

# INDUSTRIAL ECOLOGY AND MATERIAL FLOW ANALYSIS

Basic concepts, policy relevance  
and some case studies\*

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The core of industrial ecology as an emerging scientific field is the study of the **industrial metabolism**. The aim is to understand the functioning of the physical basis of our societies, the interlinkages of processes and product chain webs within the ‘anthroposphere’ and the exchange of materials and energy with the environment. However, the interest goes further to the question of how to develop the industrial system in a way that essential requirements of sustainability can be met (for a historical review, see Erkman 1997). The basic concept is that the industrial system and its societal interactions are embedded into the biosphere–geosphere system and are thus dependent on factors critical for the coexistence of both systems (Ayres and Simonis 1994; Baccini and Brunner 1991). The paradigmatic vision of a sustainable industrial system is characterised by minimised physical exchanges with the environment, with the internal material loops being driven by renewable energy flows (Richards *et al.* 1994). However, in the current situation the industrial metabolism is still depleting its resources and overloading the environment with wastes and emissions in many respects.

Analysis of a variety of material and substance flows has provided interesting insights into the industrial system and has led to the discussion of examples and strategic levers for improvement (Ayres and Ayres 1996). Recycling of materials, optimisation of cascaded use and increases in energy efficiency and in solar inputs may all contribute to sustaining the industrial metabolism (Graedel and Allenby 1995).

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The findings of industrial ecology research are increasingly being used in practice. However, the influence on public policy is still rather limited and a broad-scale application of its principles is not yet in sight. The reasons are plentiful. One reason seems to be a missing link between research and the proposal of concrete political targets. In addition, monitoring instruments for the industrial metabolism that can be applied not only for single technologies but also for whole countries are lacking. Moreover, the linkage of material flows and economic factors has not yet received sufficient attention in research and policy.

As a result of scientific findings, traditional environmental protection started in the 1970s to control specific pollutant flows. The release of eco-toxic substances such as heavy metals and chlorinated chemicals was limited to critical levels. In the 1980s end-of-pipe measures were increasingly being substituted for integrated pollution control (i.e. by steering processes within the industrial metabolism). However, none of these measures seemed to have a significant effect in terms of the resulting quantity and quality of the material and energy throughput. Thus the industrialised economies were not able to serve as a model for worldwide and future development. Instead, the greening of industry (e.g. through the use of catalytic converters on motor vehicles, the use of waste incinerators and the adoption of recycling systems) to a significant extent solved the immediate concerns by shifting the problems to, for example, other media or other countries. Moreover, an increased demand for products (e.g. cars) counteracted the results of the use of cleaner technologies in the industries concerned.

In the 1990s, another, more pragmatic, approach to influencing societal metabolism was started from science-based non-governmental organisations (NGOs) in Europe, beginning with a study on Action Plan Sustainable Netherlands (Buitenkamp *et al.* 1992). The disparity between industrialised and developing countries was seen to contradict the equity principle that had been declared a constituent element of sustainable development in Agenda 21 at the 1992 Earth Summit at Rio de Janeiro. As a pragmatic policy goal a reduction of between 80% and 90% of primary resources and emissions to air was recommended for the Netherlands in order to allow the necessary environmental space for each person (Weterings and Opschoor 1992).<sup>1</sup>

Schmidt-Bleek (1992) proposed a factor of 10 (**Factor 10**) as a general goal for the increase of resource productivity of industrialised countries within the following 50 years in order to cut in half the global resource requirements. Later, von Weizsäcker *et al.* (1995) suggested the more moderate Factor 4. The proposals were based on a systems perspective according to which the volume of outputs of the anthroposphere must not be reduced whereas the 'input locks' are left open. It also reflected the fact that the enormous material flows do not enter the economy but are moved in mining and agriculture to obtain the use of raw materials. These 'ecological rucksacks' (Schmidt-Bleek 1994b) or hidden flows of primary production burden the environment locally by devastation of natural habitats, groundwater contamination, landscape changes and so on.

The Factor 4 and Factor 10 concepts have attracted international attention and created remarkable resonance with politicians as well as industrial decision-makers. The main reason has been the reconciliation of economic and ecological requirements. The task is to provide better services and continuous welfare with less resource consumption. Expe-

1 The required environmental space reflects the eco-capacity of resource availability and waste assimilation (see Weterings and Opschoor 1992).

rience and examples are increasing indicating that this is indeed possible (see also the contribution of Stahel in this volume). However, the effect on the overall performance of industrial systems has still to be proven.

Thus an assessment of the industrial metabolism in terms of sustainability requires an analysis of critical substance flows and total material throughput (Bringezu 2000). Here, I will shortly discuss the complementary function of both types of analysis. Before the background of the actual debate on policy goals, I will examine the total resource requirements and major emissions of selected industrialised countries in relation to their economic performance.

## 1.1 Analyses of industrial metabolism

Understanding the structure, quantity and quality of the industrial metabolism depends on analyses of material flows from resource extraction to final waste disposal. Such analyses can be directed at:

- Products and services on a life-cycle basis. Here the methods of life-cycle assessment (LCA) provide comprehensive insights, and methods that determine certain key parameters such as cumulative energy requirements (CERs) or material input per service unit (MIPS) can be used to quantify cumulative resource requirements.
- Firms. The physical balance of inputs and outputs is increasingly being used as part of an environmental performance report and provides substantial information for environmental management.
- Sectors and branches. Bottom-up or, to a larger extent, top-down approaches are used to analyse the flows of materials through industrial sector.
- Communities, regions and national economies. The metabolism of these entities is becoming more and more important as a basis for policy decisions; monitoring instruments are being developed with respect to the sustainable supply and use of resources, on the one hand, and emissions to the environment, on the other hand.

Since the mid-1990s, analyses of material flows through regional economies, up to the level of economic regions such as the European Union and down to the firm level have been addressed under the title of 'material flow analysis' (MFA).

MFA has become a fast-growing field of research with increasing policy relevance. However, there are various methodological approaches that are based on different concepts and target questions, although each study may claim to contribute to sustaining the industrial metabolism (Table 1.1). However, the strategies used to pursue that aim are basically quite different. On the one hand, the 'detoxification' of material flows and the reduction of environmental pollution are traditionally assumed to be important goals. On the other hand, the 'dematerialisation' and the restructuring of the industrial or societal metabolism—especially in terms of resource productivity—is increasingly being

	<b>Basic strategy</b>	
	Detoxification and pollution reduction	Dematerialisation and eco-restructuring
<b>Accounting type</b>	<b>I</b>	<b>II</b>
Objects of primary interest	Specific environmental problems related to certain impacts per unit of flow of substances (e.g. Cd, Cl, Pb, Zn, Hg, N, C, CO <sub>2</sub> , CFCs) and materials (e.g. wooden products, energy carriers, moved masses, biomass, plastics) within certain compartments, sectors and regions	Problems of environmental unsustainability related to the volume and structure of the throughput of sectors (e.g. production sectors, the chemical industry, the construction industry) and regions (e.g. total or main throughput, mass flow balance, global material input) associated with substances or materials

C, carbon; Cd, cadmium; ; CFCs = chlorofluorocarbons; Cl, chlorine; CO<sub>2</sub>, carbon dioxide; Hg, mercury; N, nitrogen; Pb, lead; Zn, Zinc

Table 1.1 **Basic types of material flow analysis for achieving the conceptual target of environmental sustainability**

Source: Bringezu and Kleijn 1997

advocated as a prerequisite for environmental sustainability. Consequently, either the impact potential per unit of material flow or the volume and structure of material flows attract special attention. In the end, both strategies will be necessary to foster sustainable development and they should be addressed as being complementary rather than as being exclusive.

Based on these different views, however, the starting point for MFA may be different. Although a continuum of different approaches exists in practice, two basic types of accounting may be distinguished according to the objects of primary interest.

Type I accounting starts with specific problems related to selected substances or materials. The flow of eco-toxic substances such as heavy metals is studied because these substances are associated with environmental problems (e.g. through accumulation). The flow of nutrients such as nitrogen is accounted for because it may be critical in eutrophication. The flow of carbon is studied because it is associated with, for example, global warming. The flows of chlorinated substances are quantified because they are rendered to be critical for various pollution problems. Selected flows of materials may also be of interest. Energy carriers, moved masses, plastics, wooden products, biomass and metals may be associated with certain environmental pressures and/or may be studied in order to optimise economic use or to improve recycling and cascading strategies. Studies relating specified emissions to the production of base materials or to the various sectors of industry lead to the next type of analysis.

Type II accounting starts with the question of whether the volume and structure of the throughput of selected sectors or regions is sustainable. For instance, industrial sectors

such as the chemical or construction industries are studied with respect to their throughput of substances or materials. Cities, regions or national economies are studied with regard to selected material flows, the total material throughput or the global material requirements. One major aim of such studies is the derivation of indicators of environmental pressure. This refers not only to total mass throughput but also, for instance, to the relation between renewable and non-renewable inputs or the amount of materials shifted from the Earth's crust to the atmosphere, in order to indicate structural properties of the regional metabolism.

## 1.2 Policy relevance

Following the realisation of the existence of environmental problems and the history of environmental protection since the 1990s, Type I analyses were applied first to control the flow of hazardous substances such as heavy metals. Substance flow analysis has been used to determine the main entrance routes to the environment, the processes associated with these emissions, the stocks and flows within the industrial system and the resulting concentrations in the environment (Udo de Haes *et al.* 1997).

The conclusions of governmental policy based on substance-flow analyses of heavy metals and chlorinated compounds have been described by Bovenkerk (1998) and Hansen (1998) for pollution control in the Netherlands and in Denmark, respectively. The results contributed to policy in different ways:

- An integrated view of the many types of data relevant for specific substance flows supported strategic and priority-oriented design of control measures.
- The analyses assisted in finding a consensus on the data, which is an important prerequisite for policy measures.
- MFA led to new insights and to changes in environmental policy (e.g. the abandonment of the aim of closed chlorine cycling in favour of controlling the most hazardous emissions).
- The analyses discovered new problems (e.g. the mercury stocks in chlorine plants).
- They also contributed to the discovery of new solutions (e.g. source-oriented input reduction in the case of non-degradable substances).

There was a significant influence on policy, at least in some cases. From a government point of view, however, analyses of single substance flows are a rather costly and time-consuming effort. They should be commenced only when a sufficient level of detail and limitations of the analysis have been clarified.

The impact of substance-specific findings is not restricted to government policy but includes industry itself, especially when related to certain products. Lifset (1999a) reports on the effect of a scientific debate on the assessment of lead emissions associated with electric vehicle production, arising from increased use of lead–acid batteries. Lave *et al.* (1995) calculated that the total amount of lead discharged into the environment from all

phases of the battery life-cycle exceeded the amount that would be released if a conventional vehicle with an internal combustion engine were to be supplied with leaded gasoline. Socolow and Thomas (1997) responded, arguing that a proper risk assessment should also consider the different types of mobilisation and bio-availability of the resulting emissions. The debate pressured the lead and battery industry to attend to those issues in order to counter criticism.

The policy relevance of Type II analyses has been increased in recent years, in three interrelated ways:

- The provision of material flow accounts for regular use in official statistics
- The derivation of indicators for progress towards sustainability
- The support for policy debate on goals and targets

Whereas European statistics in the 1980s started to use Type I analyses, economy-wide MFAs of Type II started to play a significant role in the 1990s (Beltran 1998; Eurostat 1997). Material flow accounts of national economies have been used for integrated environmental and economic accounting in Germany (Radermacher and Stahmer 1998), Denmark (Peddersen 1999), Finland (Hoffrén 1999) and Japan (Environment Agency of Japan 1998; see also Moriguchi 1998). The accounts may provide:

- An overview of the material throughput of the economy
- Insight into the material metabolism of the economy by sector
- A basis for the derivation of indicators for sustainability
- Information on the eco-efficiency of the economy

On the one hand, the structure of the different input and output flows of the economy provides information that goes beyond singular indicators. On the other hand, MFA can be used to derive aggregated indicators for sustainability, especially those relating to pressures on the environment and their relation to economic performance (Berkhout 1999; Bringezu 1997). The intention is for them to provide the basis for political measures and the evaluation of the effectiveness of those measures, although they are rarely used for that purpose as yet. For this purpose, bulk material flow analyses and substance flow analyses could be combined, and the monitoring of progress towards sustainability could be gradually improved in a stepwise approach (Bringezu 1999; Bringezu *et al.* 1997a).

The policy relevance of MFA has increased significantly with the growing acceptance of the goal of achieving Factor 4 or Factor 10. Similarly, the availability of empirical studies (see below) on economic metabolism has underpinned the necessity for such an increase in resource productivity. At the programme level, the Factor 4 and Factor 10 concepts were adopted by a special session of the United Nations (UNGASS 1997: paragraph 28) and the World Business Council for Sustainable Development (WBCSD 1998). The environmental ministers of the Organisation for Economic Co-operation and Development (OECD 1996a) expected progress towards this end. In Japan a Factor 10 Institute has been founded. Several countries included the aim in political programmes (e.g. Austria, the Netherlands, Finland and Sweden; see also Gardener and Sampat 1998). In Scandinavian countries research was launched to test the broad-scale feasibility of Factor 4 or Factor 10

improvements (NCM 1999). In Germany the draft for an environmental policy programme (BMU 1998) referred to a factor 2.5 increase in productivity of non-renewable raw materials (from 1993 to 2020). An increase in eco-efficiency is also being regarded as essential by the environmental ministers of the European Union (1999: paragraph 3). Certainly, these goals will have to become more concrete policy targets. The definition of reference categories, the setting of target values and the monitoring of the effectiveness of any measures will depend on available statistics and assistance provided by MFA.

### 1.3 Selected results of material flow analysis

One of the case studies that significantly influenced the political debate and stirred further MFA research was the *Resource Flows* report by Adriaanse *et al.* (1997). In a comparative manner the total material resource requirements of four industrial countries were determined.

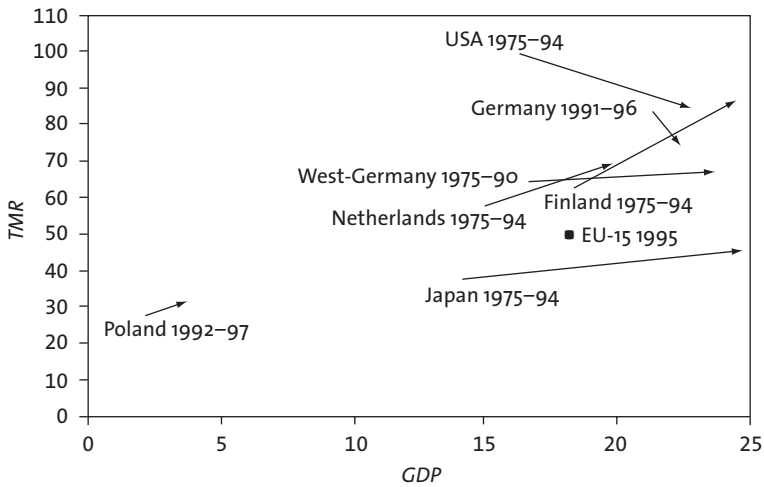
The total material requirement (TMR) is the total mass of primary materials extracted from nature to support human activities. Thus, TMR may be used as a highly aggregated indicator for the material basis of an economy. TMR includes materials used for further processing (direct material input [DMI]) and hidden flows—that is, extracted material that is not used further but that has an environmental impact (e.g. overburden and extraction waste). TMR includes all extracted materials, excluding water and air, both those obtained from domestic territory and those associated with imports. Changes in the balance between the foreign and the domestic amount of TMR indicate possible shifts in environmental impact between countries.

The TMR value indicates the generic pressure on the environment, giving information similar to that obtained from calculation of energy requirements and water consumption. Whereas primary energy requirements are restricted to energy carriers and are measured in joules, TMR comprises non-energetic primary materials and is measured in tonnes. The volume of resource extraction determines the scale of local disturbances (by total extraction, including hidden flows), the throughput of the economy (DMI) and subsequent amounts of emissions and wastes.

After first calculations of the TMR for Germany (Bringezu 1997; Bringezu and Schütz 1995),<sup>2</sup> Adriaanse *et al.* (1997) also determined the TMR for the USA, the Netherlands and Japan. Meanwhile, the method has also been applied for Finland (Mäenpää and Juutinen 1999; Muukkonen 2000), Poland (Mündl *et al.* 1999; Schütz *et al.* 2002), Italy (de Marco *et al.* 1999), China (Chen and Qiao 2000), the United Kingdom (Bringezu and Schütz 2001a) and the European Union (Bringezu and Schütz 2001b, 2001c). A first approach was started for Egypt (el Mahdi 1999).

In 1995, the EU's TMR amounted to 18.1 billion tonnes, or 49 tonnes per capita (Fig. 1.1). This is significantly lower than that for the USA for 1994 (84 tonnes per capita), but higher than that for Japan (45 tonnes per capita) for 1994. Both the USA and Japan have a higher gross domestic product (GDP) per capita than the EU. In comparison, the GDP per capita for Poland was 20% of that for the EU in 1995, but the TMR per capita was

2 In these publications, the term 'total material input' (TMI) was used rather than TMR.



Note: GDP per capita is measured at constant 1990 prices and exchange rates.

Figure 1.1 **Total material requirements (TMR; in tonnes per capita) and gross domestic product (GDP) per capita (in thousands of US dollars) of the European Union compared with selected member states and other countries**

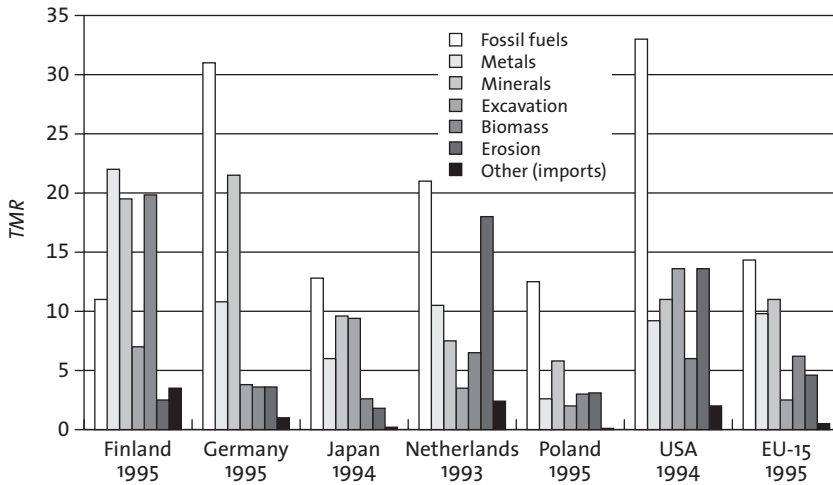
Sources: Adriaanse *et al.* 1997; Bringezu and Schütz 2001b, 2001c; Mäenpää and Juutinen 1999; Mündl *et al.* 1999

almost 60% of that of the EU. Owing to the materials involved and their hidden flows, the EU's TMR is dominated by energy, metals and mineral resources.

With respect to future development the question arises whether the EU—or countries such as China where first data indicate a TMR–GDP relation similar to that of Poland—can successfully decouple further economic growth and TMR and improve resource productivity even further than countries such as Japan. In 1994 the materials productivity of Japan was 1.5 times higher than that of the EU-15 in 1995. One may expect that the materials productivity of a country such as Poland will need to rise 3.1 times simply to approach the current EU average. Nevertheless, within EU-15 there is a significant range of materials productivity. Materials productivity in Finland, the Netherlands and Germany are all below the average level (62%, 80% and 87%, respectively).

The main reason for the much lower total resource requirements in the EU compared with the USA is the difference in material flows related to fossil fuels. Owing to less use of energy in the EU and a reduced use of coal, Europe's fossil fuel resource requirements are only 44% of those of the USA (Fig. 1.2).

The analysis of the composition of TMR reveals differences in national patterns of material requirements. Germany, for example, still depends to a large extent on coal extraction; material flows related to fossil fuels are the same order of magnitude as in the USA. Germany and Finland have the highest rate of mineral extraction because of the extraction of sand and gravel, as well as natural stones, in Germany and gravel extraction in Finland. German TMR values for minerals are twice those for the EU as a whole as a



Note: hidden flows are included in fossil fuels, metals and minerals or are represented by excavation and erosion.

Figure 1.2 **Composition of total material requirement (TMR; in tonnes per capita) in the European Union, selected member states and other countries**

Sources: Adriaanse *et al.* 1997; Bringezu and Schütz 2001b, 2001c; Mäenpää and Juutinen 1999; Mündl *et al.* 1999

result of construction work on houses and infrastructure that still relies on high inputs of minerals for concrete. In Finland, where metal manufacturing still represents a significant element of industrial production, resource requirements for metals are relatively high. The same is true for biomass in Finland, which is dominated by forestry (timber is a significant Finnish export). The high material flows associated with erosion in the Netherlands reflect the large quantity of agricultural imports from non-European countries. Products such as coffee and cocoa that are traded and processed in the Netherlands are associated with high levels of erosion in countries of the southern hemisphere.

When comparing countries for which the TMR as well as the DMI have been calculated, there is an indication that DMI is correlated with TMR. If such a correlation (which is significant for six countries and the EU) could be corroborated, the more easily calculated DMI could be used to monitor materials productivity regularly. A full domestic TMR still needs to be determined if the burden of resource extraction on the national environment is to be assessed. In addition, foreign TMR can be used to indicate the sharing of burdens and the shifting of problems between countries and regions. In general, DMI increased with growing GDP in the member states of EU-15 from 1980 to 1997 (Fig. 1.3). However, the level of DMI and GDP as well as the individual trends varied considerably.

In the study period France and Germany managed to increase their GDP with reduced DMI. With reduced extraction of building minerals and fossil fuels both countries proved that absolute dematerialisation is possible. Constant levels or relatively moderate increases of DMI can be recorded for Finland, the Netherlands, the United Kingdom, Italy

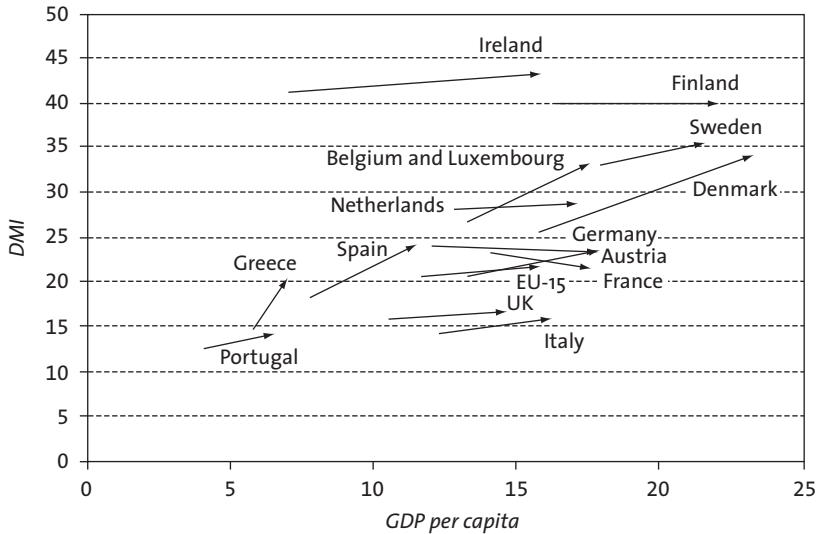


Figure 1.3 **Trend of direct material input (DMI in tonnes per capita) and gross domestic product (GDP) per capita (in thousands of 1990 ECU) in the 15 member states of the European Union between 1980 and 1997**

Source: Bringezu and Schütz 2001c

and Sweden. In the other countries increase of resource productivity (based on DMI) was associated with significantly raised DMI.

With regard to the level of DMI, two groups can be distinguished:

- Group A. DMI less than 25 tonnes per capita: Austria, France, Germany, Greece, Italy, Portugal, Spain, the United Kingdom
- Group B. DMI greater than 25 tonnes per capita: Belgium and Luxembourg, Denmark, Finland, Ireland, Netherlands, Sweden

With respect to the level of direct materials productivity (GDP/DMI), three groups can be distinguished:

- Group 1. GDP/DMI greater than ECU 0.74 per kilogram: Austria, France, Germany, Italy, the United Kingdom
- Group 2. GDP/DMI ECU 0.50–0.74 per kilogram: Belgium and Luxembourg, Denmark, Finland, Netherlands, Sweden
- Group 3. GDP/DMI less than ECU 0.50 per kilogram: Greece, Ireland, Portugal and Spain

This shows that there is no simple linear relation between DMI and GDP per capita. High per capita DMI values tend to be associated with high GDP. However, low per capita DMI

can be found in countries with high or low GDP per capita. Again, this shows that GDP is not an appropriate indicator for material resource flows and the related environmental pressure. The finding underpins the use of a physical indicator such as DMI for considering the material flow implications of economic performance. It should be noted that the values of the EU member states do not add up to the EU value because member states' DMI include intra-EU trade whereas the DMI of the EU does not.

Heading towards increased materials productivity and dematerialisation, countries of group 3 are challenged to stabilise material requirements while growing further in economic terms. Countries of group 2 have the highest DMI per capita and should strive to move forward to absolute delinking. Countries of group 1 are ahead and should continue to strengthen activities that lead towards dematerialisation and resource efficiency.

The overall performance of the EU-15 will depend on the success of each of the member states to define and implement policies that foster a further development of increased resource productivity. A variety of measures can be taken to support technological and societal innovation. Improved information and education, the implementation of demand-side management and recycling strategies, a shift towards service provision instead of selling hardware and integrated resource management on various levels may all contribute towards this future.

Of course, such measures would not only diminish resource inputs but also, at the same time, the output flows to the environment. In an internationally comparative study these flows were quantified by Matthews *et al.* (2000). In an internationally comparative way their work provided interesting insights into the industrial metabolism. Waste deposition, emissions to air and water, and dissipative use of products (including fertiliser, manure, sewage) were considered comprehensively. The output flows are attributed to the releasing sectors (agriculture, manufacturing, energy supply, transport, households).

The following results seem to be of special importance:

- Outputs from processed materials (without hidden flows) exhibit a rather constant trend in each of the studied countries between 1975 and 1996. This leads to a relative decoupling from GDP (Fig. 1.4). Thus, by and large, the situation on the output side reflects the tendencies on the input side (which is only trivial for constant stock or stock change). Regarding both inputs and outputs in relation to economic performance, the eco-efficiency of the countries studied has increased, whereas the absolute burden to the environment due to material flow volumes has not decreased.
- Whereas some emissions (e.g. sulphur dioxide) could be significantly reduced (Fig. 1.5) by specific policy measures and the use of cleaner production technologies, the overall amount of releases to the environment remained constant. Here, the limitation of traditional pollution control becomes obvious, not being designed comprehensively to diminish outflows to the environment. A wider systems perspective of MFA now allows us to detect shifts of environmental burden.
- The dominant emission from processed materials is carbon dioxide. The trends within the studied countries give rise to serious doubts whether the Kyoto Protocol targets will be met. In the countries studied so far no significant decline can be measured (Fig. 1.6).

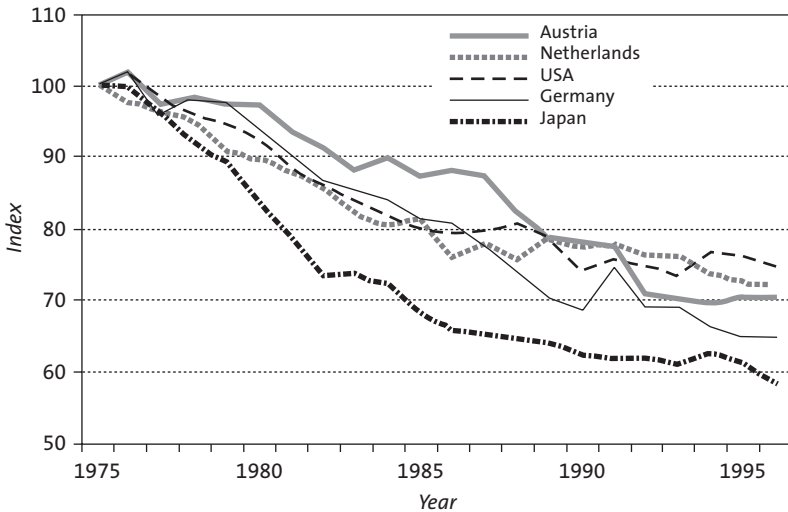


Figure 1.4 **Waste intensity of industrial countries: domestic processed output (DPO) per GDP. DPO comprises the total amount of waste deposition, releases to air and water, and dissipative use of products, without hidden flows. West German data from 1975–90.**

Source: Matthews et al. 2000

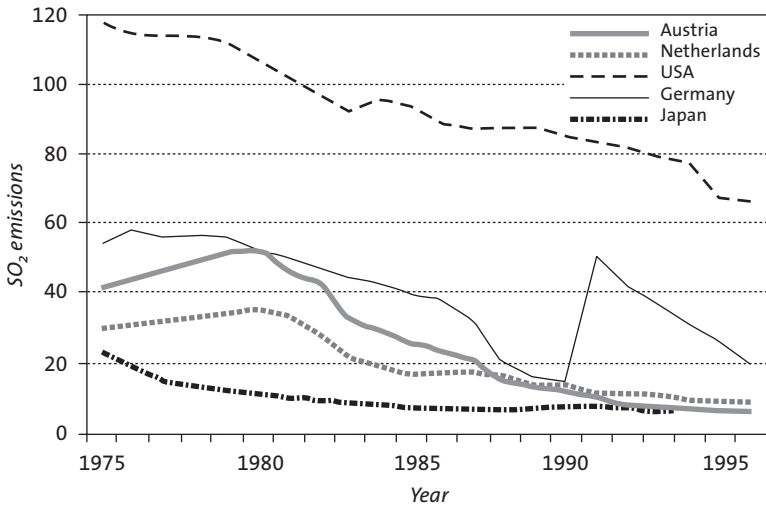


Figure 1.5 **Emissions of sulphur dioxide (SO<sub>2</sub>; in kilograms per capita). West German data from 1975–90.**

Source: Matthews et al. 2000

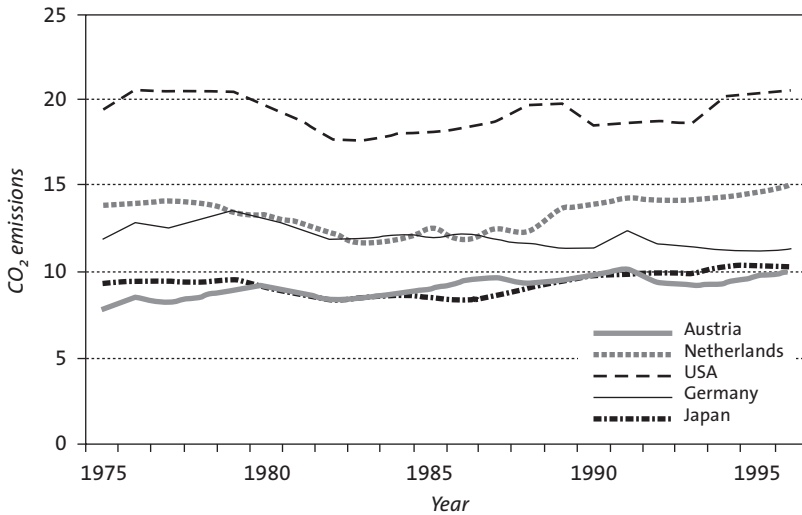


Figure 1.6 **Emissions of carbon dioxide (CO<sub>2</sub>; in tonnes per capita), including combustion products from use of bunkered fuels. West German data from 1975–90.**

Source: Matthews et al. 2000

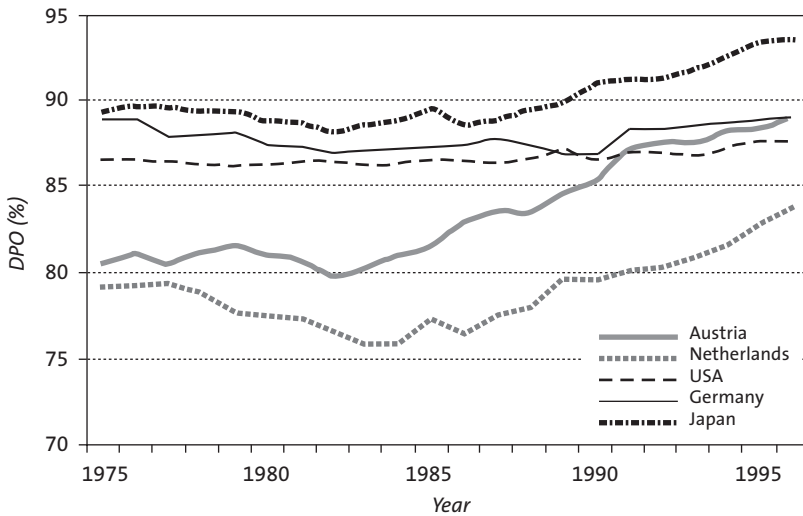


Figure 1.7 **Percentage of domestic processed output (DPO) released to the atmosphere. West German data from 1975–90.**

Source: Matthews et al. 2000

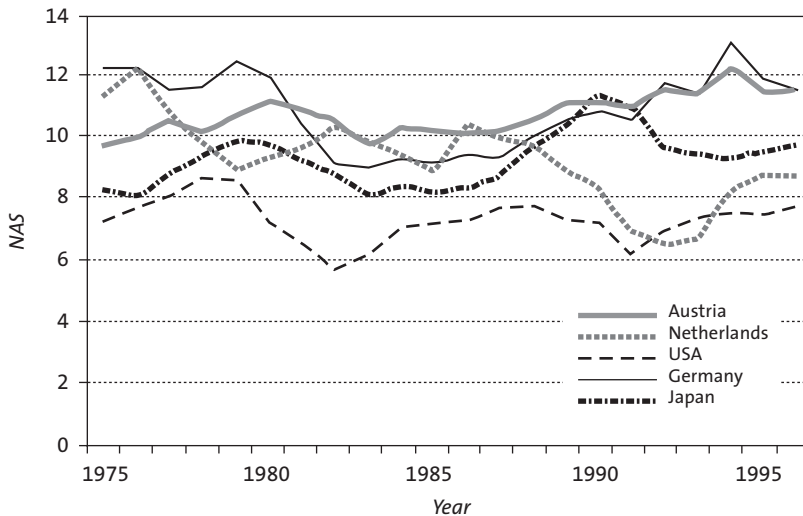


Figure 1.8 **Net addition to the stock of materials (NAS; in tonnes per capita) within the 'technospheres' of the studied countries. West German data from 1975–90.**

Source: Matthews *et al.* 2000

- The proportion of outputs that is released to the atmosphere is increasing significantly (Fig. 1.7). This also results from effective measures to reduce waste deposition by recycling and incineration. As a consequence, there is an increasing tendency to globalise the impacts of national activities on the environment.
- There is a considerable net addition to the stock (NAS) of materials (measured by material balancing of the whole economy and cross-checked with an analysis of construction material flows). Despite international differences and national fluctuations, the rate of physical growth of the 'technosphere' remains constantly high in most of the studied countries (Fig. 1.8). This further contributes to a loss of reproductive and natural land (built-up area) and increases requirements for maintenance. Altogether, there is no significant indication of a tendency towards a flow equilibrium between inputs and outputs (NAS = 0 tonnes per capita). This would be a necessary condition for a metabolic situation that can be sustained.

## 1.4 Conclusions

- Understanding industrial metabolism is the basis of industrial ecology research and requires the analysis of material flows on different levels and various scales.
- Material flow analysis (MFA) on the regional or (supra)national level examines factors critical for sustaining the industrial metabolism. The focus may be on flows of specific hazards (per unit of flow), or the analysis may be driven by an interest in the volume and structure of the (total) system throughput. Both approaches are complementary rather than exclusive, reflecting that detoxification of the industrial metabolism is necessary as well as dematerialisation of today's industrial economies in order to sustain the physical exchange with the environment.
- MFA has contributed to the management of critical substance flows. It is increasingly gaining policy relevance in operationalising the Factor 4–10 concept, which aims to change the interlinkage of economic performance and resource requirements.
- Economy-wide MFA can be used to derive indicators for sustainability and to examine whether necessary conditions for a sustainable industrial metabolism are being met.
- International MFA comparisons reveal similarities as well as differences in the metabolism of industrial economies. Although the composition of materials may be different in the studied countries, there has been a trend of decoupling of economic growth and total throughput of processed materials, the latter remaining at a rather constantly high level.
- MFA reveals the physical growth of industrial economies and the increasing shift of material flow burden between environmental media and towards other countries. These aspects will require more attention and research for sustaining the societal metabolism in the future.