

Society's Metabolism

The Intellectual History of Materials Flow Analysis, Part II, 1970–1998

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Summary

"Societal metabolism" provides the appropriate conceptual basis for the rapidly growing development and analytical and policy interest in materials flow analysis (MFA). Following the review of the earlier intellectual background of societal metabolism in the first installment of this two-part article, this paper focuses on the current state of the art by examining more recent research referring to societal metabolism in terms of material and substance flows. An operational classification of the literature according to frame of reference (socioeconomic system, ecosystem), system level (global, national, regional, functional, temporal), and types of flows under consideration (materials, energy, substances) highlights some of its characteristic features. There follows an integrated discussion of some of the major conceptual and methodological properties of MFA, with a particular focus on the field of bulk materials flows on a national level, comparing the major empirical results. Finally, the theoretical stringency, research productivity, and political relevance of the MFA-related studies are assessed.

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Introduction

Here we continue a literature review on "society's metabolism," or materials flow analysis (MFA), examining the more recent time period from 1970 to 1998. Part I of this review (Fischer-Kowalski 1998) was devoted to the intellectual background of this concept from the nineteenth century and across various disciplines. It closed with a description of the approaches of those pioneers in the late 1960s that may be looked upon as founders of a new research tradition. This research tradition examined society's metabolism in the light of environmental concerns—a focus that has become increasingly productive since then.

For the sake of this wider perspective, we have stuck to the general concept "society's metabolism," instead of the maybe more common term "industrial metabolism" (as coined by Ayres 1989). Whereas industrial metabolism may be thought of as "the whole of the materials and energy flows going through the industrial system" (Erkman 1997, 1), society's metabolism, or (interchangeably) socioeconomic metabolism, does not restrict its coverage to industrial societies but also refers to nonindustrial modes of subsistence. For the review at hand, this does not make much of a difference: The bulk of contemporary literature on socioeconomic metabolism does indeed refer to industrial societies.

In the following sections we will try to give an overview of the literature about socioeconomic metabolism during the last three decades. Before doing so, we have to explain the process through which this literature has been selected. The following decisions have been taken:

1. Whereas, in Part I of this review, we tried to unveil the "roots and traces" of some contemporary research strategies over a wide field of disciplines, we now had to narrow down to some more closely related approaches and exclude others. First, we confined ourselves to systemic rather than linear approaches (i.e., to research that focuses on some social system and not just on a group of processes). Readers looking for publications on emissions and emission reduction from cars, for example, (which

technically in fact *are* a metabolic problem of societies) will not find them here. Equally, we have not dealt with research that comes under the heading "life-cycle assessment" of products or services.¹ Second, we have given preferential treatment to publications on material rather than on energy flows. The *energetic* metabolism of industrial societies has been subject to a great deal of research, directed at technological alternatives and energy-saving strategies, that will not be represented in this review.² Similarly, we have hardly touched upon the metabolism of industrial societies in *monetary* terms. Obviously, *economic* input-output analysis teaches much about societal metabolism, and there are various approaches to relate this to environmental concerns. These approaches will not be reviewed here.³ Finally, MFA can be broken down into "substance flow analysis" (SFA) that usually deals with chemically defined substances, as opposed to "bulk materials flows" that are natural or technical compounds (such as wood, or air, or construction minerals) (Udo de Haes et al. 1997). We have put more emphasis on MFA in the sense of bulk materials flows, because this relates to socio-economic systems in a more comprehensive way, thus complementing the longer and more well-known tradition of SFA.

2. In screening the literature, it became apparent there had been several "waves" of related research, with later efforts typically unaware of, or not taking notice of, previous publications. This was to be expected in view of their scattered nature, both in terms of the disciplines and the media of publication involved, but it did not ease our task as reviewers. As we have demonstrated, beyond some approaches in the early postwar years, a major "first wave" of research on socioeconomic metabolism surged in the late 1960s. This stimulating research had a great deal of conceptual power to mold issues in the light of the new debate over environmental concerns, and it mainly originated

from the United States, where environmental issues were also the most advanced politically. We referred to first-wave publications more extensively in the earlier review (Fischer-Kowalski 1998) because they set milestones for subsequent research strategies. The “second wave,” which we are going to review here, is mostly very recent: Much of it dates from the early nineties and represents the contemporary state of the art.⁴ This second wave is largely European in origin, with the bulk of publications derived from German-speaking or Scandinavian countries and from the Netherlands.⁵

3. As far as possible, we will refer to very comprehensive publications on the one hand and to original research reports (in their published rather than their report versions) on the other hand. We will not refer to repeatedly updated versions of the same research containing only minor revisions unless they are more accessible in terms of language by being written in English. Papers not presenting any empirical results but contributing to conceptual clarifications will be mentioned in the course of the discussion but will not be included in the summary found in table 1.

We will now proceed as follows: We will first present a comprehensive overview of empirical research from 1970 to 1998, loosely grouping it according to its focus (see table 1), and then discuss the overall characteristics associated with such a focus. In the next section we will proceed to describe some of the major conceptual and methodological options of MFA: system boundaries and system compartments, the inclusiveness or exclusiveness of materials flows, and the problem of evaluating environmental impacts. In this section some of the research mentioned in table 1 will reappear to help illustrate different approaches, and new literature of a more theoretical nature will be introduced. In a last section, we will try to draw some conclusions about the theoretical stringency, research productivity, and political relevance of the research tradition under consideration.

Outlining the Paradigm: An Overview of Classification

The overview of the “second wave” of MFA literature has been structured by classifying the studies according to several major criteria. These criteria are explained in the discussion below. However, it is important to note that the allocation process has required the identification of the major relevant dimensions of what are typically complex and multifaceted analyses. Furthermore, the studies within each class are often very diversified in terms of other aspects of their research.

Frame of Reference: Socioeconomic System/Ecosystem

There are basically two ways of handling anthropogenic material and energetic flows: It is possible, first, to focus on some social or *socioeconomic system as a unit of analysis*, treating it like an organism or some sophisticated machine. Second, one may look at such a system from an “environmental” perspective corresponding to the *ecosystem perspective* in biology. In the second case, one looks at the larger system within which the socioeconomic system operates and relates inputs and outputs to the stocks and flows of the larger system.

Whereas the first type of approach, the socioeconomic system perspective, was usually developed as a social science frame of analysis, the second type, the ecosystem perspective, is rather a natural science enterprise. Both of them, however, are concerned with the fate of social systems of human beings and the sustainability of their metabolism—within different frames of reference. These approaches, of course, can be linked, and suggest themselves to be linked, by *mutual feedback loops*. This may be achieved within an overall formal model trying to simulate interactions between socioeconomic and natural systems or as a combination of analytic and normative modeling techniques that are frequently used in more recent (usually national) projections of “sustainable development” (for examples, see table 1).

Table 1

Analyses of the metabolism of industrial society by research paradigm: Overview of the literature 1970–1998

	<i>Focus on socioeconomic system</i>	<i>Focus on ecosystem or feedback-loops</i>
Global	Starr 1971, Malenbaum 1978, Jänicke et al. 1989, Larson et al. 1986, Baccini and Brunner 1991, Jänicke et al. 1992, Rogich et al. 1993b, Ausubel and Langford 1994	Bolin 1970, Brown, H. 1970, Brown, L. 1970, Cloud and Gibor 1970, Deevey 1970, Delwiche 1970, Oort 1970, Penman 1970, Singer 1970, Woodwell 1970, Meadows et al. 1972, Lieth and Wittacker 1975, Vitousek et al. 1986, Turner et al. 1990, Meadows et al. 1992, Wright 1990, Gleick 1993, Kates 1994, Munasinghe and Shearer 1995
National	<p><i>"Bulk" (total) material metabolism</i></p> <p>Ayres et al. 1970, Kneese et al. 1974, Gofman et al. 1974, Auty 1985, Steurer 1992, Environment Agency Japan 1992, 1993, 1994, Rogich et al. 1993a, Schütz and Bringezu 1993, 1995, Fischer-Kowalski et al. 1994, Steurer 1994, Kuhn et al. 1994, Statistisches Bundesamt 1995, 1998, Konijin et al. 1995, Wernick and Ausubel 1995, Femia 1996, Haberl 1996, Hüttler et al. 1996, Bringezu et al. 1997a, Adriaanse et al. 1997, Stahmer et al. 1997, Schandl 1998</p> <p><i>Selected materials, substances, services</i></p> <p>Cook 1971, Billen et al. 1983, Ayres et al. 1989, Herman et al. 1989, Baccini and Brunner 1990, Gerhold 1990, 1992, 1994, Daniels 1992, Binswanger 1993, Kranendonk and Bringezu 1993, Lauber 1993, Liedke 1993, Stiller 1993, Ayres and Ayres 1994, Ayres et al. 1994, Husar 1994, Kleijn et al. 1994, Kluge et al. 1994, Moore and Tu 1995, Lohm et al. 1994, Bressers 1995, Lundqvist 1995, Liedtke et al. 1995, Manstein 1995, Mez 1995, Nickel and Liedtke 1995, Russel and Millstone 1995, Weidner 1995, Picton 1996, Van der Voet 1996, Ayres and Ayres 1996, Ayres 1997, Ayres and Ayres 1997, Kleijn et al. 1997, Tukker et al. 1997</p>	Weterings and Opschoor 1992, Buitenkamp et al. 1993, Muhkherjee 1993, Kosz 1994, Bund and Misereor 1996, Opschoor 1995, Enquete-Kommission 1994, 1997, Haberl 1997a, Hüttler and Payer 1997
Regional unit	Newcombe 1977, Newcombe et al. 1978, Boyden et al. 1981, Baccini and Brunner 1991, Brunner and Baccini 1992, Baccini et al. 1993, Van der Voet et al. 1994, Narodoslavsky et al. 1995, Baccini 1996, Binder 1996, Baccini 1997	Ayres and Rod 1986, Brunner et al. 1990, 1994, Stigliani and Jaffe 1993, Stigliani and Anderberg 1994, Spangenberg 1995
Functional and economic unit	Thompson 1979, Nappi 1989, Fischer-Kowalski et al. 1994, Behrensmeier and Bringezu 1995, Kisser and Kirschten 1995, Windsperger et al. 1997, Zangerl-Weisz and Schandl 1997, Glenck and Lahner 1997, Schandl and Hüttler 1997, Moll and Femia 1997, Stahmer et al. 1997	
Historical perspective	Kemp 1971, Rappaport 1971, Starr 1971, Netting 1981, Kabo 1985, Cane 1987, Layton et al. 1991, Fischer-Kowalski and Haberl 1993, Ayres and Ayres 1994, Ayres et al. 1994, Brunner et al. 1994, Trömel 1995, Fischer-Kowalski and Haberl 1997a, 1998, Siefert 1997	Boserup 1965, Loucks 1977, Cooter 1978, Gliessmann 1978, Siefert 1982, Altieri 1989, Vasey 1992, Kates 1994, Siefert and Müller-Herold 1998

Reference System: Global, National, Regional, Functional, Temporal

Socioeconomic systems can be looked upon at different levels. One may choose to look at the *global* anthroposphere—involving humankind in the global economy—with the geo-biosphere as the corresponding ecosystem perspective, or one may choose to look at a *nation* state or a *national* economy, at some *regional* unit (such as a city or a watershed),⁶ or, finally, at some *functional* unit (such as a firm, a household, or an economic sector). In these latter cases the corresponding ecosystem is not so easy to determine.

It seems important, however, that the unit chosen may be properly looked upon as a social system (i.e., that it is integrated by social and economic organization). The less this is the case, the more difficult it becomes to consistently draw a borderline between the system and its environment. This problem is intimately linked to another distinction, to be discussed later, concerning the compartments of the system. From the point of view of ecosystems analysis, the further one moves down the hierarchical levels of organization, the more difficult it becomes to find an appropriate ecosystem in which the socioeconomic system can be thought of as being embedded: The side effects of the metabolism of a particular social system such as a city, or an economic sector, are usually not confined to a certain territory or to a specific ecosystem. For systematic reasons, therefore, the respective cell in column 2 of table 1 is often empty.

Flows under Consideration: Energy, Material(s), and Chemical Substances

In analyzing the metabolism of a socioeconomic system, or the materials flows between this system and its environment, one may look at its *total* turnover in terms of *matter* or *energy* (or both), or one may select certain flows of materials or chemical substances. Some studies look at the role of certain *input materials* in the metabolic process (for example, metals and minerals, or energy carriers) and try to determine their uses as well as their pathways through the system in question. Other studies look at *output materials* and try to determine how the system generates them (e.g., carbon dioxide, ozone-depleting substances, or phosphates).

The same distinctions apply to the ecosystem and the feedback frame of analysis: Certain *system inputs* may be related to *resource availability* in the reference ecosystem. Typical research topics in this tradition include comparisons of the production rates of certain resources within the reference ecosystem to their “rates of consumption” on behalf of a particular social system (e.g., the proportion of net primary production of plants, or NPP, that is appropriated by a certain nation state). In the case of so-called “nonrenewables,” (i.e., resources taken from long-term geological sinks) the relation of stocks to rates of extraction may be analyzed, or the rates of devaluation of stocks (through declining concentrations of some resources, for example). Similarly, one may concentrate on system outputs (emissions and wastes) and relate them to absorption or storage capacities within ecosystems or simulate the ecosystem’s reactions to these outputs (such as global warming). Other authors compare the *total of flows of certain substances* mobilized by a social system to the total of these flows in a reference natural system.

Time Horizon: Contemporary Point in Time, Time Series, and Long-Range Historical Perspective

The time horizon of the research reviewed is not fully represented in table 1. Here we just distinguish as a separate group those studies that perform or permit a comparison between the metabolism of industrial socioeconomic systems to other types (other social formations, modes of subsistence, or historical systems). This is both of conceptual and of practical interest: What happens if all societies attempt to change their traditional, current metabolism to an industrial metabolism? Such a question can be approached both from an historical perspective, comparing over long time periods, and by a cultural anthropological perspective that portrays preindustrial modes of living of contemporary communities.

Review and Discussion of the Classified Literature

Research on the Global Level⁷

On the global level it is relatively easy to define the ecosystem corresponding to the

"anthroposphere": It is, of course, the geo-biosphere of our planet. Both columns of table 1, which refer to the different frames of analysis, contain several entries of research publications concerned with global problems. With regard to the focus on socioeconomic systems, "globalness" is of course hard to substantiate empirically. The number of people making up the global population is known approximately, as are many economic parameters. The latter, however, are largely in the form of data in monetary terms, occasionally in energetic terms as well, but hardly in terms of materials weight. The entries in this segment of the table refer, therefore, either to comparative approaches dealing with the amounts of certain selected materials produced or consumed (such as Baccini and Brunner 1991; Jänicke et al. 1993; Rogich et al. 1993b) or to technological trend analyses (Ausubel and Langford 1994; Larson et al. 1986). This limitation also applies to the entries in the second column of table 1, such as the classic "Club of Rome" reports by Meadows and colleagues (1972, 1992). Their model simulating feedback processes between a growing socioeconomic world system and its natural environment operates theoretically on the level of material amounts (of agricultural and industrial production, for example). The data that entered the models, however, were monetary data that—for all that is known so far—are different in their dynamics.⁸ The famous "limits to growth" models, therefore, were very influential in framing a certain worldview and in supporting a systemic perspective. They were not that influential when it came to the development of empirical research strategies concerned with socioeconomic metabolism, mainly for lack of appropriate data and for the lack of emphasis on the need to generate such data in the first place.⁹ The ecosystem perspective on the global level (see column 2 of table 1) was strongly promoted by the September 1970 issue of *Scientific American*. The whole issue, under the heading "Biosphere," was devoted to material and energetic cycles (carbon: Bolin 1970; oxygen: Cloud and Gibor 1970; nitrogen: Delwiche 1970; mineral cycles: Deevey 1970; water: Penman 1970; plant energy: Woodwell 1970), placing material and energetic socioeconomic processes within this framework (materi-

als production: Brown, H.; 1970; food: Brown, L., 1970; energy: Singer 1970). Other entries in this cell refer to a research tradition relating overall plant energy storage (NPP) to its human appropriation (Lieth and Wittacker 1975; Vitousek et al. 1986; Wright 1990; Munasinghe and Shearer 1995) and similarly for water-cycles (Gleick 1993).

Research on the National Level

The national level seems to have been the most productive approach in terms of conceptual development and empirical research. On this level, the socioeconomic system can be analyzed by means of a great deal of data provided by a number of institutions concerned with national economic accounting. Meanwhile, there are three countries that have incorporated such overall materials flow statistics on a regular basis into their standard public statistics (Austria, Germany, Japan),¹⁰ and some other countries are on the verge of doing so (e.g., Denmark, Finland, France, Italy, Netherlands, and Sweden). For the United States one finds a fairly comprehensive overview of material metabolism for 1990 (Rogich et al. 1993a, 1993b; Wernick and Ausubel 1995; Wernick 1996). An incorporation of bulk materials flow data in national statistics in the United States does not seem to be in sight. The World Resources Institute recently took the initiative to produce material accounts for the United States for the period 1975–1994 using, among others, data from the (former) Bureau of Mines to compare them with the materials flows of Germany, Japan, and the Netherlands (Adriaanse et al. 1997).

The calculation of an *overall material metabolism* of a national economy is methodologically quite demanding. It requires, as a database, economic statistics for all materials not only in monetary terms but also in terms of mass (analogous to the more common energy statistics in joules). This *totality of materials flows* of a national economy is particularly important as a parameter that can be presented in time series and related to economic performance in monetary terms.

For the totality of materials flows of a national economy, it is, however, practically impossible to establish a corresponding "ecosystem."

The overall material or energetic metabolism of a nation state (i.e., the national economy of an industrial country) is embedded in the geo-biosphere of the whole planet as its natural environment. Accordingly, some normative assumptions are required concerning the "share" of the worldwide materials flows held by a particular national economy, and this can only be established for selected materials. Therefore the corresponding cell in column 2 of table 1 is empty.

This is not the case when it comes to selected material or substance flows on the national level. The research on selected materials flows links up well with more traditional research approaches of environmental science concerning emissions and wastes (column 1), as well as with depositions (column 2); it also ties in well with statistics concerning economic production and consumption, and it often relates to certain national environmental policies of emission control (see, for example, the policy-oriented volume by Jänicke and Weidner (1995), from which several of the entries in column 1 are drawn). Compared to the analysis of overall national material metabolism above, this approach is not as demanding with regard to conceptual and data integration. One major field of application of such analyses is the various national programs of "sustainable development" launched, sometimes officially by national governments and sometimes by non-government organizations (NGOs), as can be seen from column 2 (see Weterings and Opschoor 1992; Buitenkamp et al. 1993; Kosz 1994; Spangenberg 1995; BUND and Misereor 1996; Enquete-Kommission 1994, 1997).

For selected materials flows, it is somewhat easier to define an ecosystem that is affected by the socioeconomic processes, but it is still quite difficult: As a general rule, atmospheric and water systems do not respect national boundaries, and many materials flows cannot be confined to territorial parameters. The only major exception is energy stored in plant biomass, which can reliably be established for a national territory and related to human consumption (see Haberl 1997b). In the process of defining standards of sustainable development on national levels, however, it may be expected that research efforts in this area will increase further.

Research on a Regional Level

Generally speaking, the advantage of research on a regional level is that the region may be chosen in a way that ensures that biophysical system definitions largely coincide with political and economic system definitions, thus allowing for approaches within both frameworks. This may be the case with relatively small regional units (a city, for example, see Wolman 1965; Newcombe et al. 1978; Boyden et al. 1981; or a secluded rural area, see Narodoslavsky et al. 1995; Binder 1996; a valley/watershed, see Ayres and Rod 1986; Stigliani and Jaffe 1993; Brunner et al. 1994; Stigliani and Anderberg 1994; or with large units such as Europe as a whole, see Voet et al. 1994; Spangenberg 1995). Whereas for cities and regional administrative units, socioeconomic statistical data are mostly available (with the exception of transboundary flows), a typical problem of valley or watershed units is the lack of reliable statistical socioeconomic data. They often have to be generated by very expensive empirical efforts.

Research on the Level of an Economic Unit

Some researchers propose to analyze materials flows by types of social activities (e.g., nourishment, transportation, cleaning; see Baccini and Brunner 1991). Other units under consideration include households (see Thompson 1979; Baccini et al. 1993), individual firms (e.g., Liedtke et al. 1998), industrial sectors, that is, branches of economic activity (e.g., Katterl and Kratena 1990; Behrensmeier and Bringezu 1995; Moll and Femia 1997; Stahmer et al. 1997; Zangerl-Weisz and Schandl 1997). This seems to be a promising area of research because it can easily be linked to industrial policies and economic forecasting (Jänicke 1995a, 1995b; Jänicke et al. 1997) on the one hand and to microeconomic efforts of cost reduction by increasing material and energy efficiency on the other hand. The most sophisticated and elaborate attempt along these lines is represented by the physical input-output tables (PIOT) for the 58 sectors of economic activity for Germany (1990) published by Stahmer and colleagues

(1997). In analogy to economic (monetary) input-output tables, all materials flows within and between these economic sectors are registered in physical terms (tons of raw materials, commodities, and residues), as well as in material stocks. This approach is particularly valuable for its conceptual and methodological stringency, which we will comment upon further down.

Long-Range Historical Perspective

So far there have been only tentative efforts made to compare industrial metabolism (structurally or in tons per capita) with the metabolism of agricultural societies or with hunting and gathering societies. Usually this is done in a fairly sweeping way (Boyden et al. 1981; Brunner et al. 1994; Fischer-Kowalski and Haberl 1993, 1997). Some research from cultural anthropology (Kemp 1971; Rappaport 1971; Netting 1981; Kabo 1985; Cane 1987; Layton et al. 1991; Netting 1993; Fischer-Kowalski and Winiwarter 1997; Grunbuhel et al. 1998) and agroecology (Loucks 1977; Gliessman 1978; Cooter 1978; Altieri 1989; Hanks 1992; Vasey 1992) should be of great help in establishing more systematic comparative perspectives. Another approach is represented by attempts to estimate long-term time series of certain substance flows, as was done by Ayres and colleagues (1994) for carbon and nitrogen or by Lohm and colleagues (1994) for chromium and lead. In line with theoretical reconstructions of a universal history,¹¹ efforts to reconstruct long-term time series of resource flows into socioeconomic systems have been renewed (Ausubel and Langford 1994; Trömel 1995; Sieferle 1997), and an interesting discussion on long-term dynamics of scaling up metabolism in the whole course of industrialization versus a merely post-Second World War syndrome has emerged (e.g. Pfister 1995; Andersen 1995).

Materials flow Analysis: Major Conceptual and Methodological Options

We will now briefly summarize some of the strengths and weaknesses, some of the critical issues (resolved and unresolved), and some of

the interesting results of the research tradition. We will confine ourselves to overall materials flow analyses on the level of national states or economies and only briefly touch upon implications for meso- and microlevels.

This selection is influenced by the fact that it is at this level that the institutionalization of data collection and publication by official statistics are most likely to have been achieved, promoted by international guidelines (UNO 1993). Such institutionalization has been successfully established in some countries (Germany, Japan, and Austria, with others in preparatory stages). Most of the research in this field has been based upon available statistics and would greatly gain from their systematic improvement. At present, in several countries, scientific research lays the groundwork for the establishment and institutionalization of appropriate concepts and operational definitions for standard statistics. Research activity will then in turn be strongly influenced by the concepts and the characteristics of available data.

We will group our discussion of the literature around three issues. *First:* How are the boundaries between the socioeconomic system and its biophysical environment defined, and what difference does this definition make? *Second:* What is considered a materials flow (into, within, and out of the system), and how are these flows classified? Again empirically: What are the respective proportions, and what are the social and political implications of these proportions? *Third:* What is the environmental relevance of materials flows? What are the criteria according to which this may be judged?

Socioeconomic System Boundaries and System Compartments

With respect to the economy, the common denominator of "money" provides a practical guideline for distinguishing what belongs to the economic system and what does not.¹² Tons or joules provide no such guideline, so the discussion about adequate system boundaries has marked the establishment of this research paradigm from its very beginning (Boulding 1966; Ayres and Kneese 1969). It seems, however, as if the formal attributes of the physicist's presump-

tion of the constancy of mass and energy, as well as of (economic) input-output analysis, are being commonly used as a guideline, resulting in the following equation:

$$\begin{aligned} & \text{The sum of material/energetic inputs into a system} \\ & = \text{the sum of outputs} + \text{changes in stock} \quad (1) \end{aligned}$$

This equation is usually applied to the system as a whole (Baccini and Brunner 1991; Bringezu 1993a, 1993b; Steurer 1992; Bringezu et al. 1994; Statistisches Bundesamt 1995, 1998; Environment Agency Japan 1993, 1994; Baccini et al. 1993; Rogich et al. 1993a; Wernick and Ausubel 1995; Baccini and Bader 1996; Hüttler et al. 1996) but not in an equally consistent manner to all its compartments or subsystems.

It would probably add to the clarity of distinctions to also consistently apply the following second equation (Fischer-Kowalski 1997):

$$\begin{aligned} & \text{The metabolism of the system} \\ & = \text{the sum of metabolisms of its subsystems} \\ & \quad \text{or compartments} \\ & \quad + \text{internal transfers} \quad (2) \end{aligned}$$

This equation follows from a systems approach, looking at an economy or society as an integrated whole in the way biology does with an organism, and looking at its "metabolism" as a kind of highly interdependent self-organizing process rather than just an assembly of "materials flows."¹³ It also follows from the mathematics of input-output analysis (Leontief 1970). Equation (2) would guide against several inconsistencies discussed below that can be observed in a number of studies.

The main methodological benefit of this equation is that it provides a guideline for explicit specifications of what the compartments¹⁴ of the system are supposed to be. Concerning socioeconomic systems on a national level, a broad consensus seems to be on its way. Most studies consider *human bodies* as a physical compartment of the socioeconomic system.¹⁵ But often this does not imply that the complete metabolism of human bodies be included. Typically human nutrition is included as an input and excretion as an output, but both respiration (i.e., the intake of oxygen and the output of carbon dioxide and water) and the burial of dead bodies is not considered (e.g., Ayres and Kneese 1969; Newcombe 1977; Steurer 1992; Rogich et

al. 1993a; Statistisches Bundesamt 1995, 1998). This violates equation (2) and causes input-output inconsistencies.

Similar considerations apply to the inclusion or exclusion of *livestock as well as domestic animals*. It makes a large quantitative difference for socioeconomic metabolism whether livestock is considered part of the socioeconomic system (and consequently its metabolism part of the socioeconomic metabolism), or not.¹⁶ This again is a source of many inconsistencies, that is, double counting (if both the crop harvested and then fed to livestock, and livestock products are considered as inputs, as discussed in Kneese et al. 1974) or omission (if crop fed to livestock is considered, and the amount of plant biomass consumed in grazing is excluded such as with Schütz and Bringezu 1993; Statistisches Bundesamt 1995, 1998; Bringezu et al. 1997a; Adriaanse et al. 1997; for a discussion see Haberl 1997a).

Also animal respiration is often not considered properly, nor are the effects of livestock upon the turnover of water (exceptions: Hüttler and Payer 1997; Stahmer et al. 1997). If livestock is included as a physical compartment of the social system, meat and milk, etc., of course, may not be treated as inputs from the environment but have to be looked upon as transfers within the social system.

Theoretical considerations have been raised about whether to include *plants* as compartments of the social system insofar as they are maintained by labor in agriculture or forestry. If agricultural plants were considered as part of the socioeconomic system, the boundary between this system and its environment would be "pushed outward" to the mineral level, except for fishing, hunting, and gathering. It is not so easy to distinguish between "social system plants" (crops) and "natural plants" (Fischer-Kowalski 1997). So most studies draw the dividing line between livestock and plants. In their elaborate physical input-output analysis Stahmer and colleagues (1997) did indeed treat agricultural plants and economically utilized forests as compartments of the socioeconomic system. One might even go one step further and include the agriculturally used part of the topsoil as a compartment of the social system. This would internalize fertilization as a process within

the socioeconomic system and frame eroded topsoil as an emission to the environment. We do not know of any case where the distinction was actually drawn in this manner.¹⁷

Finally, a consensus seems to exist to include *human-made and -maintained technical structures* as physical compartments of social systems. This applies to buildings, machines, vehicles, and the like but also to roads, dams, or sewers. If this is done, according to equation (2), all the materials that are used for making and maintaining these structures belong to the social system's metabolism. Also included are the energy and the materials (such as water, air, and various raw materials) used to make them function and produce those goods and services for which the social system has constructed them.¹⁸

Once the physical compartments of the social system are defined, it becomes possible to distinguish between stocks and flows. Some efforts have been invested in this distinction (Baccini and Brunner 1991; Lehmann and Schmidt-Bleek 1993b; Bringezu 1993a, 1993b; Wernick and Ausubel 1995; Fischer-Kowalski 1997), but so far no common practice has emerged. We would suggest *equating stocks and the material compartments of the socioeconomic system* mentioned above. Such a definition provides a certain clarity and simplicity on the theoretical level, and a common guideline for operationalization. A reliable distinction between stocks and flows is a prerequisite for determining empirically whether a socioeconomic system is still "growing" (in physical terms), in a steady state, or shrinking (Bringezu and Schütz 1996; Wernick and Ausubel 1995; Wernick 1996). This should refer to the size of the population, the size of the livestock, eventually the stock of (economically used) forests, and the weight of the infrastructure. Accordingly, an operational distinction between "size" and "metabolic rate," and between the "growth rate" and the energetic and material "turnover" of the social system can be drawn. Typically, only the technical infrastructure (mainly buildings) is considered as material stocks and not the live beings, that is human and livestock populations. From a strict input-output perspective, this results in inconsistencies, and theoretically this shows an "industrial" bias that is hard to justify.

Lehmann and Schmidt-Bleek (1993), as well as Bringezu (1993a) and Bringezu and colleagues (1994), have suggested another mode of compartmentalizing the system: into commodities or production processes as elements. They compute the material intensity of each production process of a commodity or a service (material input per service unit, or MIPS; Schmidt-Bleek 1993a, 1993b, 1994). This approach attempts to combine the basic ideas from life-cycle assessment (accounting for all material inputs, "from the cradle to the grave" of a product) with those of national MFA relating the final consumption to all material inputs required. Several ongoing efforts exist that systematically relate this approach to national accounting and monetary input-output analysis (Behrensmeier and Bringezu 1995; Hinterberger et al. 1996, 1997; Moll and Femia 1997). On a theoretical level, such a product-oriented cradle-to-grave approach seems distinct from, but compatible with, a system-oriented approach at the level of a national economy (as is, for example, well represented methodologically above by the work of Stahmer and colleagues, 1997). Also the MIPS-related approach raises some problems on the operational level that have not quite been resolved yet.¹⁹ (Examples of this type of analysis include Kranendonk and Bringezu 1993; Stiller 1993; Manstein 1995; Liedtke et al. 1995; Stiller 1995a, 1995b.)

Whereas the boundaries with the natural environment are still a matter of dispute (see also the next paragraph), a consensus has been reached with regard to handling the boundaries between different socioeconomic systems. It is a common feature of all studies to distinguish between "extractions from the environment" or "primary inputs" on the one hand and "imports" from other socioeconomic systems on the other hand. The same applies to the output side: "depositions," "emissions," and eventually "dissipative uses" and "losses" are distinguished from output in the form of "exports" to other socioeconomic systems. Imports and exports, as established so far, are being handled very much in the same fashion as by economic statistics (i.e., they do not include the import of depositions, for example). Specialized studies then may look into the material or ecological "rucksack"²⁰ of im-

ported goods or services (Kranendonk and Bringezu 1993; Bringezu et al. 1994).

Inclusiveness or Exclusiveness of Materials Flows, and Their Classification

A methodological consensus has not yet been achieved either with regard to system boundaries toward the environment or with classification or naming of aggregates of materials flows. The empirical results, nevertheless, are very similar. If all the materials flows needed for reproducing the socioeconomic material stocks are considered, it is clear that the so-called free environmental goods, water and air, make up by far the largest proportion of input materials needed (somewhere between 85% and 90% of the total).²¹

The "total," though, is not clearly defined: There remains a substantial fuzziness, on a theoretical level, with respect to the following question: Where do materials flows induced by economic activity or human labor start and where do they end? This is the cradle-to-grave problem that has been given much attention.²² The choices made lie somewhere between a fairly restrictive definition following the boundaries of the economy (all materials that are economically valued are considered as inputs but not, for example,

earth removed for construction or used in ploughing). The same would be true, symmetrically, for outputs. Or there is chosen a very extensive definition including all materials touched upon by technology or labor. The differences implied with these definitions have the order of several factors of magnitude.²³ The more encompassing the definition becomes, the more the materials that have economic value tend to disappear quantitatively in the total; on the other hand, a neglect of the quantities of rucksack materials tends to hide environmental burdens associated with imports and materials extraction from nature ("hidden flows"). We try to illustrate the problem and some of the distinctions used in figure 1.

Most studies would not lump together the input of water and air and the rest of material input (consisting of biomass, fuels, other minerals, and semimanufactures). This has to do with the common-sense idea of not literally "drowning" economically valued raw materials and commodities in water and air. So, however water and air may be looked upon as vitally indispensable for socioeconomic metabolism, they tend to be kept separate because of their sheer amounts and the supposedly low impact of their use (Bringezu et al. 1997a; Statistisches Bundesamt 1998; Stahmer et al. 1997; Hüttler et al. 1996; Schandl

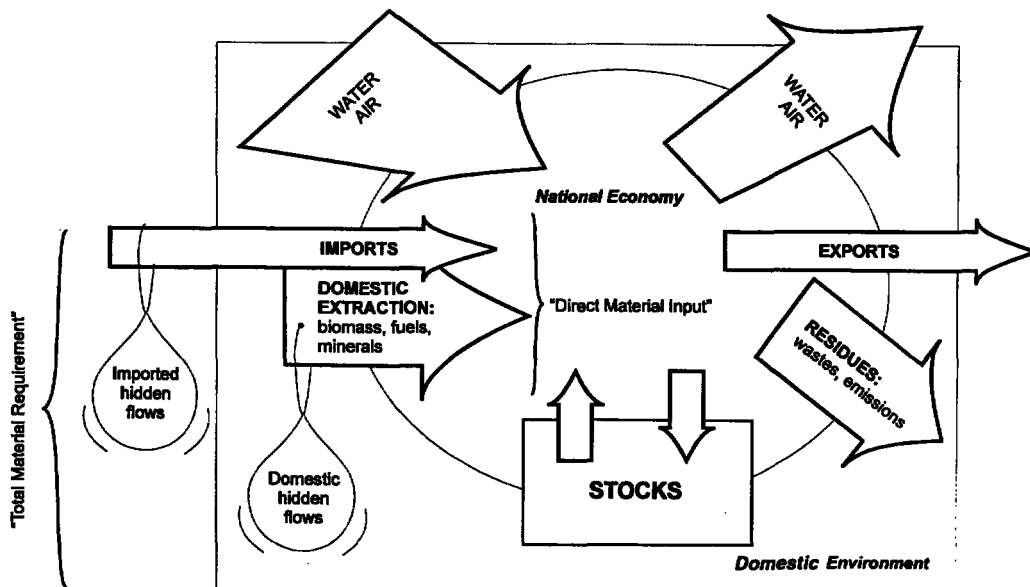


Figure 1 Relevant material flows, terminology, and system boundaries (national level).

1998; Environment Agency Japan 1994) or because their use varies widely among regions (Adriaanse et al. 1997).

Within the nonair, nonwater fraction of material input, a distinction that has proved to be quite practical has been established between "used" or direct and "unused" (but nevertheless mobilized) materials. Unused materials chronically are more difficult to quantify empirically but are at least of the same order of magnitude of used materials (Schütz and Bringezu 1993; Bringezu et al. 1997a; Statistisches Bundesamt 1995, 1998; Adriaanse et al. 1997; Schandl 1998; see table 2). Generally it can be said, of course, that the statistical basis of unused materials is much weaker. An attempt to express this more encompassing figure of (nonair, nonwater) material inputs was the term "total material requirements" (TMR) used in Adriaanse and colleagues (1997, figure 1). This number does encompass "used" (direct) material inputs in national economies plus (import and domestic) rucksacks. The trouble with this parameter is that it cannot be added up internationally: If country A imports raw materials or commodities from country B, the rucksack of those imports would be counted in the TMR of country A as well as in the TMR of country B. The same mistake occurs and can be overlooked even more easily when per capita TMR figures are multiplied by population numbers.

In another trial-and-error process, it is being determined currently which relevant categories of materials should be distinguished. Whereas some of the pioneer work of Jänicke and colleagues (1992) sought to represent the total by some selected "strategic materials" (such as cement, water, steel, aluminum, chlorides, pulp and paper) and establish time series for many countries, others sought to break down (varying) totals into qualitative compartments. A useful strategy was chosen by Hüttler and colleagues (1997a), combining the common distinction—fuzzy upon closer scrutiny—of nonrenewable versus renewable resources, with the distinction between biogenic (fossil fuels, biomass) and nonbiogenic materials (metals and minerals on the one hand and air and water on the other) and analyzing each flow of input materials separately. Stahmer and colleagues

(1997) distinguish between "raw materials" (i.e., nonproduced biomass, mineral resources, water, air, and topsoil), "commodities" (everything produced from raw materials for use), and "residuals" (sewage, emissions, and wastes). Most other studies use varying less-systematic distinctions, relying upon existing statistical traditions.

It seems to be feasible—given the economic statistics available—to establish the (*direct material input of national economies*) (Schütz and Bringezu 1993; Environment Agency Japan 1993, 1994; Steurer 1992; Wernick and Ausubel 1995; Statistisches Bundesamt 1995; Hüttler et al. 1996; Adriaanse et al. 1997; Schandl 1998, see table 2). This leads to internationally comparable results once the same definitions are applied (Hüttler et al. 1997a; Adriaanse et al. 1997), and roughly corresponds conceptually and even numerically to the "pioneer studies" of the 1960s (see table 1 in Fischer-Kowalski 1998). Equally, it seems to be possible to quantify the TMR (see figure 1 and table 2). Both indicators, calculated per capita of inhabitant, appear to be in the same order of magnitude internationally for rich industrial countries (see table 2).

Table 2 presents a set of metabolism core indicators in terms of domestic materials use for five industrial countries. The comparison shows a characteristic metabolic profile of industrial societies, amounting to a (direct) resource consumption of about 20 tons per capita and year. About half of this material consists of energy carriers (about one-quarter each biomass and fossils) and the other half is made up by metals and minerals.

It appears to be very hard to approach the same goal from the "output" side, from an estimate of wastes, emissions, and dissipative losses, however (Baccini and Brunner 1991; Baccini et al. 1993).²⁴ One of the main insights of this type of research may be that however sophisticated the world of products and services in industrial economies may seem, there is a very limited number of quantitatively important input materials. The residues of the metabolic process, though (i.e., the outputs to the biophysical environment), tend to be both chemically and physically complex and hard to establish in a systematic quantitative manner. Three decades of emissions and waste statistics

Table 2 The metabolic profile of industrial countries on the national level (1991, tons per capita)

	Austria	Germany	Japan	Netherlands	United States	Unweighted arithmetic mean
Total Material Requirement (TMR)		85	46	85	84	75
Direct Material Input	23	22	17	38	20	24
Hidden Flows / Direct Material Input		2.8	1.7	1.2	3.1	2.2
Domestic Consumption*						
Biomass	5.6	2.6	1.5	10.2	3.0	4.6
Oil, coal, gas	3.0	6.2	3.3	6.4	7.7	5.3
Metals, minerals, others	11.2	10.7	11.8	5.9	8.0	9.5
Total domestic consumption	19.8	19.5	16.6	22.5	18.7	19.4
Population (mio)	7.8	80.0	124.0	15.0	252.8	95.9

Sources: Data on Germany, Japan, Netherlands, and the United States from Adriaanse et al. (1997); data on Austria from Schandl (1998).

*Own calculations from above sources: materials input minus exports. Data include used materials, exclude air, water, and "hidden flows" (overburden, erosion) (see figure 1).

have generated a considerable amount of classifications, usually differing for each medium into which residuals are discharged, that can hardly be summarized (or internationally compared) to generate an overall picture. What may come as a surprise for many, however, is the fact that in most countries it seems to be the atmosphere that serves as the waste-deposit that is most important quantitatively. Up to now, there is little agreement in studies on socioeconomic metabolism about the classification and statistical handling of outputs, as well as residuals, to the point of theoretical inconsistency (e.g., in the treatment of animal manure as a recycling process within agriculture or as a "dissipative use" of material). These problems can hardly be resolved without explicit input-output models like the one Stahmer and colleagues (1997) have presented.

What Appears to be the Problem with the Metabolism of Contemporary Society?

Why bother with industrial metabolism? What are the major concerns as well as major remedies? The answers to these questions originate from a wide spectrum of worldviews and

scientific paradigms. Without any pretension of theoretical stringency, we will try to loosely group them into the following six issues.

1. *Exhaustion of resources.* With respect to so-called renewable resources, this concern dates back to the very beginnings of political economics and the theory of diminishing returns (originally with respect to agriculture). Now there are specialized discourses centered around the old issue of population-food-agricultural productivity-erosion (and, more recently, deforestation) as resource-oriented approaches (e.g., Brown, H. 1956, 1970; Woodwell 1970; Brown, L. 1970; Netting 1993; Kates 1994; Munasinghe and Shearer 1995) and a more conservationist approach concerned with the limits of human appropriation of plant energy (NPP) and its effects on biodiversity (Vitousek et al. 1986; Wright 1990; Haberl 1997b). A second major concern is freshwater resources (Wolman 1965; Gleick 1993). These concerns are very important in the contemporary debate on sustainable development but somewhat less for the discussion of socioeconomic

metabolism. In this tradition the possible exhaustion of so-called nonrenewable resources has always been prevailing, referring to fossil energy resources (Scarlott 1956; Meadows et al. 1972) or metals and mineral ores (McLaughlin 1956; Ordway 1956; Brown, H. 1970). The "limits to growth" that repeatedly have been projected have not asserted themselves yet.

2. *Pollution.* Pollution was clearly the dominant environmental concern in the last decades and, of course, also played a role in the paradigm of socioeconomic metabolism (e.g., Ayres and Ayres 1994; Ayres et al. 1994; Weidner 1995). Basically, however, the paradigm of system metabolism sought to overcome the preoccupation with single, usually toxic, pollutants often procured in very small amounts and drew attention to the ecological effects of large materials flows. The paradigm permitted the anticipation of possible global climatic effects of (non-toxic) carbon dioxide emissions for their sheer amounts at a time when hardly anyone was considering the possibility of such an effect (Ayres and Kneese 1969).
3. *Entropy.* The concept of entropy and of human economic activity contributing to entropy, generalized by Georgescu-Roegen (1971) from energy to matter, entered the debate of materials flows at an early stage. "Dissipative losses" or the "dissipative use of materials" serve as qualifications and help to specify this abstract concept for the nonspecialist. Time and again, attempts are being made to interpret the whole process of societal metabolism in terms of entropy (Georgescu-Roegen 1980; Odum 1988; Binswanger 1992; Ayres 1994b). Destroying the use value of materials by transforming concentrated geological storage into dust particles seems a damage many can accept as an analogy to the transformation of usable energy into diffuse low-temperature radiation. Others, however, object to the generality of this idea by referring to living systems (that also have their part in socioeconomic metabolism) that do indeed invert this process: they start off from dispersed particles and generate structures of very low entropy.
4. *Inefficiency of services.* The basic idea that it is neither energy or materials that are needed for the satisfaction of certain needs, but services, and that these services should be rendered with the least amount of material and energy investment, belongs to the core ideas of this research tradition (Ayres and Kneese 1969). Optimizing the material relationship between material and energetic inputs on the one hand, and the services produced on the other hand, serves as a strategic goal and results in several comparative measures of energetic or materials intensity (Schmidt-Bleek 1993a, 1993b, 1994; Fischer-Kowalski et al. 1994). This corresponds well to basic technological rationalization strategies (e.g., Weterings and Opschoor 1992; Weizsäcker et al. 1995).
5. *Closing open cycles.* The idea of creating closed cycles ("closed-cycle-economy") that are not forced to extract ever new resources from the environment or do not spill over large amounts of residues has always been very attractive to technicians who had the experience that pollution could be minimized if cycles were closed by adequate technical means (Kisser and Kirschten 1995; Ayres and Ayres 1996). The recycling of waste materials was one of the policy issues that promised relief both ideologically and practically. Upon closer scrutiny it is obvious, however, that this option applies only to a narrow range of materials and processes. Overall recycling rates of materials on national levels nowhere exceed 5% of the direct material input of national economics (Berkhout 1998), and this cannot be simply attributed to political inertia (Jänicke 1995a).
6. *Scale and growth of metabolic throughput.* Various authors argue that, irrespective of the further specific effects socioeconomic metabolism may have on the environment, it is the sheer scale of turnover that presents a burden. Moreover, if an industrial metabolism of this dimension serves as a development model for the rest of the

world, resources and sinks for residuals will be hopelessly overburdened within a short period of time. (Schmidt-Bleek 1994; Factor 10 Club 1995; Weizsäcker et al. 1995; Spangenberg 1995). Meadows and colleagues (1972, 1992) add to this argument the problem of speed: The more rapid the movement (of growth), the less time there is available between the moment when people become aware of some danger and when an effective reaction is needed. For the same reason, Daly and Cobb (1989) used the popular image of a lake with water lilies that double their numbers every morning: The time span between the moment when the lake is half filled and when it is full is but one day.

More recently, these arguments are reconsidered within the framework of so-called environmental Kuznets curves (de Bruyn et al. 1996). Starting off from a publication of the World Bank (1992) claiming an inverse U relation between

welfare and environmental damage, several authors analyzed the relationship between per capita income on the one hand and per capita pollution, energy, and materials consumption on the other. According to de Bruyn's (1997) review, as well as according to Berkhout's (1998) analysis of overall materials flow data published by Adriaanse and colleagues (1997), a general relative delinking of economic welfare (in terms of per capita gross domestic product, or GDP) and material throughput seems to have taken place within the last two decades.²⁵ But if material throughput does not grow as fast as income, this does not mean it does not grow at all; and, second, this delinking does not seem to happen "automatically" but only relative to economic and environmental policies promoting such a change.²⁶

With respect to considerations of "sustainable development," to which most of the contemporary analyses of socioeconomic metabolism relate, all arguments reviewed above are in the process of being repositioned in a framework of

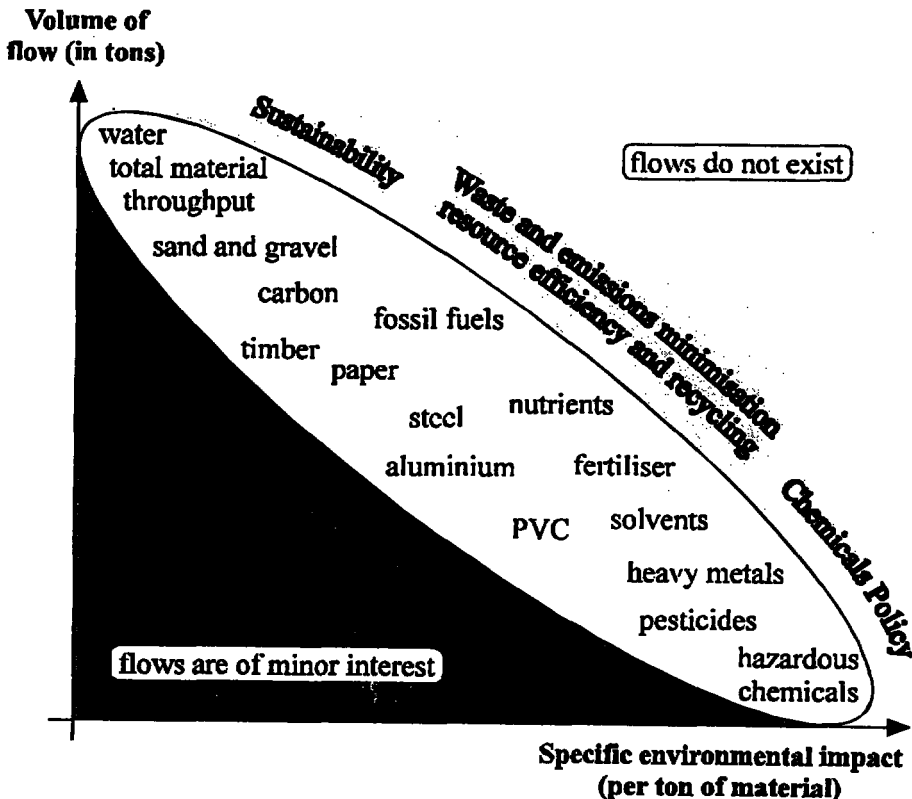


Figure 2 Stylized map of the materials of particular interest for accounting (Steurer 1996).

intergenerational, and often also international, equity.

Steurer (1996) has made a first attempt to allocate policy instruments to materials flows. The spectrum within the ellipse in figure 2 reaches from small-volume flows with high impact potential (e.g., toxic metals) to medium-volume flows like timber, paper, steel, cement, etc., which per unit mass have lower impacts, to finally high-volume flows like sand and gravel with very low specific environmental impacts.²⁷ These three overlapping clusters of materials correspond to main areas of policy interest. Whereas policy instruments such as pollution control, bans, and substitution directed toward chemicals were often successfully applied to hazardous chemicals, policy referring to medium-volume flows focuses on reducing materials and energy intensity or production, minimization of emissions and wastes, and closing loops through recycling. For high-volume flows, policy objectives will be concerned with depletion of natural resources, disruption of habitats during resource extraction, and impacts on natural sinks. The role of direct regulation will be very limited, whereas changes in demand for those materials require macro-level policies acting over longer time periods (Steurer 1996; Berkhout 1997, 1998).

Conclusions

As far as the interdisciplinary discourse on indicators of environmental performance of society is concerned, it appears that socioeconomic metabolism and the analysis of materials flows provide powerful tools to integrate various concerns. The overall material and energetic turnover of national economies constitute macroparameters for environmental performance and efficiency that relate well to the established economic macroparameters generated by national accounts. Even the methodology and the database behind these parameters are similar, which makes these concepts easily transferable within the arena of economics and of economic and industrial politics. The paradigm also smoothly fits into the way technicians and managers think of efficient processes, and it operates with notions with which the life sciences

are well acquainted. The simplicity of the paradigm seems to secure its success within the interdisciplinary arena of environmental politics. Let us briefly review the merits already achieved and the promises still pending according to the following criteria: theoretical stringency, research productivity, and political relevance.

Theoretical Stringency

As was apparent in the above review of the literature, the core concepts are fairly simple and work on several different levels of abstraction. This makes them easy to communicate across different academic disciplines and beyond this, in public discourse.²⁸ This may be looked upon as the most important strength. So far, a consensus seems to have emerged concerning the overall procedures, but most theoretical and operational specifications are not properly and consistently settled yet. This process will be supported by large-scale international panels of researchers aiming at harmonizing concepts and methods²⁹ and by corresponding steps on behalf of national statistical offices toward an integration of materials flows into standard statistics in an internationally comparable manner.³⁰ This integration of data collection and publication in national statistics will be crucial for the future of this approach: On one hand, as it has happened with economic national accounting, the official statistical categories will exert a strong influence upon future concepts and definitions in research. On the other hand, statistical offices will probably handle them with a care for consistency and continuity, which the scientific community itself would not be well equipped to secure.³¹ We would conclude, therefore, that socioeconomic metabolism and materials flows between society and nature are on the verge of becoming well-defined and agreed-upon operational tools. They provide macroindicators for the environmental performance of societies that can be compared internationally, over time and with respect to subsystems of society, and that may be related to many other social and economic variables.

It is likely, therefore, that MFA is going to become one of the most powerful tools in describing and analyzing environmental problems

as well as problems of sustainable development on a macro level. Whether socioeconomic metabolism is going to become a powerful paradigm for the way social science views society remains to be seen. As was apparent from the approaches discussed in the first part of this review, cultural anthropology did traditionally make use of concepts related to metabolism and, therefore, could join the first stage of research efforts arising in the course of environmental concerns. In economics, the issue of socioeconomic metabolism has been well taken up (see Martinez-Alier and Schlüpmann 1994; Folmar et al. 1995; Erkman 1997). Sociology, on the other hand, had little to build upon and a great deal of epistemological resistance against taking nature seriously. Sociological skills, however, are required to generate a sufficiently complex image of the social system and the way it works; otherwise it will not be possible to understand, let alone to change, the intricate ways in which socioeconomic metabolism is regulated.

Research Productivity

As can be gathered from the above review, the most recent years have seen a virtual explosion of research relating to socioeconomic metabolism—the approach has acquired a major share among interdisciplinary approaches toward environmental problems. If one looks at content, however, one still finds mostly research efforts to establish empirical quantities of materials flows, therewith striving to clarify operational definitions. As yet, there is too little research linking the characteristics of metabolism to other social or economic variables. There are some efforts to relate material to economic growth (such as Auty 1985; Binswanger 1993; Jänicke et al. 1993; Rogich et al. 1993a; Kuhn et al. 1994; Opschoor 1995; Picton 1996), demonstrating a relative independence of the former from the latter; there is a great deal of technical and microeconomic research on material and, in particular, on energy-saving potentials (which we have not referred to in detail in this review) and needs in favor of a more sustainable form of development (e.g., Weterings and Opschoor 1992; Enquete-Kommission des Deutschen Bundestags 1994, 1997). The International Hu-

man Dimensions Programme on Global Environmental Change (IHDP)³² chose the issue of “industrial transformation” as one of its main research focuses in June 1997. In their scoping report (Vellinga et al. 1996), they stress the importance of reconstructing what is happening within industrial economies in a physical sense. They suggest providing an overview of existing data and developing new frameworks for their presentation as an important next step (Vellinga et al. 1997). Similarly, the Scientific Committee on Problems of the Environment (SCOPE)³³ proposes materials flow analysis to the UN environment program as one major innovative approach to operationalizing the concept of sustainable development (Moldan and Bilharz 1997). But there is as yet not much research of a more sociological nature or with a bent toward political science. This may be expected to increase as soon as basic definitions and data-generation procedures will have become, as may be expected, more standardized.

Political Relevance

Research dealing with “environmental problems” usually aims at political relevance and intends social change, sometimes at the price of clarity and depth of analysis. Research on socioeconomic metabolism is no exception to this rule. Most of this research unites behind the effort to establish paths of “sustainable development” for industrial society. It legitimates its focus on highly developed industrial countries by stressing their dominant position in shaping the world economy and acting as models for economic development. Several of the parameters from materials flow analysis serve as devices to define targets for national programs of sustainable development. Some even use the overall material turnover as a targeting variable for reduction (“factor 10,” Schmidt-Bleek 1994, or “factor 4” as with Weizsäcker et al. 1995).³⁴

It seems interesting to note, though, that the use of materials flow indicators for specifying political targets may be somewhat different for the United States than in Europe. In the United States the political conclusions mainly point in the direction of recycling, using renewable instead of fossil raw materials (e.g., Andrews et al.

1994), keeping track of hazardous substances (Rejeski 1998), and intelligent industrial design. In the nineties (as opposed to the sixties and early seventies), scaling down the overall material turnover of the national economy is not a goal that would easily be traced in environmental programs of U.S. origin.³⁵ In Europe, by contrast, political programs of "ecological modernization" (Huber 1982; Dryzek 1997; Mol 1997) strongly relate to the idea of delinking economic growth from overall resource consumption and often explicitly define reduction targets. Whereas quantities of materials flows lend themselves very well to the operational definition of political goals, it takes an extra effort to relate them to goal-oriented strategies—an effort that, in most cases, has yet to be made (as examples, see Spangenberg 1995; BUND and Misereor 1996; Carley and Spapens 1997).

What seems to be common to the North American and the European way of relating materials flow analysis to politics is the distance from, even rejection of, the tools of traditional direct regulation. Rather, there seems to be a strong emphasis on the economic actors themselves and on markets, with the role of policy making concentrated on providing correct incentives by "getting the prices right" (Kneese 1998, 4) through the removal of misleading subsidies and through taxing resource consumption rather than labor. Thus, policy interventions into socioeconomic metabolism are generally seen as a task for economic as well as political actors not so much within the realm of "environmental politics" but rather in a broader approach to economic, technological, and social transformation.

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Many final corrections owe themselves to advice from the part of the referees.

Notes

1. Life-cycle analysis (LCA) investigates the energy and the materials needed for a certain product or service "from the cradle to the grave" and attempts to evaluate their environmental impact. MFA usually focuses a certain system and tries to describe the flows associated with it.
2. See, however, the review done by Rosa and colleagues (1988); an excellent historical perspective is provided by Siefert (1982, 1997).
3. This might generate a somewhat skewed picture of relevance. The early criticism of economic growth by economists (e.g., Boulding 1966; Daly 1973) as well as the application of input-output models to physical exchanges between the national economy and its natural environment (e.g., Leontief 1970; Duchin 1989, 1992) have played a major role in molding the paradigm of "industrial metabolism."
4. The years in between—(i.e., the late seventies and the eighties) have generated a large body of specialized literature on pollutants but seem to have missed some of the systemic "bite" then regenerated in the nineties on a larger scale. Thus, the time distribution of the citations, so we would claim, is not simply a bias resulting from unequal sampling, but it mirrors a change in research focus.
5. In such a dynamic field as the one presented here, one may easily overlook important recent research. Because efforts are made within the European Union to support continuous mutual exchange in this field, chances were better that we would know of related European rather than American efforts. We have also attempted to cover relevant Japanese publications in English and those from Australia. A comprehensive overview referring to ongoing research in regional and national materials flow accounting is put together in Bringezu and colleagues (1997b). More detailed information can be found within the inventory of MFA research on the World Wide Web (<http://www.wupperinst.org/Projekte/ConAccount/index.html>; <http://www.Leiden.nL/interfac/cml/ConAccount/Litera2.htm>). A further bibliographical database is accessible via <http://www.univie.ac.at/iffsocec>.
6. Regional can refer to either supranational units or subnational units.
7. In recent years, research on "global change" that usually relates to materials flows in one way or another (e.g., the relation between CO₂ emis-

- sions and climate change) has vastly expanded. It is not within the focus of this review to give coverage of this literature. This has been done elsewhere (see, for example, Schlesinger 1997). Here we confine ourselves to publications with a direct focus on materials flows.
8. The classic critique of Meadows and colleagues concerns the seeming failure to incorporate price effects. We consider this critique inadequate: The model is not supposed to be a model portraying monetary flows, but physical interrelations.
 9. At the International Institute of Applied Systems Analysis (IIASA) in Laxenburg, Austria, one of the high-profile research centers for global studies, two of the "founding fathers" of materials flow analysis, R. U. Ayres and F. Schmidt-Bleek, tried to establish such a research focus for years, with little success (Ayres and Schmidt-Bleek 1994).
 10. For the current state of materials flow statistics in Austria, see Schuster (1998) and Wolf and colleagues (1998); for Germany, see Radermacher (1998); and for Japan, see Moriguchi (1997, 1998).
 11. For the emergence of the so-called Modern World System, cf., among others, Wallerstein (1974, 1980, 1989).
 12. Although this criterion does not pass without critics: see, for example, discussions about (unpaid) household labor.
 13. In the background of this argument looms the "revolution" of systems theory by Maturana and Varela (1975). They explain the specific properties of living systems, namely, self-organization and self-reproduction, as "autopoiesis." This reasoning was taken up and elaborated for social systems by the German sociologist Niklas Luhmann (e.g. 1994) and his school. This does not imply that one needs to import all the other connotations of "organismic" functioning.
 14. We use "compartment" here in its ecological sense, that is, as subdivisions of a system that are in themselves regarded "as units that receive inputs from, and provide output to, other such units" (Ricklefs 1990, 804).
 15. This may depend on the social system chosen for analysis. Although it can hardly be avoided to consider humans as physical compartments of nation states, for example, it may be questionable to consider the bodies of the employees as compartments of a firm, and in fact it is rarely done. As has been suggested above, it makes sense to consider those objects as compartments of a system that the system is working to keep in a certain state. This may be the case for a firm's buildings and machines, maybe even the attitudes of its employees, but rarely their bodies (an exception may be an opera or a football club).
 16. Ecologically speaking, it makes a big difference on which trophic level human nutrition enters the materials flow statistics. If humans live on a vegetarian diet, they need about one-tenth of the plant biomass (and the land required for this) compared to the biomass required if they live on meat and dairy products. So if the statistics just count the materials weight of meat and dairy products, and not the weight of the crops needed for feeding the livestock, the numbers will be much smaller. A very interesting early example of a thorough analysis of these differences is represented in Boyden and colleagues (1981), who analyze the effects of different modes of human nutrition in terms of land area required for Hong Kong in comparison to Sydney. Japan's low biomass input shown in table 2 results from the same difference: the Japanese consume fish (from wild catch) and import most of their meat.
 17. Editor's note: For a discussion of the use of mass balances in the context of agro-ecosystems, see S. W. Moolenaar and T. M. Lexmond, Heavy metal balances, Part I: General aspects of cadmium, copper, zinc, and lead balance studies in agro-ecosystems, *Journal of Industrial Ecology* 2(4): 45-60.
 18. There remain some ambiguities that play a role in more technical debates concerning the operationalization of materials flow accounting and the borderline between the compartments of social systems and the environment. Particularly water, important for its sheer amounts, raises several difficulties: Should the water in drainage pipes be considered a societal materials flow? Or even more relevant: The huge amounts of water passing through hydropower plants? Theoretical considerations might imply yes, they should, but pragmatically speaking, it is not desirable to have these amounts virtually drown all other information.
 19. So, for example, it is hard to establish, let alone compare over time, what "one" good or service is. For a case like orange juice, this seems relatively trivial; and the materials flows associated with the life cycle of this good can be established. But what if the service "listening to music" were chosen? What difficulties would one encounter to compare the material intensity of this service between the United States and Germany, for example, or over the past 20 years?
 20. It was Schmidt-Bleek (1993c) who created the famous expression of "material rucksack." This refers to the total of raw materials mobilized, from

- resource extraction to the final product or service (measured in terms of mass minus the mass of the product itself), even if some of the materials never acquire economic value (such as: overburden in mining, materials translocated in construction, topsoil moved in ploughing, etc.; see figure 1).
21. This is not trivial, but a particular feature of the industrial mode of subsistence: This high-energy mode relies a great deal on combustion, for which both air (i.e., oxygen) and water (much of it for cooling purposes) are needed in excess. With other modes of subsistence, nevertheless, water and air also constitute the largest proportion of materials flows needed (Fischer-Kowalski and Haberl 1993), as is the case for all life on this planet.
 22. This problem has been imported from "life-cycle analysis" and ecobalancing of products but of course also applies to socioeconomic systems and the materials flows they instigate.
 23. An example for aluminum: To produce 1 ton of aluminum, more than 9 tons of raw material have to be extracted and about 3 tons of water and about 200 gigajoule of energy are needed (world average, Bundesanstalt für Geowissenschaften und Rohstoffe 1998).
 24. The per capita values of material throughput calculated on the basis of these data are very much at variance with all other data. This also results from the use of different units of analysis by Baccini and colleagues (1993): Their basic unit is the household and, therefore, they miss all the materials that enter the production process but get lost as wastes before they ever become goods for final consumption.
 25. Editor's note: For a discussion of the Kuznets curve in the context of materials intensity, see C. Cleveland and M. Ruth, Indicators of dematerialization and the materials intensity of use, *Journal of Industrial Ecology* 2(3): 15–50.
 26. So it was particularly marked in the early 1970s, when the international oil crises stimulated policies for the reduction of energy consumption.
 27. As an approximation of environmental impact Steurer refers to indicators such as toxicity of the material or emissions associated with production or disposal.
 28. Jänicke (1995a) uses the German term "Politikfähigkeit," (i.e., arguments that are commensurate for politics).
 29. Such as the concerted action "ConAccount" coordinated by the Wuppertal Institute and financed by the European Commission for 1996–1997 (Bringezu et al. 1997b, 1998a, 1998b), the international data compendium issued by the World Resources Institute (Adriaanse et al. 1997), and the provision of such efforts via internet (see the ConAccount homepage provided by the Wuppertal Institute). (<http://www.wupperinst.org/WI/Projekte/ConAccount/index.html>.)
 30. See, for example, Kuhn and colleagues (1994), Statistics Sweden (1996), EUROSTAT (1997a, 1997b), Radermacher & Stahmer (1998).
 31. It may happen, though, as has been observed in several countries lately, that severe cuts in public spending diminish the means of statistical offices to proceed along the internationally agreed path (UNO 1993) and may even lead to a termination of necessary basic statistics that research has been using so far for the purposes of materials flow analysis.
 32. The International Human Dimensions of Global Environmental Change Programme (IHDP), initiated in 1990 by the International Social Science Council, fosters research-related activities that seek to describe and understand the human role in causing global environmental change and the consequences of these changes for society. Industrial Transformation (IT) has been identified as one of the six priority research topics within IHDP.
 33. The Scientific Committee on Problems of the Environment (SCOPE) was created by the International Council of Scientific Unions (ICSU) in 1969 to assemble, review, and assess the information available on manmade environmental changes and the effects of these changes on man.
 34. Editor's note: For a review of "Factor 4" and "Factor 10," see L. Reijnders, The factor X debate: Setting targets for eco-efficiency, *Journal of Industrial Ecology* 2(1): 13–22.
 35. In international politics, this same reservation can be observed with the United States position on the reduction of greenhouse gases, this being one of the main issues related to bulk materials flow reduction.

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