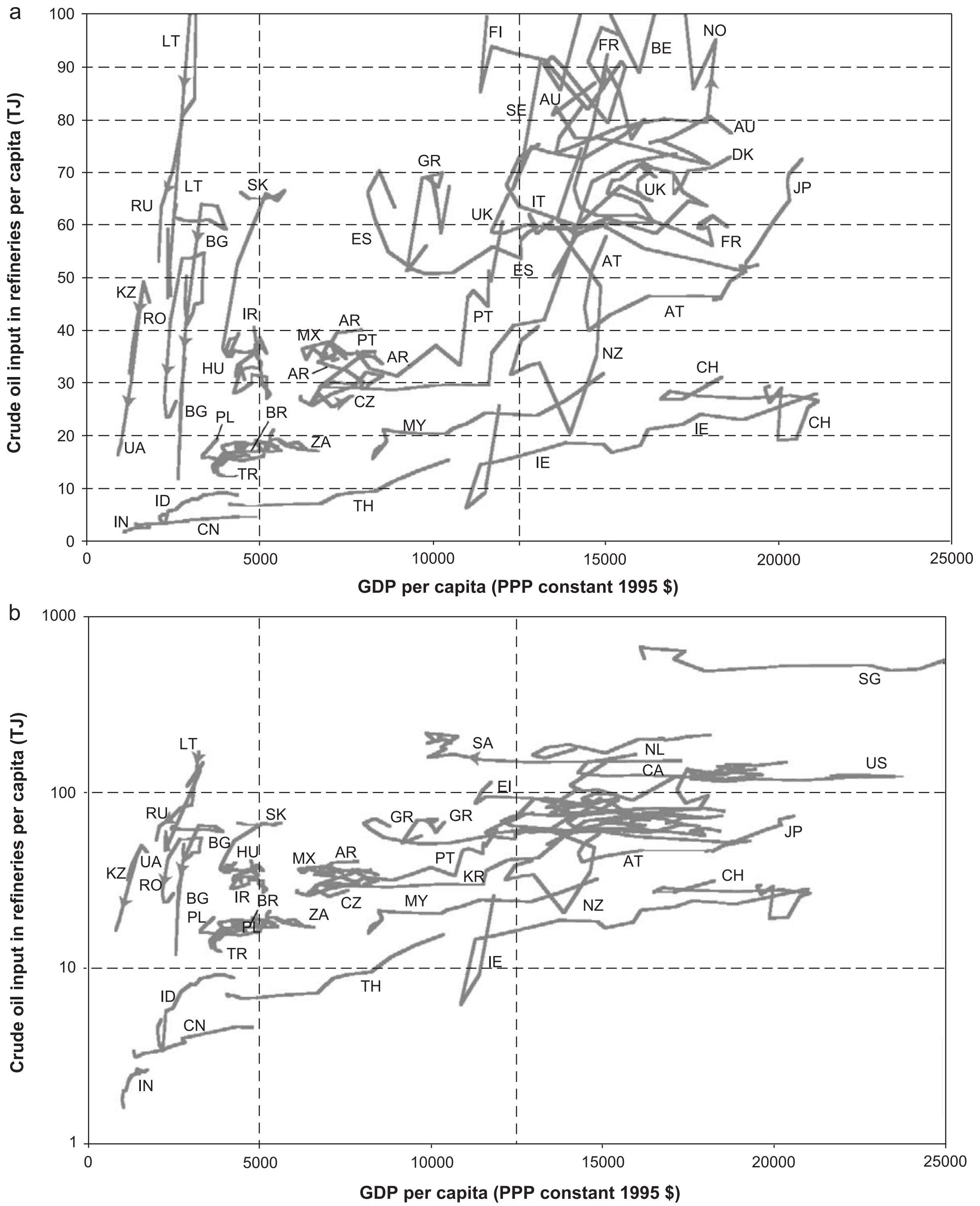

Fig. 7. Input per capita of crude oil in the refining industry, on a normal (a) and a logarithmic (b) scale, vs. per capita income (based on purchasing power parity) for industrialised and developing countries from 1987 until 1995. Lines are from left to right, unless indicated otherwise by arrows.

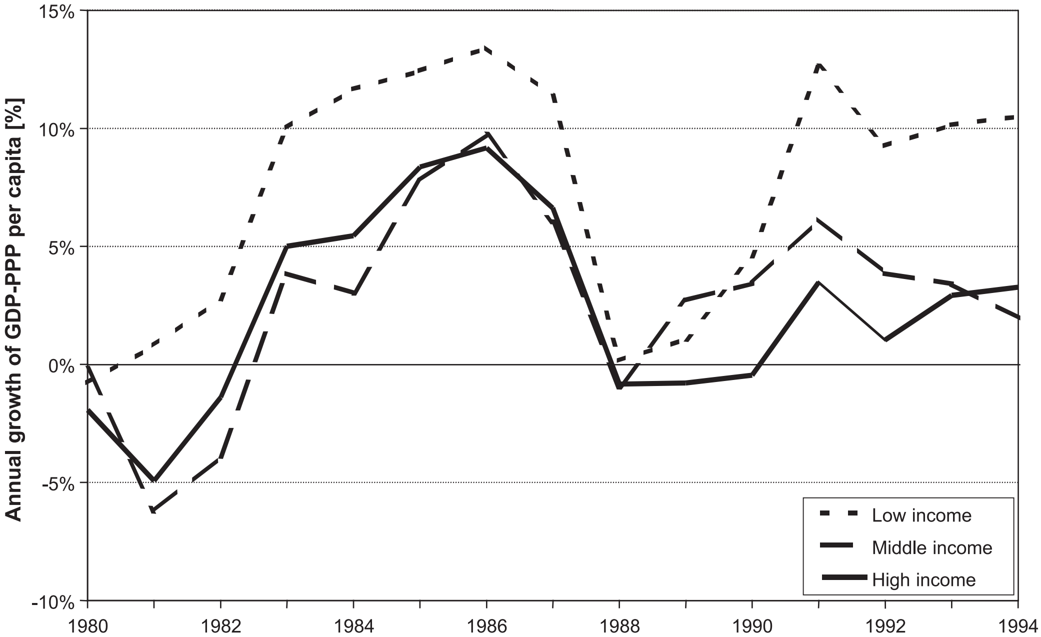

Fig. 8. Annual growth of GDP (based on purchasing power parity) per capita for three income groups of countries. Countries included are presented in Table A1 in Appendix A.

and all economies in transition but the Czech Republic. In countries with per capita incomes between US$5000 and 12,500 (the middle income countries), per capita production levels have not become saturated for any of the commodities. Finally, in the high-income countries with over US$12,500 per capita incomes, saturation of per capita production levels can be observed for a number of commodities, in particular steel, cement, and crude oil input in *refineries*.

5. Historical growth rates of per capita production output

In the previous section, we used differences in growth trends with increasing *income* as a classification criterion to make income groups of countries. In the following section, we wish to look further into each of these income groups and calculate different growth rates over *time* for each of these income groups of countries.

Now, the question might be raised if an ex post classification of countries, based on different growth rates, would not differ from the ex ante classification that we based on per capita income. We will show here that this is not the case. Fig. 8 presents the change in per capita income for the groups of low-, middle-, and high-income countries. It clearly shows that patterns in per capita income change over time are similar in all income groups. It follows that a classification on the basis of growth trends with increasing income will not be substantially different from a classification on the basis of growth trends over time.

Therefore, a replacement of per capita income by time on the horizontal axis of the Figs. 2–7 will presumably not change the nature of the patterns of the lines for the various countries, even while the precise shapes of the lines may change. This entails that a classification based on growth trends over time would not lead to other insights than the ones we drew based on the classification we presented above, which was based on growth trends with increasing income.

Having classified countries into income groups based on per capita production levels, we calculated annual growth rates for per capita production of the five commodities and of crude oil input in refineries in each of the income groups of countries.

Table 4 shows the per capita growth rates and their standard deviations for each of the commodities separately. It must be noted that the economies in

Table 3
1990 CO_2 emissions (Mt) in six industrial subsectors (IEA, 1997)

Income group	Iron and steel	Nonmetallic minerals	Nonferrous metals	Pulp and paper	Chemical industry	Refineries
Low	383	233	23	38	295	134
Middle	56	27	4	5	57	104
High	355	181	35	162	495	503
Economies in transition	221	33	2	6	85	22
Total	1015	474	64	211	933	763

transition have been listed separately because their economic history of the last decade, i.e., the strong recession at the beginning of the 1990s, distinguishes them from other countries with comparable per capita incomes.

Table 4 also includes an historical growth rate for heavy industry as a whole based on the growth rates in each of the industrial subsectors. To this end, we needed to establish factors that would determine the weight of each of the subsectors' growth rates in the total heavy industry figure. We chose to base these factors on the 1990 CO_2 emissions in each of the sectors (Table 3), since the ultimate objective of this study is to contribute to a more detailed insight the direct driving forces of future CO_2 emissions to be able to produce bottom–up CO_2 emission scenarios. Therefore, heavily emitting subsectors should be given greater weight in an aggregate growth figure for heavy industry.

Some emission figures presented in Table 4 cover more products than the commodities under investigation here. This restriction brought us to making assumptions on CO_2 emissions in some of the subsectors in this study. IEA (1997) does not provide emission figures for the cement, aluminium, and petrochemicals industries, and we had to turn to other sources to estimate these. In general, these complementary sources regard the industrialised world only.

An estimation of cement-related CO_2 emissions had to be derived from CO_2 emissions in the nonmetallic minerals subsector as a whole, which also comprises glass and ceramics. To this end, we took into account that primary energy consumption in the cement industry equals 2.5% of global primary energy consumption (Hendriks et al., 1999), which can be calculated to correspond to 87% of primary energy consumption in the nonmetallic minerals sector. We also considered that half of the CO_2 emissions in the cement industry are related to fuel combustion, and the other half, to the process emissions during clinker production. Therefore, we assumed that total CO_2 emissions in the cement sectors equal 174% of the CO_2 emissions in the nonmetallic mineral sector.

We based our estimate for the aluminium industry on the observation that it accounts for 60% of the primary energy consumption in the nonferrous metals industry in the European Union (Worrell et al., 1994) and on the assumption that the share in CO_2 emissions is the same.

CO_2 emissions in the petrochemical industry had to be estimated from emissions in the total chemical industry. Phylipsen (2000) reports 1 EJ primary energy consumption (excl. feedstocks) for the global petrochemistry. In addition, we know that worldwide primary energy consumption in total chemical industry is 10.2 EJ. Based on this share of primary energy, we assume that petrochemicals account for 10% of the emissions of total global chemical industry emissions.

The CO_2 emissions in the six subsectors were used to establish a weighted average for historical annual growth of per capita production in heavy industry since halfway the 1980s. The weighted average growth rates for various income groups of countries and the transition economies are listed in the rightmost column of Table 4.[8]

6. Translating historical growth rates to medium-term future growth rates

We described how growth rates of per capita production of a number of commodities alter in

[8] For a correct determination of the weight factors, more detailed statistics on the CO_2 emissions related to the production of the various commodities would be desirable. More precise monitoring of CO_2 emission requires a further specification of the IEA categories nonferrous metals (especially a distinction of the aluminium industry), nonmetallic minerals (in particular, cement), and most of all the chemical industry.

Table 4
Average annual growth rates (%) and standard deviation (between brackets) of per capita production of five commodities and of per capita input of crude oil in refineries in four groups of countries

Income group	Per capita income (1995 US$[a])	Crude steel	Cement	Total aluminium	Total paper and board	Key petrochemicals	Crude oil input	Heavy industry; weighted average[b]
		1985–1994	1987–1995	1987–1995	1980–1995	1987–1995	1980–1995	
Low	<5000	4.9 (3.7)	8.9 (6.3)	7.4 (3.3)	6.9 (3.4)	4.2 (3.5)	1.9 (3.4)	5.9
Middle	5000–12500	2.6 (3.1)	1.8 (3.2)	−0.7 (7.4)	2.6 (5.1)	15[c] (34)	1.3 (2.5)	1.1
High	>12500	0.3 (3.8)	1.5 (3.1)	2.6 (5.3)	2.2 (1.6)	1.9 (7.0)	−0.2 (3.4)	0.8
Economies in transition	<8000	−12 (1.7)	−13 (14)	2.1 (5.6)	3.6 (11)	−2.5 (12)	8.4 (6.0)	−11
All −/− EIT[d]		1.1 (2.8)	4.8 (3.1)	2.7 (4.2)	2.1 (1.7)	2.2 (7.6)	−0.3 (3.0)	2.0

Figures for economies in transition are for 1992 onwards.
[a] Based on purchasing power parity.
[b] Based on CO_2 emissions in six subsectors.
[c] Based on Argentina and Turkey only.
[d] Excluding economies in transition.

successive stages of the development of an economy. Commodity output per capita in low-income countries (less than 1995 US$ 5000 per capita) increased, on average, by 5.9%, in middle-income countries (1995 US$5000–12,500 per capita), by 1.1%, and in high-income countries (over 1995 US$12,500), by 0.8%. These insights can be used to better estimate future growth rates of the energy-intensive commodity production per capita in various income groups of countries.

A crucial assumption in proceeding along this line is the notion that any country goes through a similar trajectory with increasing income. This trajectory is characterised by increasing production levels for all commodities during its early development and stabilising levels later on for steel, cement, and petroleum products. Building on the assumption that a country moves from one income group to the next, we used both the growth figure from the income group it is currently in and from the subsequent income group to estimate per capita growth rates in the coming decades.

To this end, we further divided the low-income group in a ‘lower low’ and an ‘upper low’ group and the middle income group in a ‘lower middle’ and an ‘upper middle’ group.

The projected growth rates derived from the historical averages are given in the right most column of Table 5. They should be understood as generic figures, describing roughly how growth differs between countries in varying development stages. These projected per capita growth rates are to be combined with a population scenario for the coming decades.

The economies in transition in Europe and Central Asia are not included in Table 5 because they take a

Table 5
Overall annual growth rates of per capita commodity production in six industrial subsectors for five income groups of countries

Income group		Income	Annual historical growth per capita (1980s onwards) [%][a]	Per capita growth average of	Projected annual growth per capita [%]
Lower low	LL	<2500	5.9	LL,UL	6
Upper low	UL	2500–5000		UL, LM	3–4
Lower middle	LM	5000–8750	1.1	LM,UM	1
Upper middle	UM	8750–12500		UM, H	1
High	H	>12500	0.8	H	0.5–1

[a] Based on historical growth rates in six industrial subsectors that per capita were weighted according to CO_2 emissions in the subsectors.

distinct position. The economic collapse at the beginning of the 1990s and the accompanying sharp decrease in the output of commodities make it difficult to fit them in the described patterns. Therefore, we did not apply our projection methodology to these countries in a straightforward manner. However, it can be argued that, despite their deviating historic pattern in bottom–up emission scenarios, these economies should be attributed the same growth as other countries with similar income levels. Thus, since most economies in transition have income levels similar to the upper low-income countries, they would experience a per capita growth of 3–4% per year. The improvement and reorganisation of transportation infrastructure, energy networks, and urban development are high priorities for the transition economies to facilitate private sector growth, enhance employment, and improve the standard of living (World Bank, 2000). This seems to bring about a natural need in the near future to raise per capita production levels of infrastructure-related commodities such as steel and cement, especially in countries of the Commonwealth of Independent States (CIS). In addition, it is probable that the throughput of materials, especially in consumer goods, falls behind OECD levels, considering the low income levels in these countries. This implies that, sooner or later, a catching up of the energy-intensive industry in these countries may be expected.

7. Comparison with World Energy Council projections

It would be interesting to see how the future growth rates that we established would fit in the latest IPCC scenarios (2000). However, the lack of a generic bottom–up specification of the SRES scenarios makes it difficult to relate the established growth figures in this study to any of the SRES scenarios in particular. Instead, we will now compare our estimation of future growth rates with one of the very few scenarios that use physical production levels of energy-intensive commodities. Most scenarios comprise projections in monetary terms, but these may well deviate from physical production growth rates. This is because the valuation of products may alter or because production shifts towards more highly valued products. Farla and Blok (2000), for example, reports, for the Netherlands, a near doubling of value added in refineries in the period 1980–1995, whereas the physical production increased by only 35%.

The World Energy Council (1995), however, did publish an outlook on energy consumption in industry and buildings, which comprises a projection of future physical production in the energy-intensive industry. In this study, various trajectories have been explored, along which energy efficiencies might evolve, but in all scenarios, the same assumptions were made on the growth of physical production. These are presented in Table 6. We want to assess these WEC projections using our own findings. To this end, we corrected, in the upper half of Table 7, the estimations for total growth for population growth in the three sets of countries according to a medium population scenario. In this table, a weighted average for growth in the four subsectors is presented too, based on CO_2 emissions as has been argued and explained in the previous section.

The classification of countries that has been used by WEC (1995) does not match the income-based classification we used, which hampers comparison with our projections in the previous section. Therefore, we will now present our projections for the WEC (1995) classification of countries. Whereas Table 5 included a projection for per capita growth in heavy industry as a whole, Table 8 presents projections for four different subsectors, based on recent trends.

Projections for the different income groups were weighted to estimate future growth in developing countries and in the OECD. In each sector, we

Table 6
Projections of annual growth in total commodity production (%) up to 2020 based on a Business-as-Usual scenario (WEC, 1995)

	Steel (%)	Cement (%)	Paper (%)	Petroleum refining (%)
OECD	0.7	1.0	1.5	1.0
Economies in transition	0.1	1.0	1.5	1.0
Developing countries	4.0	4.0	5.5	3.0

Table 7
Projections of annual growth in per capita commodity production (%) based on a Business-as-Usual scenario from 1990 until 2020 (WEC, 1995) and on this study's projections based on growth trends from the 1980s onwards

	Steel (%)	Cement (%)	Paper (%)	Petroleum refining (%)	Weighted average[a] (%)
Business-as-usual (WEC, 1995)					
OECD	0.2	0.5	1.0	0.5	0.5
Economies in transition	0.3	1.2	1.7	1.2	0.0
Developing countries	2.9	2.9	4.4	1.9	2.7
This study's projections					
OECD	0.6	1.5	2.3	−0.1	0.8
Developing countries	3.6	5.2	4.8	1.2	4.6

Original estimates for total production growth (Table 6) corrected for medium population growth according to UNDP (1999), which estimates annual population growth up to 2020: 0.5% in the OECD, −0.2% in the economies in transition, and 1.1% in developing countries.

[a] Based on CO_2 emissions in the four subsectors.

calculated the weighted average of per capita production growth proportionate to the share of each income group of countries in physical production in that subsector. This resulted in projections for the four subsectors as presented in the lower half of Table 7. Now, we wish to compare these estimations of subsectoral growth rates to the WEC (1995) projections in Table 7.

Overall growth projections, weighted according to CO_2 emissions in the four subsectors, are in the same order of magnitude for the OECD. The overall projection for developing countries presented by WEC (1995) is substantially lower than what can be expected on the base of recent historical growth trends. Considering the subsectors separately, it appears that WEC (1995) projections for steel, cement, and paper production are lower than what might expected, according to the method presented in this article. On the contrary, the WEC (1995) projection seems to overestimate growth in the petroleum refining subsector. Recent history showed an actual decrease in per capita growth in this subsector, which leads to negative growth assumptions according to the method.

Table 8
Projections of per capita commodity production (%) in five income groups of countries based on growth trends from the 1980s onwards

Income group	Steel (%)	Cement (%)	Paper (%)	Petroleum refining (%)
Lower low	5	9	7	2
Upper low	3–3.5	5–5.5	4–4.5	1.5
Lower middle	2.5	1.5–2	2.5	1–1.5
Upper middle	1.5	1.5–2	2.5	0.5
High	0–0.5	1.5	2–2.5	−0.5–0

8. Discussion

We had good reasons to study material flows on a production basis rather than on a consumption basis (see Section 3). However, the implication of doing so is that international trade flows are disregarded. Some countries may produce large volumes of materials for export rather than for domestic consumption. This phenomenon of specialisation should be kept in mind while interpreting Figs. 3–8. For instance, Belgium's per capita stabilisation level for crude steel production is roughly 10 times Ireland's stabilisation level. This difference cannot undo our point that, for certain commodities, there are production stabilisation levels, while for others, such a level is absent. Furthermore, part of the international trade flows takes place within a particular income group of countries, especially the high-income countries. Only large trade flows between income categories would result in a considerable difference between production and consumption growth rates. This regards, in particular, the relocation of raw material extraction and industrial production to less affluent countries in the South. For instance, large exports from low- to high-income countries would imply that historical consumption growth rates in the low-income countries are lower than the production growth rates in Table 5. For HICs, on the contrary, consumption growth rates would exceed the production growth rates in Table 5.

With the number of countries and commodities in our sample, we believe the weighted average growth rates that we have calculated to be rather robust in the near term. Projecting growth rates for scenarios with a time horizon of several decades, however, is more problematic, because countries' industrial production growth will slow down with increasing income. There are several ways to deal with this problem.

One possibility would be to determine ex ante how long a country is to stay in a certain development phase or income group. This could be based on historical information from industrialised countries. However, this would require the rather glaring assumption that all countries undergo development towards a mature infrastructure and a more or less complete consumption package for its inhabitants, no matter how subjective these notions may be, in the same time span. This assumption seems unrealistic and does not do justice to the phenomenon of the rapidly industrialising countries in Asia in the previous decade, or to the existence of some rather stagnating economies.

It seems more suitable, therefore, to judge on the base of per capita income when a country moves to another development stage, since this is the indicator that we used to distinguish between development stages in the first place. This entails that we need an economic scenario. For the purpose of scenario building, several economic scenarios may be used to produce a number of scenarios of commodity production to deal with the uncertainty surrounding future economic developments. For application in a differentiation scheme to calculate future greenhouse gas emission allowances, stakeholders should reach consensus on the appropriate economic baseline.

One might argue that, despite our objections to the uncertainties surrounding economic scenarios, still, economic scenarios are needed to describe per capita income as an indicator for development. However, we are of the opinion that, even so, projections on a per capita basis may still be more robust than projections that draw from historical I-U trends.

This is particularly obvious for high-income countries. These countries have already reached the upper step of the development ladder. It can be assumed that they will remain high-income countries (for which, of course, no guarantee exists, but which is an assumption most people would probably endorse), and no economic scenario is needed to determine their trajectory towards economic maturity. Based on aggregate per capita production, growth in these countries can be assumed to remain below 1%.

Furthermore, our study resulted in the recommendation to use 1% growth for per capita production in both upper and lower middle-income countries. These similar rates imply that, once a country passed the lower threshold of the middle-income category, the exact per capita income does not affect the applicable growth rate until it enters the high-income group. Thus, the question regarding per capita income need not be answered very precisely for middle-income countries.

The choice of an appropriate growth rate may be most tricky for the low-income countries. Their precise trajectories of per capita income determine at what moment per capita production growth is adjusted. Considering the high growth rates (in the order of 3–4% to 6%), this adjustment is a sensitive matter, more so than for the middle-income countries. However, it seems to us that this uncertainty cannot be circumvented by projecting low-income developments from historic trends of material intensity in these regions' economies. Whereas the uncertainty surrounding the economic future would be the same in both cases, there is no evidence that historical material intensity trends in low-income countries would be more robust than per capita production levels. On the contrary, economic fluctuations in these countries may easily affect material intensity, whereas the size of the population is a more constant quantity. Therefore, starting from historic per capita production trends is likely to be the lesser of two evils.

Finally, the implications of our recommended growth projections for global emissions and international climate policy are worth considering. Naturally, the precise consequences for emissions growth would require including technological developments and population growth.

A technology assessment of six branches of heavy industry would be outside the scope of this paper. Nevertheless, if technological development is disregarded and emission growth is assumed to be much like per capita production growth, some general statements can be made with respect to consequences for international climate policy.

Our findings imply that low-income countries are attributed large production growth rates in differentiation schemes for emissions allowances, contributing to large emission allowances for these countries. This is particularly important for developing countries that are on the rim of taking up mitigation commitments. The implications thereof are twofold.

On the one hand, such room for growth might well appeal to developing countries. It might increase their willingness to join a global climate regime, which is vital for successful climate change mitigation (see, e.g., Berk and den Elzen, 2001). On the other hand, attributing large room for emissions growth to developing countries involves the risk of creating hot air. Countries for which actual emission developments for one reason or another remain below their assigned growth might sell their surplus to industrialised countries. These can use their acquired emission rights to comply with their own targets with a diminished domestic effort or a reduced acquisition of permits in Joint Development projects or projects under the Clean Development Mechanism abroad.

For this reason, some have argued that baseline assessment for developing countries should be discarded altogether (Baumert et al., 1999; Philibert and Pershing, 2001). They prefer decarbonisation commitments for these countries, specifying the greenhouse gas intensities of their economies. However, autonomous decarbonisation trends for developing countries vary substantially (Baumert et al., 1999), and specifying reasonable decarbonisation objectives may well be equally awkward. The debate on this is likely to continue over the coming years.

9. Conclusions

In this study, we found distinct patterns in the growth of per capita production of various energy-intensive commodities. Since the 1980s, crude steel and cement and the refining industry show increasing production levels with increasing per capita income and stabilising levels in high-income countries. Per capita aluminium production shows a rather weak relationship to income. Petrochemical and total paper and board production per capita do not level off with increasing income. The latter makes it unlikely that the intensity of use of these materials, i.e., material flows expressed per unit of GDP, would decrease already.

We have classified countries on the basis of their stage of development using GDP per capita as a proxy. We then calculated overall historical growth rates as the weighted average of growth in the different subsectors with weights proportionate to CO_2 emissions in the subsectors.

Based on these recent per capita growth rates in the energy-intensive industry, we project aggregate growth rates of industrial production per capita for the coming decades of around 6% for the lower low-income, 3–4% for the upper low-income, 1% for the middle-income, and 0.5–1% for the high-income countries. These growth rates should be understood as generic figures describing roughly how per capita growth differs between countries in varying development stages and should be combined with a population scenario. Various economic scenarios may serve to indicate countries' possible development trajectories, to pick appropriate growth rates at any particular moment in the future. Our growth estimations compare fairly well with the growth of overall industrial production in physical terms, as projected by the World Energy Council (1995) for the OECD. However, WEC projections for the developing world seem on the low side, in particular, for the cement industry.

The results may serve as useful input for the construction of short- and medium-term bottom–up scenarios, and in differentiation schemes for greenhouse gas emission allowances. They may help to underpin more precisely developing countries' claims for sufficient room for emissions growth to accommodate their development, although technological improvement may cause emission growth to be lower than the growth in commodity production.

Projecting emission growth trends is not a simple matter. Nevertheless, per capita growth rates of historical and future physical production of energy-intensive commodities in this study combine a firm empirical basis with state-of-the-art theoretical insights. Thus, rather than having a intuitive shot at future emissions from heavy industry, new projections may be underpinned in a manner that does justice to reality.

Appendix A

Table A1
Countries included in the calculation of historic growth rates of per capita production output in six industrial subsectors

	Per capita income (1995 US$)[a]	OECD	Crude steel	Cement	Total aluminium	Total paper and board	Key petrochemicals	Crude oil input
Lower low income								
India	1812		•	•	•	•		•
Upper low income								
Brazil	4644		•	•	•	•	•	•
China	4877		•	•	•	•	•	•
Indonesia	4338		•	•	•	•		•
Iran	4846		•	•	•	•		•
Economies in transition								
Bulgaria	2834		•	•		•	•	•
Czech	7662	X	•	•		•	•	•
Estonia	2151			•		•	•	
Hungary	4558	X	•	•	•	•	•	•
Kazakstan	1233		•	•			•	•
Latvia	1380			•		•		
Lithuania	2435			•		•		•
Poland	4251	X	•	•	•	•	•	•
Romania	2581		•	•	•	•	•	•
Russia	2077		•	•			•	•
Slovakia	4389		•	•		•		•
Ukraine	885		•	•			•	•
Lower middle income								
Argentina	8100		•	•	•	•	•	•
Mexico	6746	X	•	•	•	•		•
South Africa	5392		•	•		•		•
Turkey	5519	X	•	•	•	•	•	•
Upper middle income								
Greece	10462	X	•	•	•	•		•
Portugal	11989		•	•	•	•		•
Saudi Arabia	9953		•	•		•		•
Thailand	10439		•	•		•		•
High income								
Australia	18606	X	•	•	•	•		•
Austria	19360	X	•	•	•	•		•
Belgium	19185	X	•	•	•	•		•
Canada	18742	X	•	•	•	•	•	•
Denmark	18551	X	•	•	•	•		•
Finland	14297	X	•	•	•	•		•
France	18488	X	•	•	•	•	•	•
Iceland	16124	X		•	•			
Ireland	21061	X	•	•		•		•
Italy	16920	X	•	•	•	•	•	•
Japan	20642	X	•	•	•	•	•	•
Malaysia	14907		•	•		•		•
Netherlands	18200	X	•	•	•	•	•	•

Table A1 (*continued*)

	Per capita income (1995 US$)[a]	OECD	Crude steel	Cement	Total aluminium	Total paper and board	Key petrochemicals	Crude oil input
High income								
Norway	20416	X	•	•	•	•		•
New Zealand	14985	X	•	•	•	•		•
Singapore	33639		•	•		•		•
South Korea	17004	X	•	•	•	•	•	•
Spain	13425	X	•	•	•	•	•	•
Sweden	15419	X	•	•	•	•	•	•
Switzerland	19682	X	•	•	•	•		•
United Kingdom	16426	X	•	•	•	•	•	•
United States	23790	X	•	•	•	•	•	•

[a] Based on purchasing power parity.

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