Society’s Metabolism

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Summary
In this article, we inquire into the intellectual history of the application of the biological concept of metabolism to social systems—not as a metaphor, but as a material and energetic process within the economy and society, vis-à-vis various natural systems. The paper reviews several scientific traditions that may contribute to such a view, including biology and ecology, social theory, cultural anthropology, and social geography. It assembles widely scattered approaches dating from the 1860s onward and shows how they prepare the ground for the pioneers of “industrial metabolism” in the late 1960s. In connection to varying political perspectives, metabolism gradually takes shape as a powerful interdisciplinary concept. It will take another 25 years before this approach becomes one of the most important paradigms for the empirical analysis of the society-nature-interaction across various disciplines. This later period will be the subject of part II of this literature review.

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Introduction

Contemporary research on human-induced global environmental change deals increasingly with two broad and overlapping fields of study: One is “industrial metabolism,” which focuses on the flow of materials and energy in modern industrial society through the chain of extraction, production, consumption, and disposal. Industrial metabolism has been the subject of multidisciplinary work engaging mainly scientists from physics, chemistry, and engineering, as well as experts from the life sciences and economics. Although industrial metabolism is a common term among industrial ecology specialists, only a few are aware of related approaches, across various scientific traditions and beyond the scope of industrial societies.

Starting from a social science perspective (see Fischer-Kowalski 1997), the basic question that guides the task at hand is to what degree do material and energetic processes that fit under the label “metabolism” provide a useful understanding of the interrelation of society with nature? I first elaborate on the biological and ecological meaning of this term and then review some of its early uses in sociology, cultural anthropology, and social geography. This attempt to screen the relevant literature, given the lack of a clearly circumscribed scientific context, is less of a critical and more of an arbitrary organizational task of putting together pieces of an emerging idea. The application of the term metabolism to human society inevitably cuts across the “great divide” between the natural sciences, on the one hand, and the social sciences and the humanities, on the other. In the 1860s, when this divide was not as wide, the concept of metabolism, which then was emerging in biology, quickly found resonance in much of classic social science theory. Later, while being developed further in biology and ecology, the social science usage of this concept became more or less restricted to outsiders.

The awakening of environmental awareness and the increase in cultural acceptability of a critical view of economic growth during the late 1960s triggered a revival of interest in society’s metabolism with a new perspective (Wolman 1965; Ayres and Kneese 1968, 1969; Neef 1969; Boyden 1970; Meadows et al. 1972; Daly 1973). With the description of the achievements of the pioneers of this new research tradition, linked with a new policy concern, this first part of the review will come to a close.

The period since the 1960s, in which there has been a virtual explosion of research dealing with industrial metabolism, will be the subject of the second part of this review, and will be published in a subsequent issue of the Journal of Industrial Ecology.

Metabolism in Biology and Ecology

In one of the standard textbooks in biology, Purves et al. (1992, 113) wrote that “to sustain the processes of life, a typical cell carries out thousands of biochemical reactions each second. The sum of all biological reactions constitutes metabolism. What is the purpose of these reactions—of metabolism? Metabolic reactions convert raw materials, obtained from the environment, into the building blocks of proteins and other compounds unique to organisms. Living things must maintain themselves, replacing lost materials with new ones; they also grow and reproduce, two more activities requiring the continued formation of macromolecules.” They added further, “Metabolism is the totality of the biochemical reactions in a living thing. These reactions proceed down metabolic pathways, sequences of enzyme-catalyzed reactions, so ordered that the product of one reaction is the substrate for the next. Some pathways synthesize, step-by-step, the important chemical building blocks from which macromolecules are built, others trap energy from the environment, and still others have functions different from these” (130).

In another classic text, Beck et al. (1991, 175) explained that “Metabolism includes the following processes:

- All the chemical processes by which food and its derivatives are broken down to yield new building blocks and energy. This segment of metabolism is termed catabolism.
- All the chemical processes by which living cells and tissues are produced and built up. This is anabolism (buildup of new molecules by biosynthesis).
All the regulatory mechanisms that govern these intricate systems."

Whereas the concept of metabolism is widely applied at the interface of biochemistry and biology when referring to cells, organs, and organisms in biology, it appears to be a matter of dispute about whether to use this term further up the biological hierarchy. E. P. Odum, a leading system ecologist, clearly favor(s) the use of terms such as "growth" or "metabolism" on every biological level from the cell to the ecosystem (see, e.g., 1973, 7). The following statement in Beck et al. (1991, 679), for example, is not controversial in biology: "The metabolism of the whole body is simply the sum of all the metabolic processes in all the cells of the body." To aggregate cells to an organism seems always to be legitimate. Which processes may and should be studied on hierarchical levels beyond the individual organism, however, has been a subject of debate since Clements (1916).\(^5\)

This is basically a debate about "holism" (or organicism) versus "reductionism." Do populations (i.e., the interconnected members of a species), communities (i.e., the total of living organisms in an ecosystem), or ecosystems (i.e., the organisms and the effective inorganic factors in a habitat) have a degree of systemic integration comparable to individual organisms? Does evolution work upon them as units of natural selection? These questions are contested in biology, and thus using the term metabolism for a system constituted by a multitude of organisms does not go unchallenged. What would be challenged is not the energy conversion and the nutrient cycling in ecosystems, which are taken as a fact. Rather, the contested point is whether there exist any controls, information-mediated feedback cycles, or evolutionary mechanisms working on the systems level as such—and not just via individual organisms.\(^6\) Notwithstanding the answers to these questions, it is widely accepted that, in effect, biotic communities and ecosystems have self-organizing properties that allow them to optimize the utilization of energy and nutrients.\(^7\)

According to these standards, it is obvious that humans maintain a metabolism. Like any other animal, they are heterotrophic organisms, drawing their energy from complex organic compounds (foodstuffs) that have been (directly or indirectly) synthesized by plants from (mainly) air and water, utilizing the radiant energy from the sun. The human organism converts most of these organic compounds (biomass) through respiration (utilizing oxygen from the air) into carbon dioxide and water, thus extracting chemical energy. The metabolic rate is roughly determined by body weight energetically (so humans fit into the scale of mammals somewhere between dogs and horses), and by physiology qualitatively. Humans can digest only certain foodstuffs, and they cannot synthesize all the amino acids they need from carbohydrates alone (as most herbivorous animals can). So much for thermodynamics and biochemistry, and no one claims that humans can be exempted from either. If humans are to survive and reproduce, they must be able to sustain their metabolism.

Because humans are social animals with an ability to communicate and cooperate beyond that of any other known species, they have tended to solve this problem collectively. It makes sense, therefore, to look at human communities and societies as organizations serving human survival. Societies will, in effect, sustain a metabolism that at least equals the total metabolism of their human members. If they cannot maintain this metabolic turnover, they will die out. But if there is a surplus, this will rarely be processed through the cells of the human body. From an ecosystem perspective, for example, the materials birds use in building their nests constitute a relevant material flow associated with birds. In standard biological terminology, however, this would never be considered as part of a bird's metabolism, regardless of whether it may be vital for the bird's reproduction. So, in fact, the concept of metabolism needs to be expanded to encompass material and energetic flows and transformations associated with "living things" but extending beyond the anabolism and catabolism of cells. Whether it is a population or some other entity, the overall material and energetic turnover of a subsystem of an ecosystem, its consumption of certain materials, their transformation and the production of other materials may be an ecologically useful parameter. In biology, and even less so in biochemistry, this would not be called metabolism.
We know that humans sustain at least part of their metabolism not by direct exchanges with the environment (as they do, for example, in breathing), but via the activities of other humans. This is a matter of organization. Any attempt to describe this organization in terms of a biological system—whether it be the organism, a population in a habitat, or an ecosystem—must draw on analogies and thus runs the risk of being reductionist. On the other hand, the concept of metabolism in biology has valuable features: it refers to a highly complex self-organizing process that the organism seeks to maintain in widely varying environments. This metabolism requires certain material inputs from the environment, and it returns these materials to the environment in a different form.

Roots and Traces of Metabolism in the Social Sciences

Metabolism in Social Theory

Within the nineteenth-century foundations of social theory, it was Marx and Engels who applied the term metabolism to society. “Metabolism between man and nature” is used in conjunction with the basic, almost ontological, description of the labor process. “The labour-process . . . is human action with a view to the production of use-values, appropriation of natural substances to human requirements; it is the necessary condition for effecting exchange of matter between man and nature; it is the everlasting nature-imposed condition of human existence, and therefore independent of every social phase of that existence, or rather, is common to every such phase” (Marx and Engels 1867, 183f). The “elementary factors” of the labor process are (1) the personal activity of man (i.e., work itself), (2) the subject of work (Arbeitsgegenstand), and (3) its instruments (178).

“In the labour-process . . . man’s activity, with the help of the instruments of labour, effects an alteration, designed from the commencement, in the material worked upon. The process disappears in the product; the latter is a use-value, Nature’s material adapted by a change of form to the wants of man.” (180). The subject of labor may be “spontaneously provided by nature,” or it will have been “filtered through past labour.”

According to Benton (1989, 66), “The intentional structure of the labour-process is, for Marx, a transformative one.” This view does not, says Benton, properly encompass all forms of labor, particularly not what he terms “ecoregulation” (e.g., most of farm work) and “primary appropriation” (hunting, gathering, mining, etc.), in other words, those types of labor closest to natural processes. It also does not cover unintended consequences and various other ecologically important characteristics of the labor process. Thus Benton concludes, as Marx’s and Engels’ theory presents itself in the mature economic writings, it bears several theoretical defects, “. . . the net effect of which is to render the theory incapable of adequately conceptualizing the ecological conditions and limits of human need-meeting interactions with nature.” (Benton 1989, 63).

Marx’s and Engels’ notion of metabolism (Stoffwechsel) was molded by the biology of their times and popular writings from physiological materialists such as Moleschott (1852), who described metabolism as an exchange of matter between an organism and its environment, rather than as a cellular biochemical conversion, as modern textbooks do. Marx and Engels did not use this notion only in a metaphorical sense: they meant to imply a material exchange relation between man and nature, a mutual interdependence beyond the widespread simple idea of man “utilizing nature.” The notion points to a fundamental material interrelatedness on an anthropological level, but it is not used as a tool to analyze capitalist society. In their writings there exists no such idea as the accumulation of capital having to do with the appropriation of the accumulated “wealth” of nature (e.g., fossil fuels); appropriation as a basis for capital accumulation is always and only appropriation of surplus human labor, as Martinez-Alier (1987, 218–224) points out. In other contexts Marx uses the expression “societal metabolism” as an analogue to describe the exchange of commodities and the relations of production within society (see Schmidt 1971, 92).

The writings of Marx and Engels are not the only reference to societal metabolism to be gained from the founding fathers of modern social science. Most social scientists of the period
tended to be highly interested in the advances of biology, particularly in evolutionary theory and its implications for universal progress (e.g., Spencer 1862; Morgan 1877). The process of societal progress and the differences in stages of advancement among societies relate to the amount of available energy, as Herbert Spencer stated in his First Principles in 1862: societal progress is based on energy surplus. First, it enables social growth and thereby social differentiation. Second, it provides room for cultural activities beyond basic vital needs.

Wilhelm Ostwald, 1919 Nobel Prize winner in chemistry, made a somewhat similar contribution. Referring to the second law of thermodynamics, he argued that minimizing the loss of free energy is the objective of every cultural development. Thus, according to Ostwald (1909), one may deduce that the more efficient the transformation from crude energy into useful energy, the greater a society's progress. For Ostwald the increase in efficiency has the characteristics of a natural law affecting every living organism and every society. He stressed that each society has to be aware of the "energetic imperative" (Energetischem Imperativo): In the words of Ostwald, "Don't waste energy, use it" (1912, 85). In addition, Ostwald was one of the few scientists at the time who was sensitive to the limitations of fossil resources. He believed that a durable (sustainable) economy must use solar energy exclusively. This work provided Max Weber, one of the founding fathers of sociology, with an opportunity for an extensive discussion. Weber reacted in quite a contradictory manner. On the one hand, he dismissed Ostwald's approach as "grotesque" (1909, 401) and as full of "mischief" (381), and challenged its core thesis on natural science grounds: "In no way would an industrial production be more energy efficient than a manual one—it would only be more cost efficient" (386f.). At the same time he rejected natural science arrogance toward the "historical" sciences and the packaging of value judgments and prejudices in natural science "facts" (401). On the other hand, although he admitted that energy may possibly be important to sociological concerns (399; see also Weber 1904), he never elaborated such considerations.

Sir Patrick Geddes, cofounder of the British Sociological Society in 1902, sought to develop a unified calculus that was based on energy and material flows and was capable of providing a coherent framework for all economic and social activity. He proclaimed society's emancipation from monetary economy and movement toward an economy of energy and resources (Geddes 1884), an attempt "rewarded with near-instant oblivion," according to Rosa et al. (1988, 150). Martinez-Alier (1987, 89ff.), on the other hand, devoted a whole chapter to Geddes, claiming that he was a major predecessor of ecological economics. In four lectures at the Royal Society of Edinburgh, Geddes developed a type of economic input-output table in physical terms: the first column would contain the sources of energy and the sources of materials used. Energy and materials are transformed into products in three stages: extraction of fuels and raw materials; manufacture; and transport and exchange. Between each of these stages losses occur that have to be estimated: thus the final product might then be surprisingly small in proportion to the overall input (Geddes 1885). So Geddes appears to have been the first scientist to approach an empirical description of societal metabolism on a macroeconomic level.

Frederick Soddy, another Nobel laureate in chemistry, also turned his attention to the energetics of society, but did so with an important twist: he saw energy as a critical limiting factor to society, and was thus one of the few social theorists sensitive to the second law of thermodynamics (Soddy 1912, 1922, 1926). He therefore took issue with Keynes's views on long-term economic growth. Similarly, Werner Sombart (1902, vol. 2, 1137f.), in his analysis of late-eighteenth-century development, at least recognized the social relevance of energy; the scarcity of fuel wood, according to Sombart, was at that time seriously threatening the advancement of capitalism altogether. In the mid-1950s, Fred Cottrell (1955) again raised the idea that the availability of energy limits the range of human activities. According to Cottrell, this is one of the reasons why pervasive social, economic, political, and even psychological change accompanied the transition from a low-energy to a high-energy society.

For the development of sociology as a discipline, these more or less sweeping energetic
theories of society remained largely irrelevant. Even the influential Chicago-based school of sociology, with its promising label of "human ecology" (e.g., Park 1936), carefully circumvented any references to natural conditions or processes. Later authors such as O. D. Duncan operated using the term "ecological complex," which implied a weblike interdependence among population, organization, environment, and technology (the "POET"-model). However, what Duncan calls "the environment" is devoid of physical characteristics; rather, it is a social, and at best a spatial, variable (Duncan 1959, 1964). Before the advent of the environmental movement, modern sociology just did not refer to natural parameters as either causes or consequences of human social activities. Neither the system- nor the interaction-oriented US-American traditions, nor the "materialist," Marxist traditions revived in the 1960s, dealt with possible physical properties of society and society-nature interaction. This view is strongly supported by Dunlap and Catton's (1979) review of the American literature. One of the few exceptions they mention is Sorokin's underrated analysis of the social repercussions of famine (Sorokin 1942, 66-67, 122, 262-264, 289). Some well-known French sociologists, such as Michel Foucault (1975) and Pierre Bourdieu (1989, at least invite the human body onto the sociological stage. The same can be said about the German sociological theorist Norbert Elias (1969). Looking at other major macrosociological European theorists, such as Anthony Giddens (1989, 1990), Jurgen Habermas (1981), and Niklas Luhmann (1984, 1986), one will search in vain for concepts referring to the material dimensions of the society-nature interaction.

Metabolism in Cultural and Ecological Anthropology

Similar to sociology, the beginnings of cultural anthropology (see, e.g., Morgan 1877) were marked by evolutionism—that is, the idea of universal historical progress from more "natural," barbarian to more advanced and civilized social conditions. Cultural anthropology, however, split into a more functionalist and a more culturalist tradition. The functionalist line, from which contributions to societal metabolism should be expected, did not, as was the case in sociology, turn toward economics and distributional problems, but retained a focus on the society-nature interface. In effect, several conceptual clarifications and rich empirical material on societies' metabolism can be gained from this research tradition that Orlove in his critical review (1980) terms "ecological anthropology."

Leslie White, one of the most prominent anthropologists of his generation and an early representative of the functionalist tradition, rekindled interest in "energetics." For White, the vast differences in the types of extant societies could be described as social evolution, and the mechanisms propelling it were energy and technology. "Culture evolves as the amount of energy harnessed per capita and per year is increased, or as the efficiency of the instrumental means (i.e., technology) of putting the energy to work is increased" (White 1949, 366). A society's level of evolution can be assessed mathematically: it is the the product of the amount of per capita energy times efficiency of conversion. So this, in fact, was a metabolic theory of cultural evolution—however unidimensional and unconcerned with environmental constraints it may have been.12

Julian Steward's "method of cultural ecology" (Steward 1968) paid a lot of attention to the quality, quantity, and distribution of resources within the environment. His approach can be illustrated from the early comparative study "Tappers and Trappers" (Murphy and Steward 1955). Two cases of cultural (and economic) change are presented, in which tribes traditionally living from subsistence hunting and gathering (and some horticulture) completely change their ways of living as a consequence of changing their metabolism. The authors analyze this process as an irreversible shift from a subsistence economy to dependence upon trade. Eastern Montagnais, in the northeastern Algonkin (Ontario, Canada), used to live in multifamily winter hunting groups, and in somewhat larger units during the summer season of fishing and caribou hunting. With the establishment of trading posts by white settlers, the trapping of animals for their pelts and trade for hardware and foodstuffs was secondary to native subsistence activities. Accord-
ing to Murphy and Steward, “The Indians could devote themselves to the luxury of securing trade articles only after assuring themselves of an ample food supply.” (1955, 337). By relying on barter and credit, however, the Indians grew dependent on the traders, and ultimately fur trapping became more important than hunting for subsistence. This resulted in a complete restructuring of their patterns of settlement and communal ties (with a strengthening of nuclear families and territorial family property at the expense of interfamilial ties).

The second example is given for the Mundurucú, native Indians who originally lived in semisedentary villages in the gallery forests and savannah lands in the state of Pará, Brazil, on slash-and-burn horticulture and hunting, until they were drawn into “the ecology of rubber collection.” Murphy and Steward give a more elaborate description of the metabolic transformations: “During the nineteenth century (and to the present day) the Mundurucú, like the Algonkians and in fact most aborigines, had been acquiring a seemingly insatiable appetite for the utilitarian wares and trinkets of civilization... firearms, ... clothing, ... (but) also ... many strictly non-utilitarian goods, such as ... raw cane rum and beads. Reliance on manufactured goods entailed further dependence upon many adjuncts of these goods. For example, firearms required powder and lead, while garments of factory-woven cloth had to be made and repaired with scissors, thread, and needles. The substitution of metal pots for native ones of clay and of manufactured hammocks for the native product has reached the point where many young women do not know how to make these articles.... They would be helpless without the copper toasting pan used to make maniok flour. ... Despite the flourishing trade in gew-gaws, the allure of most trade goods lay more in their sheer utility than in their exotic qualities. The increased efficiency of the Mundurucú economy made possible by steel tools must have been enormous” (1955, 344f.).

If we translate this analysis into the terms of metabolism (a concept Murphy and Steward do not apply), the following transformations have taken place: (1) the substitution of metabolism based upon the natural environment by a metabolism based upon exchange with other societies, whereby these cultures become “primary producers” or “extractors” in a social division of labor on a grander scale, and (2) the substitution of certain materials and sources of energy by others, produced and distributed by completely different mechanisms on a completely different spatial scale. These changes in metabolism contribute to a transformation of many social and cultural features of these communities.

Several outright analyses of metabolism have been produced by authors whom Orlove (1980) groups together as “neofunctionalists”: Marvin Harris, Andrew Vayda, and Roy Rappaport. The followers of this approach, according to Orlove (1980, 240), “see the social organization and culture of specific populations as functional adaptations which permit the populations to exploit their environments successfully without exceeding their carrying capacity.” The unit that is maintained is a given population rather than a particular social order (as it is with sociological functionalists). In contrast to biological ecology, they treat adaptation not as a matter of individuals and their genetic success, but as a matter of cultures. Cultural traits are units that can adapt to environments and are subject to selection. In this approach, human populations are believed to function within ecosystems as other populations do, and the interaction between populations with different cultures is put on a level with the interaction of different species within ecosystems (Vayda and Rappaport 1968).

This approach has been very successful in generating detailed descriptions of food-producing systems (Anderson 1973; Kemp 1971; Netting 1981), some of which we draw upon more closely in the next section. In addition, it has raised the envy of colleagues by successfully presenting solutions to apparent riddles of bizarre habits, thereby attracting a great deal of public attention (Harris 1966, 1977). To illustrate the method, we briefly report on Harner’s (1977) famous analysis of Aztec cannibalism.

Pre-Conquest Mexicans practiced human sacrifices in unprecedented numbers. A figure commonly cited for Aztecs is 20,000 sacrifices per year. According to Harner, population pressure increased in the Valley of Mexico and wild game supplies were hardly available any longer to provide protein for the diet. Carbohydrates
could be secured by agricultural intensification, but domesticated animal production was limited by the lack of a suitable herbivore. In the Old World the domestication of herbivorous mammals proceeded apace with the domestication of food plants. In the New World the ancient hunters had completely eliminated potential herbivorous mammalian domesticates from the Mesoamerican area (in South America the llama, alpaca, and guinea pig had survived, however). This made the ecological situation of the Aztecs unique among the world's major civilizations. Large-scale cannibalism, disguised as sacrifice, was the cultural solution to an ecological problem. The estimated ratios of 5–20 war prisoners sacrificed per year per 100 inhabitants of Tenochtitlan can be looked upon as a significant contribution to protein in the diet. This practice also helps us understand a political peculiarity: the Aztecs always withdrew from conquered territories and did not seize them in the Old World fashion. Asked by Cortez to explain why, Montezuma replied that this way his people could continue to take captives for sacrifice nearby (Harner 1977, 130).

This is a clear example of a metabolic argument. Under certain environmental conditions (that have, at least in part, been produced by previous human cultures), the metabolic needs of a population translate into specific cultural practices. These practices in fact serve human metabolism. Harner, however, does not discuss the overall ecological efficiency of these practices. Presumably it is not high: humans are not good at converting energy, and, even if mainly raised on a herbivorous diet, will not use the available yield of the land very efficiently. On the other hand, these practices result in a certain kind of population control. This analysis has stood quite uncontested: Hicks (1979) objects only to a minor argument within Harner's theory, and even Orlove (1980, 243), who does not hide his dislike for functionalist interpretations, cites no sources that would substantively criticize Harner's line of reasoning.

There are, however, some theoretical and methodological problems in this approach that need to be discussed in greater detail. They entail the difficulty of specifying a unit of analysis: a local population? A culture? This is related to the difficulty of specifying the process of change and of locating intercultural (or intersocietal) interactions in this framework. These scientific traditions, however, have prepared cultural anthropologists to be among the first social scientists to actively participate in later discussions on environmental problems of industrial metabolism (see several contributions in Thomas 1956a; Kemp 1971; Rappaport 1971).

**Metabolism in Social Geography and Geology**

In 1955, 70 participants from around the world and from a great variety of disciplines convened in Princeton, New Jersey, for a remarkable conference entitled "Man's Role in Changing the Face of the Earth." The conference was financed by the Wenner-Gren Foundation for Anthropological Research; the geographer Carl O. Sauer, the zoologist Marston Bates, and the urban planner Lewis Mumford presided over the sessions. The papers and discussions were published in a 1,200-page compendium (Thomas 1956a) that documents, so I would claim, the world's first interdisciplinary panel on environmental problems of human development staged by top scientists.

The selection of the conference's title was an attempt to honor George Perkins Marsh, who in 1864 published *Man and Nature: Or, Physical Geography as Modified by Human Action*, and is considered the father of social geography. For Marsh, man is a dynamic force, often irrational in creating a danger to himself by destroying his base of subsistence. The longest chapter of *Man and Nature*, entitled "The Woods," is pleading for the recreation of forests in the midlatitudes. He was not, as the participants of the 1955 conference noted, concerned about the exhaustion of mineral resources. He looked upon mining rather from an aesthetic point of view, considering it "an injury to the earth" (Thomas 1956b, xxix).

The possible exhaustion of mineral resources was taken up by the Harvard geologist Nathaniel Shaler in his book *Man and the Earth* (1905). In considering longer time series, he noted that
since the coming of the Iron Age, the consumption of mineral resources had increased to a frightening degree. In 1600 only very few substances (mostly precious stones) had been searched for underground, but in his time, at the turn of the twentieth century, several hundred substances from underground sources were being used by man, of essential importance being iron and copper. Shaler was concerned with the limits of the resource base.

One might say this shift of focus from Marsh (1864) to Shaler (1905) reflects the change in society's metabolism from an agrarian mode of production (where scarcity of food promotes the extension of agricultural land at the expense of forests) to an industrial one, where vital "nutrients" are drawn from subterrestrial sinks that one day will be exhausted. It reflects it, but it does not reflect upon it.

With the 1956 volume the concern with a limited mineral base for an explosively rising demand of minerals is even more obvious (Thomas 1956a). Such a materials flow focus seems to have been strongly supported by wartime experiences and institutions: Ordway (1956, 988) quotes data from a 1952 report by the President's Materials Policy Commission in which concern is expressed over the soaring demand for materials. The depletion of national resources becomes part of a global concern: "If all the nations of the world should acquire the same standard of living as our own, the resulting world need for materials would be six times present consumption" (988). Based on these considerations, Ordway advances his "theory of the limits of growth," which rests on two premises: "(1) levels of human living are constantly rising with mounting use of natural resources, and (2) despite technological progress we are spending each year more resource capital than is created. The theory follows: if this cycle continues long enough, basic resources will come into such short supply that rising costs will make their use in additional production unprofitable, industrial expansion will cease, and we shall have reached the limit of growth" (Ordway 1956, 992). McLaughlin, otherwise more optimistic than Ordway, states in the same volume that by 1950 for every major industrial power the consumption of metals and minerals had exceeded the quantity that could be provided from domestic sources (McLaughlin 1956, 860).

Similarly, the 1955 conference experts discussed the likelihood of severe shortages in future energy supplies. Eugene Ayres, who speaks about "the age of fossil fuels," and Charles A. Scarlott, who treats "limitations to energy use" remind us of the limits inherent to using given geological stocks. Ayres, elaborating on fossil fuels since the first uses of coal by the Chinese about 2,000 years ago, is very skeptical regarding geologists' estimates of the earth's reserves, suspecting them to be much larger than current projections, but nevertheless concludes that "in a practical sense, fossil fuels, after this century, will cease to exist except as raw materials for chemical synthesis" (Ayres 1956, 380). Scarlott (1956) demonstrates the diversification of energy uses and the accompanying rise in demand, and then elaborates on a possible future of solar energy utilization and nuclear fusion as sources of energy.

The bulk of materials flow considerations in the 1955 conference, however, is devoted to the input side of material metabolism. The overall systemic consideration that the mobilization of vast amounts of matter from geological sinks (e.g., minerals and fossil energy carriers) into a materially closed system such as the biosphere would change the parameters of atmospheric, oceanic, and soil chemistry on a global level has not yet arisen. Still, many contributions of this conference document the transformations of local and regional natural environments by human activity, in both the past and the present. The global environmental change issue is taken up in a September 1970 special issue of Scientific American, which was devoted to the biosphere. One year later, Scientific American published an issue on energy and socioeconomic energy metabolism (vol. 224, no 3, 1971). In 1969 the German geographer Ernst Neef talked explicitly about the "metabolism between society and nature" as a core problem of geography (Neef 1969). But this belongs to our discussion on the post-1968 cultural revolution of environmentalism, to which we turn next.
Achievements of the Pioneers of Materials Flow Analysis in the Late 1960s

In the late 1960s, when it became culturally possible to take a critical stand on economic growth and consider its environmental side effects, the stage was set for a new twist in the examination of society's metabolism. Up to this point metabolism had come up in various discourses mainly by way of arguments claiming that natural forces and physical processes did, indeed, matter for the organization and development of society, and that it would be reasonable therefore to attribute to them some causal significance for social facts. The mainstream of social science dealing with modern industrial society—whether economics, sociology, or political science—had not cared about this issue at all. In the mid-1960s this started to change, and—apparently originating from the United States—a set of new approaches developed, often triggered by natural scientists, and subsequently further developed, typically in cooperation with social scientists. In these approaches the material and energetic flows between societies (or economies) and their natural environment became a major issue, governed by the worry that a "cowboy economy" might not be compatible with "Spaceship earth" (Boulding 1966). The common picture of cultural evolution as eternal progress started to give way to a picture of industrial economic growth as a process that potentially implied the ultimate devastation of human life. This must be considered as a basic change in worldview, and it took hold of a wide range of intellectuals across many disciplines. One could say that it promoted something akin to the rebirth of the paradigm of metabolism applied to industrial societies.

"The metabolic requirements of a city can be defined as the materials and commodities needed to sustain the city's inhabitants at home, at work, and at play. . . . The metabolic cycle is not completed until the wastes and residues of daily life have been removed and disposed of with a minimum of nuisance and hazard" (Wolman 1965:179). This declaration served as the introduction to the first attempt to conceptualize and operationalize the metabolism of industrial society—that is, the 1965 case study of a model U.S. city of 1 million inhabitants by Abel Wolman, a water-supply specialist and participant in the 1955 conference "Man's Role in Changing the Face of the Earth." Wolman was well aware that water is the input needed in the highest quantities by far, but he also offered estimates for food and fossil energy inputs, as well as (selected) outputs such as refuse and air pollutants. His argument is mainly directed at problems he foresaw with respect to providing an adequate water supply for American megacities.17

The economist Kenneth Boulding had also participated in the 1955 conference. Referring to Bertalanffy (1952), Boulding (1966), in his article "The Economics of the Coming Spaceship Earth," briefly outlines an impending change from what he calls a "cowboy economy" to a "spaceman economy." The present world economy, according to this view, is an open system with regard to energy, matter, and information ("econosphere"). There is a "total capital stock, i.e., the set of all objects, people, organizations and so on" that have inputs and outputs. Objects pass from the noneconomic to the economic set in the process of production, and objects pass out of the economic set "as their value becomes zero" (Boulding 1966, 5). "Thus we see the econosphere as a material process." This similarly can be described from an energetic point of view. In the cowboy economy, throughput is at least a plausible measure of the success of the economy. "By contrast, in the spaceman economy, throughput is by no means a desideratum, and is indeed to be regarded as something to be minimized rather than maximized. The essential measure of the success of the economy is not production and consumption at all, but the nature, extent, quality, and complexity of the total capital stock, including in this the state of the human bodies and minds" (Boulding 1966, 9). Here we find one of the first systematic considerations of the material components of—as I would say—"society," or what Boulding calls the "econosphere," visualized as an input-output system within the biosphere. Boulding does not, as occasionally happens with systems approaches, confound the economy or society with an ecosystem.18
In 1969 Robert Ayres, a physicist, and Allen Kneese, an economist, basically presented the full program of what in the 1990s was carried out as material flow analyses of national economies.19 Their core argument is an economic one: the economy heavily draws upon priceless environmental goods such as air and water—goods that are becoming increasingly scarce in highly developed countries—and this precludes Pareto-optimal allocations in markets at the expense of those free common goods. They conclude with a formal general equilibrium model to take care of those free common goods. They conclude with a formal general equilibrium model to take care of these externalities. In the first part of their article the authors give an outline of the problem and present a first material flow analysis for the United States between 1963 and 1965 (Ayres and Kneese 1969, table 1). They claim that "the common failure [of economics] . . . may result from viewing the production and consumption processes in a manner that is somewhat at variance with the fundamental law of the conservation of mass" (Ayres and Kneese 1969, 283). There must occur, they argue, uncompensated externalities unless (1) all inputs of the production process are fully converted into outputs, with no unwanted residuals along the way (or else they all be stored on the producers' premises), and (2) all final outputs (commodities) are utterly destroyed, made to disappear, in the process of consumption, or (3) property rights are so arranged that all relevant environmental attributes are in private ownership, and these rights are exchanged in competitive markets.

According to the authors, none of these conditions can be expected to hold. "Nature does not permit the destruction of matter except by annihilation with anti-matter, and the means of disposal of unwanted residuals which maximizes the internal return of decentralized decision units is by discharge to the environment, principally watercourses and the atmosphere. Water and air are traditionally free goods in economics. But in reality . . . they are common property resources of great and increasing value. . . . Moreover, . . . technological means for processing or purifying one or another type of waste discharge do not destroy the residuals but only alter their form. . . . Thus . . . recycle of materials into productive uses or discharge into an alternative medium are the only general options" (283).

"Almost all of standard economic theory is in reality concerned with services. Material objects are merely vehicles which carry some of these services. . . . Yet we [the economists] persist in referring to the 'final consumption' of goods as though material objects . . . somehow disappeared into the void. . . . Of course, residuals from both the production and consumption processes remain and they usually render disservices . . . rather than services" (284). Thus they propose to "view environmental pollution and its control as a materials balance problem for the entire economy" (emphasis added, 284). "In an economy which is closed (no imports or exports) and where there is no net accumulation of stocks (plant, equipment, . . . or residential buildings), the amount of residuals inserted into the natural environment must be approximately equal to the weight of basic fuels, food, and raw materials entering the processing and production system, plus oxygen taken from the atmosphere" (284).

Within these few paragraphs, almost all chords of the future debate are strung. The model of socioeconomic metabolism presented (a term that is not used in the contribution) owes more to physics than to ecology. For an organism, it is obvious that some residues have to be discharged into the environment. In population ecology, it is the efficiency of energetic conversion that would be considered—not the recycling of materials. This clearly would be the task of the ecosystem: in the ecosystem it is the "division of labor" of different species that would take care of materials recycling, and never the members of one species alone. From the point of view of ecosystems theory, therefore, the idea of residues as a "disservice" to the population discharging them would seem alien to the common concept of nutrient cycles.20 Ayres and Kneese then proceed to present an overview of the "weight of basic materials production" in the United States. They consider only what they call "active inputs" (28). The criterion they apply is whether a material undergoes chemical change in the process of being used. Thus they exclude construction materials (stone, sand, gravel, and other minerals used for structural purposes), as well as overburden and mine tailings. They consider their use as more or less "tantamount to physically moving them from
one location to the other”(28). If these materials were to be included, the authors see no logical reason to exclude material shifted in harbor dredging or plowing—"a line must be drawn somewhere."

This is a way to admit a problem not really tackled in this article: Where is the borderline between the economy, or the social system, and nature? As a consequence, it is hard to handle another problem with the necessary clarity of distinction: What is the status of livestock in a materials balance? Ayres and Kneese’s 1969 publication treats “crops” (with the exclusion of crops used to feed livestock) and “livestock and dairy” as basic material input. Thus Ayres and Kneese logically and statistically externalize parts of animal husbandry from the economy: livestock is not considered a “product” of farming, but an input from nature. In their 1974 revised version, they do include crops used for feeding livestock, which leads to double counting: those crops used to feed livestock enter the calculation both in a primary manner, as fodder, and in a secondary manner, as milk or meat. Nevertheless, the total input is underestimated: because this livestock not only feeds on crops but is also grazing, the (considerable) amounts consumed in grazing are missing. We show below the quantitative differences entailed in this fuzziness. But this does not in the least diminish the outstanding qualities of this pioneering article.

Ayres and Kneese’s active inputs also do not include air and water. Whereas in the 1969 publication the input of oxygen is no more than mentioned, in a subsequent publication by Kneese and colleagues (1974) it is considered in an extensive footnote. The category now includes the oxygen required for human and livestock respiration, as well as that required for technical combustion, which amounts to an almost tenfold increase in all respiration (53). In both publications water is not discussed as an input quantity, but only as part of the problem of pollution.

Whereas the inputs from the environment to the economy are listed in some detail, the outputs to the environment (in the sense of residuals) are treated in a sweeping manner. Nevertheless, all the problems that have marked the following decades of emission and waste policies—problems that still have not been properly resolved—are clearly represented. It is spelled out that there is a primary interdependency among all waste streams that evades treatment by separate media. Kneese and colleagues (1974) are even prophetic enough to recognize that there is one stream of waste—carbon dioxide—that is nontoxic and, hence, not interesting for emission regulation. They anticipate correctly that carbon dioxide, given its sheer quantity, might become a major problem (i.e., climate change). Finally, they are able to see that a reduction of residuals can be achieved only through a reduction of inputs. All these are the core insights of the materials balance approach these authors may be said to have “invented.” And although one should suspect that the formalized link to an economic model of externalities generated at once almost too much information packed into one article to secure an effect, this contribution by Ayres and Kneese (1969) became a starter to a research tradition capable of portraying the material and energetic metabolism of advanced industrial economies. It was not “man” any more who was materially and energetically linked to nature, but a complex, well-defined social system: “The dollar flow governs and is governed by a combined flow of materials and services (value added)” (Kneese et al. 1974, 54).

Judged by the standards of later European data, the empirical results rendered by these pioneering studies appear to be correct within an order of magnitude. Of course, the results depend upon the definition of the social system, its components, and the relevant material flows. (See line 1 of “totals” in table 1: the per capita values differ by factor 20. Once the definitions are harmonized, however, the results obtained seem to be quite in accordance [see adjusted per capita volumes in the last line of table 1]).

This even holds true for an early publication from the Soviet Union. Streibel (1990) refers to a study published in Moscow in 1974 by Gofman and colleagues that describes the overall material metabolism of the national economy of the Soviet Union, and that presents a highly aggregated quantitative model for the flows to and from the biosphere and between various parts of the economy. Because the original source is not available, it is hard to tell how thorough this analysis was and what kind of definitions it applied (e.g.,
Table 1 The structure of industrial metabolism—pioneer studies and "state of the art" compared (annual material consumption in tons, overall and per capita)

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<tbody>
<tr>
<td></td>
<td>million tons/y</td>
<td>tons/y*c</td>
<td>million tons/y</td>
</tr>
<tr>
<td>Water</td>
<td>3,100</td>
<td>15.5</td>
<td>207.3</td>
</tr>
<tr>
<td>Oxygen</td>
<td>389.5</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Food and fodder</td>
<td>218</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Other biomass</td>
<td>1,448</td>
<td>7.2</td>
<td>8.6</td>
</tr>
<tr>
<td>Fossil fuels</td>
<td>585</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>Construction materials</td>
<td>5,540.5</td>
<td>28.7</td>
<td>217.7</td>
</tr>
<tr>
<td>Other materials</td>
<td>20.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>559</td>
<td></td>
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</tbody>
</table>

1. The term "industrial metabolism" was coined quite recently in Ayres and Simonis (1994). This book raised the old issues again on a well-received international level.
2. National production plus imports minus exports.
3. Obviously, water for industrial energy generation (cooling) is not included.
4. Atmospheric oxygen only: 2.74 billion tons combustion, 0.3 billion tons animal respiration, and 0.06 billion tons human respiration.
5. Atmospheric oxygen for combustion only (without animal or human respiration).
6. Forestry products on an 85% dry weight basis.
7. "Other minerals."
8. Without oxygen and water; construction materials assumed according to German per capita values.

Water is included in the material flows, but how about oxygen?). It is interesting to note, however, that the overall amount of materials extracted from the environment (300 billion tons) matches with the data from Ayres and Knese 1969. For example, suppose that the construction materials are included in the Moscow data, the (U.S.) 2.5 million of raw materials input would have to be doubled to 5.0. Raw materials do amount to about 5% of total material throughput. So out of the 300 billion tons there should be approximately 15 million tons of raw materials, if air was not included in the total, or 12 million tons if it was. Thus the amount of material throughput in the Soviet Union in the 1970s would have been two to three times as large as that of the United States. Considering, apart from possible differences in material efficiency, that one of the two systems tried to downplay its wastes, and the other tried to exaggerate its production, the result is not altogether out of range.

We may conclude, therefore, that the pioneer studies of overall material metabolism not only set up an appropriate conceptual framework, but also arrived at reasonable empirical results. Considering this fact, it is amazing that it took about another twenty years until this paradigm and methodology became widely recognized as a useful tool.

Acknowledgments

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Notes

2. The second one concerns land-use/land-cover change, and deals with the alteration of the land surface and its biotic cover.
3. Take as an example the authors of the classic book *Industrial Metabolism*, edited by Ayres and Simonis in 1994. Out of 22 writers, 9 are from physics, chemistry, or technical engineering; 6 from the life sciences; 5 economists, 2 sociologists and historians.
4. What readers might consider an important omission, I did not do a specific inquiry into the history of economics. An excellent source for this is Martinez-Alier (1987), who aims at reconstructing the predecessors of ecological economics. He rightly claims many of the modern ecological economics’ ideas to be heir to theories of “agricultural energetics” (e.g., Podolinsky 1880; Sacher 1881). Martinez-Alier also shows some of the Austrian socialists associated with the Vienna Circle (around Mach, Wittgenstein) to have developed conceptions of society’s metabolism with an idea of distributional justice in mind, such as Popper-Lynkeus (1912) and Neurath (1925).
5. Tansley (1935, 296) established “ecosystem” as a proper unit of analysis. He did so by opposing Clements’ “creed” in an organismal theory of vegetation; he also opposed the term “community” by arguing it did not seem legitimate to lump together animals and plants as members too different to be put on equal footing. Lindemann (1942) then proceeded to analyze ecosystems in terms of energy conversion mathematically, with plants being the producer organisms to convert and accumulate solar radiation into complex organic substances (chemical energy) serving as food for animals, the consumer organisms of ecosystems. Following death, every organism then is a potential source of energy for specialized decomposers (saprophagous bacteria and fungi), thereby closing the cycle in generating inorganic nutrients for plants. This is basically what Odum refers to when talking about the metabolism in an ecosystem.
6. See the more recent debate of Engelberg and Boyarsky (1979) and Odum and Patton (1981) about the cybernetic nature of ecosystems. Engelberg and Boyarsky claim that the dominant interaction between different populations of an ecosystem is the exchange of brute matter and energy in the absence of information-mediated feedback cycles. Odum and Patton also see the food web (as an interconnection of material and energetic rather than informational processes) as the most fundamental element of ecosystems, but claim that a secondary information network is superimposed upon this network of material and energetic flows. A somewhat similar debate is carried on by Salt (1977) as contradicted by Edson et al. (1981) on the existence of “emergent properties” in ecosystems, that is, properties of the system that cannot be reduced to properties of the components, and to be distinguished from merely “collective” properties (e.g., summations or distributional characteristics of the properties of components).
7. As early as 1925, Lotka proposed a “law of maximum energy in biological systems”; similar arguments are presented in theories of succession and climax in plant communities (Odum 1959, 1969).
8. It is interesting to note that biologists tend to attribute organismic (or system integration) characteristics to the human society where they might deny them to an ecosystem. For an early example, see Tansley (1935, 290). For a critical discussion, see Oechsle (1988).
9. According to Schmidt (1971, 86), Marx drew much of his understanding of metabolism from this source and imported a notion of the trophical hierarchy, food chains, and nutrient cycling rather than an organismic, biochemical interpretation of metabolism. Besides, it should be noted that the German word *Stoffwechsel* literally means “exchange of substances” (between A and B), and does not so much convey a meaning of chemical conversion as the Latin term.
10. See the appreciation by Daly (1980).
11. To explain very briefly: While both seek to describe and explain differences between pre-industrial societies, the functionalist line (sometimes also termed “materialist” or “ecological”) focuses on problems of survival and economic reproduction, and the culturalist line...
focuses on cultural patterns, their development, and coherence.

12. Martinez-Alier (1987, 13) claims that Leslie White recognized Ostwald as one of the forebears of evolutionary ecological anthropology.

13. Orlove's criticism of the inadequate use of biological terms, in this case of group selection as a mechanism not accepted by biological theory (Williams 1966), appears to be too harsh, indeed. According to Harris, the unit to which the selection applies is not the population as such, but the elements of its culture. While cultural maladaptation to an environment may in fact harm the population concerned, it will not as a rule systematically change its genetic composition. If as a consequence cultural changes occur, they will most likely be results of learning (Harris 1991, 33–45).

14. This report is an excellent source for research into longer time series of materials consumption. Ordway (1956, 988) even quotes a number for the "raw-material consumption" of the United States in 1950 ("2.7 billion tons of materials of all kinds—metallic ores, non-metallic minerals, construction materials and fuels ..." Note the number given by Ayres and Kneese (1969) (including agricultural products, but excluding construction materials): 2.4 billion tons. With 151 million U.S. inhabitants in 1950, the President's Materials Commission (1952) numbers amount to 18 tons of raw materials per inhabitant per year, which is just a little less than Japan's numbers nowadays. [President's Materials Policy Commission (1952), commonly known as "the Paley Report."]

15. It is interesting to note that even the idea of materials consumption growing less than GDP because of increases in efficiency is taken up in the Paley Report: In its projections for 1975 the Paley Report expects U.S. GDP to double compared to 1950, but the materials input necessary for this only to rise by 50–60% (quoted from Ordway and Samuel 1956, 989).

16. This tradition is explicitly continued in a further publication, representing the contemporary state of the art of social geography, dating from 1990: The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 Years, edited by B. L. Turner II and others (1990).

17. A few years later an Australian team analyzed the metabolism of Hong Kong, concentrating on its "biometabolism" (i.e., human and animal nutrient cycles) only. A comparison with Sydney (data for the years 1970 and 1971) illustrates a "Western style" diet, with the same caloric and nutrient benefit for the consumer, to be about twice as wasteful as a diet in the Chinese tradition (Newcombe 1977; Boyd et al. 1981).

18. Sachs (1993) has drawn attention to human technical grandiosity implied in the image of the "Spaceship Earth," as if it were to be steered and maintained by humans. Later analysts of socio-economic metabolism, in contrast, propagated the humbler idea of society downsizing its own material and energetic turnover.

19. Their article is based upon a report prepared for the U.S. Congress by a Joint Economic Committee and published in a volume of Federal Programs in 1968 (see Ayres and Kneese 1968).

20. As long as a human society draws its inputs from the actual cycles within the biosphere, it may suffer from problems of resource scarcity. It will not easily, however, suffer from problems of pollution (except for some possible forms of local pollution as a consequence of spatial concentration). In theoretical terms this is a problem of coevolution. In all probability, there will exist organisms, and biochemical reactions, that will transform residues into nutrients again, or else the resources will soon have been depleted (and the problem of residues, therefore, have been solved too). It is only when a society mobilizes materials stored for billions of years from geological sinks that it may temporarily overcome problems of resource scarcity, but simultaneously generate problems deriving from residues. See also the distinction between "biometabolism" and "technometabolism" drawn by Boyd (1992, 153ff).

21. A problem once again discussed extensively by Schmidt-Bleek and colleagues from the Wuppertal Institute who have meanwhile developed a method that includes any natural material moved by man in the material flow account. The former categories of "translocated materials"—not to be included in material turnover (Schüttz and Bringezu 1993), but accounted for by way of "material rucksacks" of goods and services (Schmidt-Bleek 1993, 1994)—are now included in the national material turnover balance (Bringezu et al. 1994; Bringezu 1995).

22. It is interesting to note that a quarter of a century later this very same flaw can still be observed in the official statistical report on the material balance of Japan (see Environment Agency Japan 1993, 1994). For the Japanese metabolism it makes less of a difference, how-
ever, because they mainly import their livestock and dairy products.

References


Society's Metabolism


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Keywords
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mass flow analysis
materials flow analysis
physical economy
socioeconomic metabolism
substance flow analysis

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

<table>
<thead>
<tr>
<th>Focus on socioeconomic system</th>
<th>Focus on ecosystem or feedback-loops</th>
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<tbody>
<tr>
<td><strong>Global</strong></td>
<td></td>
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<tr>
<td><strong>National</strong></td>
<td></td>
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<tr>
<td>Selected materials, substances, services</td>
<td></td>
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<tr>
<td><strong>Regional unit</strong></td>
<td></td>
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<tr>
<td><strong>Historical perspective</strong></td>
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</table>
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), 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 Substance

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 Level

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. 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. 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 (materials 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), 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 nongovernment 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).

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), 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.
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, 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. 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:

\[
\text{The sum of material/energetic inputs into a system} = \text{the sum of outputs} + \text{changes in stock} \quad (1)
\]

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; Hütter 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):

\[
\text{The metabolism of the system} = \text{the sum of metabolisms of its subsystems or compartments} + \text{internal transfers} \quad (2)
\]

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." 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 compartments 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. 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. 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: Hütter 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; Hütttler et al. 1996; Schandl...

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**Figure 1** Relevant material flows, terminology, and system boundaries (national level).
I RESEARCH AND ANALYSIS

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; Hütter 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).

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)

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

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.

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

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.
metabolism. In this tradition the possible exhaustion of so-called nonrenewable resources has always been prevailing, referring to fossil energy resources (Scarlett 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. 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.

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).
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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. 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. 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 methods and by corresponding steps on behalf of national statistical offices toward an integration of materials flows into standard statistics in an internationally comparable manner. 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. 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. 

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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 Schlüpman 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 Human Dimensions Programme on Global Environmental Change (IHDP) 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) 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). 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. 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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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 Sieferle (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/iffsocce.

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).


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.


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
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.


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)


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.


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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