Society's Metabolism

The Intellectual History of Materials Flow Analysis, Part I, 1860–1970

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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:[1] One is "industrial metabolism,"[2] 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.[3] 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.[4] 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 favors 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.[8] 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 "eco-regulation" (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),[9] 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" (*Energetischer Imperativ*): 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.[10] 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 (1985), 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), Jürgen 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.[11] 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. According 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 gewgaws, the allure of most trade goods lay more in their sheer utility than in their exotic qualities. The increased efficiency of the Mundurú 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.[13] 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 to specify 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.[14] 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[15] 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.[16]

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 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[21]—"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 neccessary 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.[22]

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 enought 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[1]—pioneer studies and "state of the art" compared (annual material consumption[2] in tons, overall and per capita)

	U.S. national consumption 1965 (Kneese et al. 1974)		*U.S. city 1965 (Wolman 1965)*	*German Federal Republic 1970 (Stat.Bundesamt 1995)*	
	million tons/y	*tons/y*c*	*tons/y*c*	*million tons/y*	*tons/y*c*
Water			207.3[3]	33,572	568.9
Oxygen	3,100[4]	15.5		559[5]	9.3
Food and fodder	389.5	2.0	1.8	140	2.3
Other biomass	218[6]	1.1		30	.5
Fossil fuels	1,448	7.2	8.6	374	5.8
Construction materials				591	9.5
Other materials	585[7]	2.9		74	1.2
Total	5,540.5	28.7	217.7	35,340	597.5
Adjusted total[8]		20.8	22.6		19.3

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 Kneese 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.

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Notes

1. See, for example, National Research Council (1990), UN handbook (1993), European Commission (1994), Enquête Kommission (1994), SCOPE (1996), and HDP (1996).
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 reseach 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 calorific and nutrient benefit for the consumer, to be about twice as wasteful as a diet in the Chinese tradition (Newcombe 1977; Boyden 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 socioeconomic 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 beween "biometabolism" and "technometabolism" drawn by Boyden (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 (Schütz 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.

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