The Energetic Metabolism of Societies

Part I: Accounting Concepts

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energy accounting
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nutrition

Summary

Based upon the currently emerging international consensus on how to account for the materials flows of industrialized countries, this article proposes methods to account for the energetic metabolism of societies. It argues that, to fully exploit the potential of the metabolism approach in the context of sustainable development, both energetic and material aspects of societal metabolism have to be taken into account. The article proposes concepts to empirically describe energy input, internal energy transformations, and energy utilization of societies by extending commonly used notions of energy statistics in a way that is compatible with current methods of materials flow analysis. Whereas energy statistics include only the energy used in technical devices for providing heat, light, mechanical work, and data processing, an accounting system for the energetic metabolism of societies should also consider flows of nutritional energy for both livestock and humans. Moreover, in assessing the energy input of a society, all inputs of energy-rich materials (and immaterial forms of energy such as electricity and light) that cross the boundary into the biophysical structures of society should be taken into consideration, regardless of the purpose for which they are eventually used. As a consequence, an energetic metabolism accounting system treats all biomass as energy input, instead of considering only the biomass used for technical energy generation, as energy statistics do. Part II in this set of articles will apply these concepts to different modes of societal organization and explore the significance of energetic metabolism for sustainable development. In particular, it will explore the significance for policies that aim at increasing the contribution of renewable energy, especially biomass.

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Introduction

In recent years, the notion of a societal metabolism has proved to be fruitful for conceptualizing the interrelations between societies and their natural environments in a way that allows scientists to cooperate in interdisciplinary research. By analogy to the biological notion of metabolism, this approach analyzes physical exchange processes (material and energy flows) between human societies and their natural environments, as well as the internal material and energy flows of human societies (Ayres and Simonis 1994; Fischer-Kowalski 1998). This concept provides a research agenda that can be tackled through interdisciplinary projects: Social scientists can study socioeconomic dynamics behind changing patterns of material and energy flows, and natural scientists can analyze, for example, the consequences of these flows for natural processes.

Societal metabolism (alternatively termed "socioeconomic metabolism," "social metabolism," "society's metabolism," or, more narrowly, "industrial metabolism") is one of the two broad fields of study into which most research on the human dimensions of global environmental problems is currently grouped (the other field focuses on changes in land use and land cover; e.g., Meyer and Turner 1994). The patterns and socioeconomic driving forces of material and energy flows of industrial societies are a major issue in the Industrial Transformation project of the International Human Dimensions of Global Environmental Change Programme (Vellinga and Herb 1999), which is also frequently discussed in this journal. Also, a rich tradition exists in the field of human ecology of studying the flows of materials and energy related to human activities (e.g., Boyden 1992; Cook 1971; Kemp 1971; Rappaport 1971).

One can trace the precursors of the current notion of societal metabolism back into the 19th century (Fischer-Kowalski 1998; Martinez-Alier 1987). Recent years have seen a surge of empirical analyses of societal metabolism on different scales (Fischer-Kowalski and Hüttler 1998). Most of the contemporary work focuses on an accounting of the mass of materials flowing through a society or a specified socioeconomic unit. This field has developed into two broad areas of investigation: materials flow analysis, that is, the accounting of bulk material flows through a socioeconomic compartment, and substance flow analysis, that is, the assessment of the flow of chemically specified compounds such as nutrients and heavy metals.[1] In contrast to this current focus on materials, most societal metabolism studies before the early 1970s were concerned with energy flows (Martinez-Alier 1987).

This article is the first of a pair of articles in this journal that represent an attempt to return energy analysis to the metabolism research agenda (Part II will appear in a forthcoming issue of this journal). I argue that the analysis of energy flows is essential in achieving a complete understanding of societal metabolism. I then review current methodological achievements in materials flow analysis and draw conclusions for the accounting of societal energy flows. This suggests possible approaches for the analysis of the "total amount of energy 'metabolized' by society" (Giampietro 1997, 96). The overall aim of this article, together with Part II, is to broaden the scope of the metabolism approach and strengthen its usefulness for industrial ecology, environmental management, and sustainable development, as well as for more theoretically oriented research traditions such as human ecology or social ecology. More specifically, the article presents an accounting method to assess the energetic metabolism of societies.[2]

My analysis also leads to recommendations for policies aiming at sustainable development, a topic that will be addressed in the second of this pair of articles (Part II). To give some examples, I propose that the total throughput of energy, as assessed by the methods elaborated here, should be used instead of conventional measures of primary energy use as a headline indicator for sustainability of national economies. This suggests that the goal of reducing the energy throughput of industrial economies should be given priority over the goal of substituting renewable resources, above all biomass, for fossil fuels to reduce CO_2 emissions. The methods proposed are useful for analyzing the links between land-use policy and energy policy that are often overlooked but are of prime importance for sustainability. Another policy recommendation is that strategies of a cascade utilization of biomass that aim at the reuse and energetic recycling of biomass residues and wastes should be pursued (Haberl and Geissler 2000); accounting schemes such as those presented here are useful for deriving the potential to do so. Such practical conclusions will be dealt with in Part II, whereas Part I focuses on issues of methodology.

Material and Energetic Aspects of Societal Metabolism

Material flows and energy flows are but two different aspects of the same process. Hence, from a conceptual point of view, it is clear that the metabolism of a society can be adequately understood only if both material and energy are considered. Although this assertion has, to my knowledge, never been explicitly challenged, most current work on societal metabolism ignores energy flows (e.g., Ayres and Ayres 1998; Adriaanse et al. 1997; Matthews et al. 2000). One reason for this could be that—contrary to materials flow accounting (MFA)—energy flow accounting has been an important part of standard economic statistics for decades in industrialized countries. The establishment of MFA as a regularly updated statistical information tool within official statistics has been a major goal of the MFA community (Bringezu et al. 1997). MFA has only recently been implemented in some countries (Stahmer et al. 1997; Schandl et al. 2000). Another reason for the concentration on MFA could be that analyses of societal energy flows abound in the scientific literature (e.g., Cook 1971; Giampietro 1997; Odum 1971; Rappaport 1971; Smil 1992; Starr 1971), so that many may have felt there was no need to perpetuate what some had come to regard as a "calorific obsession" (Moran 1993).[3]

There could also be a more fundamental reason for the recent focus on materials flows. Most metabolism research is being carried out with the aim of contributing to sustainable development. In this respect, is has been argued that the earth, while being a materially closed system (at any practically relevant level of accuracy), is an open system with respect to energy flows (solar energy input). Therefore, it has been argued that the availability of materials could pose a more fundamental limit to the sustainability of physical socioeconomic processes than energy availability, at least in principle (e.g., see the debate of Young 1991; Daly 1992; Townsend 1992; Young 1993); however, practical constraints limit the amount of energy available to society, at least if the goal is a sustainable energy supply (see below).

I argue here that energy flows should be an integral part of the analysis of societal metabolism, most importantly because the maintenance of a continuous flow of materials is possible only when a continuous flow of energy is available to power the various transport and transformation processes constituting the material throughput of a society. Many interdependencies exist between material flows and energy flows. One part of the materials flow is used to build and maintain societal material stocks (buildings, machinery, etc.); another, consisting of energy-rich materials, is used for energy provision (power, heat, light, nutrition, etc.). Energy can be used to increase the availability of materials. An example of this is the energy used in agriculture to raise yields. Materials can be used to reduce energy flows, insulation materials being an example (Nishioka et al. 2000). Conversely, energy can be used to increase the efficiency of material use, as in recycling. Moreover, industrial ecology could—and actually is beginning to (Ligon and Votta 2001)—learn from energy policy, where strategies aiming to increase energy efficiency are an important issue, as in the debate on least-cost planning (Geller 1989). The utilization of the energy contained in waste materials is an important possibility for increasing the efficiency with which resources are being used (Haberl and Geissler 2000); indeed, this is one of the policy recommendations that can be derived from analyses of socioeconomic materials and energy flows. Because energy and materials flows are interwoven in these and other ways, I believe that a narrow focus on materials flows would hamper further progress in understanding the changing patterns of societal metabolism in space and time, and would thus be inadequate for sustainability research.

The study of societal materials flows is useful in that it provides a common ground for cooperation between social and natural scientists

(Fischer-Kowalski and Weisz 1999). A prerequisite for this is not only that societal metabolism be directly linked to socioeconomic concepts (e.g., social organization, institutions, economic accounting systems such as the system of national accounts, economic processes, and political decisions), but also that it be relevant in biological and ecological terms. Because energy flows are one of the most important unifying concepts in ecology (Odum 1969); studying societal energy flows seems to be necessary to guarantee the communicative value of the metabolism approach.

More practical reasons for considering energy flows also exist. One of the motives for materials flow analyses is the development of environmental indicators, MFA being seen as an instrument for aggregating various environmental aspects into a few strategic headline indicators such as the total material throughput of a society (per capita or per unit of gross domestic product). These headline indicators are often seen as proxies for the total environmental impact of a society. Thus, they are a requirement for integrating ecological and socioeconomic goals into strategies of sustainable development (Bringezu et al. 1998; Jänicke 1995)[4]; however, although the provision of a long-term sustainable energy supply, for example on the basis of solar energy, may be possible in theory, actual patterns of societal energy use suggest that energy throughput is at least as closely related to a wide variety of environmental problems as society's material throughput is.

Energy-related environmental problems are not solely the result of fossil-energy use causing CO_2 emissions and resource exhaustion. The utilization of renewable energy can also cause significant environmental problems. Hydropower causes a variety of social and environmental problems, ranging from the forced resettlement of indigenous peoples living in the prospective reservoirs to negative impacts on water quality, flow regime, river and floodplain ecology, biodiversity, and so on (Goldsmith and Hildyard 1984). Biomass utilization for energy generation is restricted by available area and its biological productivity (net primary production [NPP]). Moreover, changes in land cover and biomass harvest associated with biomass use lead to a reduction of the energy available for ecological food chains. This process, called "human appropriation of net primary production" (HANPP), possibly contributes to biodiversity loss (Haberl 1997; Vitousek et al. 1986; Wright 1990; see Part II of this article). Harnessing solar energy and wind power necessitates installations that require energy, materials, and area. If sensibly planned, however, these may be the least environmentally detrimental renewable options. The social and environmental problems associated with nuclear power have led to a rapid decline in nuclear development schemes in most countries (notable exceptions being France, China, and Japan). Whether nuclear energy should be regarded as a sustainable option is a question that is left for the reader to decide. Nevertheless, the above examples should suffice to show that the total amount of energy consumed by a society is a headline indicator, which is at least as interesting as its total material (or carbon) throughput. Whereas data on primary energy throughput of a national economy are indeed included in many sets of sustainability indicators, these figures of primary energy use are calculated on the basis of conventional energy balances that leave out substantial parts of the energy throughput. One aim of this article is to propose an accounting framework that corrects this omission.

Although metabolism studies can benefit from the systematic consideration of energetic aspects, the reverse is equally true. The metabolism concept can contribute to systematizing the different approaches to analyzing societal energy flows and can provide a common framework of analysis that can be useful for, among other things, comparing different modes of subsistence or human societies under different ecological conditions (see Part II).

Recent Conceptual Achievements of Materials Flow Analysis

Basically, any empirical study of societal metabolism begins with an analysis of societal inputs and outputs. Without going so far as to claim that society can be sufficiently described by analyzing physical processes, studies of societal metabolism rely on the notion that biophysical structures of society can be discerned that maintain physical exchange processes with their natural environment. From the perspective of the natural sciences, then, biophysical structures of society could be regarded as ecosystem compartments—a perspective better suited for understanding complex society-nature relations than the widely used concept of human disturbance of the natural evolution of ecosystems (McDonnell and Pickett 1997).

The first step in an analysis of societal metabolism regards the biophysical structures of society as a black box drawing material or energetic inputs from its environment, building up internal stocks and discharging outputs into the environment. Here, one must obviously be able to discern the boundary that a material has to cross in order to be regarded as an input or an output of society. Thus, for materials and energy flow analyses, it is necessary to draw a theoretically plausible operational boundary between biophysical structures of society and their natural environment in order to identify relevant flows.

Drawing such a boundary is anything but trivial. Traditional disciplinary boundaries are a major hurdle to achieving this. For example, sociology tends to conceive of society as an entirely symbolic entity—for instance, a system of communication (Luhmann 1984)—devoid of material aspects. As another example, the natural sciences usually draw a sharp line between their objects of study and human agency. Consequently, materials and energy flow accounting, a task that at first glance seems quite technical and straightforward and is often treated as such, involves theoretical reasoning that touches upon fundamental tenets of sociological theory (Fischer-Kowalski and Weisz 1999). Moreover, it challenges many of the preconceptions commonly found in ecological research (McDonnell and Pickett 1997). Because these theoretical questions are discussed elsewhere in detail (Boyden 1992; Fischer-Kowalski et al. 1997; Fischer-Kowalski and Weisz 1999; Godelier 1986; Sieferle 1997a), this article instead describes pragmatic solutions currently practiced in materials flow accounting.[5]

One of the ideas behind materials flow analysis is that societal materials flows can be regarded as the flows of materials used to produce or reproduce societal material stocks, that is, the materials building up the biophysical structures of society. A key question arising here is What is included in these biophysical structures of society? Most ecologists feel comfortable with the notion that society is made up of humans and, thus, societal metabolism encompasses the sum of the individual metabolisms of its members. Human nutrition is indeed often investigated in human ecology (e.g., Harris 1987; Vayda 1987a, 1987b).

Limiting the metabolism of a society to the food consumed by its members, however, would severely restrict the explanative power of the metabolism approach. Human metabolism is to some extent variable (Leslie et al. 1984), but the caloric needs of humans differ by factors of between 2 and 3, at most, not by orders of magnitude. What is indeed highly variable is the share of societal metabolism not passing through human bodies. What are the stocks produced and reproduced by societal metabolism in this larger sense? Obvious candidates for this second category are the physical objects that anthropologists refer to as "artifacts," such as buildings, machines, tools, and so on. Artifacts do not include all human-made objects but only those that are still kept in a certain condition, namely, all that are being used and maintained. Artifacts that are no longer being used and maintained should instead be regarded as waste and leftovers on their way to renaturalization (Fischer-Kowalski 1998). Accepting artifacts as part of the material compartment of society means that all material and energy transfers used to produce, use, and maintain artifacts as well as all discharges to the environment resulting from these activities are regarded as societal flows.[6]

A third, perhaps less obvious category comprises animals that are kept by humans, that is, domestic animals and livestock. Animals are used for a variety of purposes, for example, as prime movers and as sources of food and other materials (bone, leather, fur, etc.). Their genotypes and phenotypes have been and continue to be altered in the processes of domestication and breeding, and their nutrition is provided by society. Today, according to Smil (1992, 77), domesticated animals account for about 69% of the global biomass of vertebrates (humans 28%, wild animals 3%). Excluding the metabolism of domesticated animals as a part of societal metabolism would, therefore, mean neglecting a major human-driven phenomenon that is highly relevant for sustainable development. Most materials flow accounts include livestock and domestic animals, which means that, for example, grass grazed by livestock and grains harvested are counted as societal inputs, whereas grains fed to livestock and animal produce are treated as internal flows (e.g., Ayres and Ayres 1998; Bringezu et al. 1997).

Some authors also include agricultural crops in the biophysical structures of society. Materials flow accounting then involves assessing the uptake of CO_2, H_2O, and minerals by crop plants (Stahmer et al. 1997). In this case, energy flow accounting would have to consider the solar energy uptake of crops; that is, photosynthesis would be regarded as an energy conversion process within society. Solar energy absorbed by crops would then probably be *the* dominant societal energy flow; however, all materials flow accounts I know of, except that presented by Stahmer et al. (1997),[7] define the harvest of plants as the point where plant biomass is assumed to enter society. I endorse this approach on the grounds that, although plants are genetically influenced and altered to an extent similar to that of domesticated animals, their energetic metabolism is much less directly determined by society. Moreover, this definition can be more easily connected to ecological energy flow analyses (see below) and is empirically more tractable.

Drawing a boundary between the socioeconomic unit under consideration and other socioeconomic units can also be a difficult undertaking. Materials or energy flows between different socioeconomic units are, for example, the exchange between nations, as accounted for in national MFAs, or the material and energy flows between a city and its surroundings, as investigated in studies of the metabolism of cities. In MFA, the following two approaches are currently being used (Bringezu et al. 1997; Fischer-Kowalski and Hüttler 1998):

1. Based upon the definition of a boundary between units to be studied—for example, the boundary between nations or other regional units—one may account for any material inflows and outflows by counting the tons of material actually crossing this boundary. In a national materials flow analysis, such an approach mirrors the physical dimensions of the production and consumption process in a country's economy—a kind of "physical gross domestic product" (Schandl et al. 1999).
2. Alternatively, one may try to figure out how much material is used to provide for the goods and services consumed by the population in a given country or region. In this case, it is common to account for all materials used in producing the imported items, inside *and* outside the economy under consideration, that is, materials mobilized abroad to produce imported goods are accounted for in a kind of "from the cradle to the grave" scheme. For reasons of consistency, exports have to be treated accordingly (Schmidt-Bleek 1994).

From the perspective of environmental policy, each approach can be used to answer different questions. Whereas the first approach is useful in formulating policies aimed at an ecological restructuring of the economy, the second is preferable in articulating policies aimed at changes in consumption patterns.[8]

Figure 1 summarizes the notions used in current materials flow analyses on a national level. "Direct material input" refers to the materials flow actually entering the economy and being used to produce and maintain the three societal stocks discussed above, namely, humans, domesticated animals, and artifacts. The direct material input is measured at the weight crossing the border. In contrast, the "total material requirement" also encompasses so-called hidden flows, that is, flows that do not enter the national economy under consideration but are mobilized to produce the goods or services consumed. Hidden flows consist of domestic hidden flows, such as overburden, material mobilized but not utilized, soil plowed over, and so on, and imported hidden flows such as materials flows mobilized abroad (Adriaanse et al. 1997).

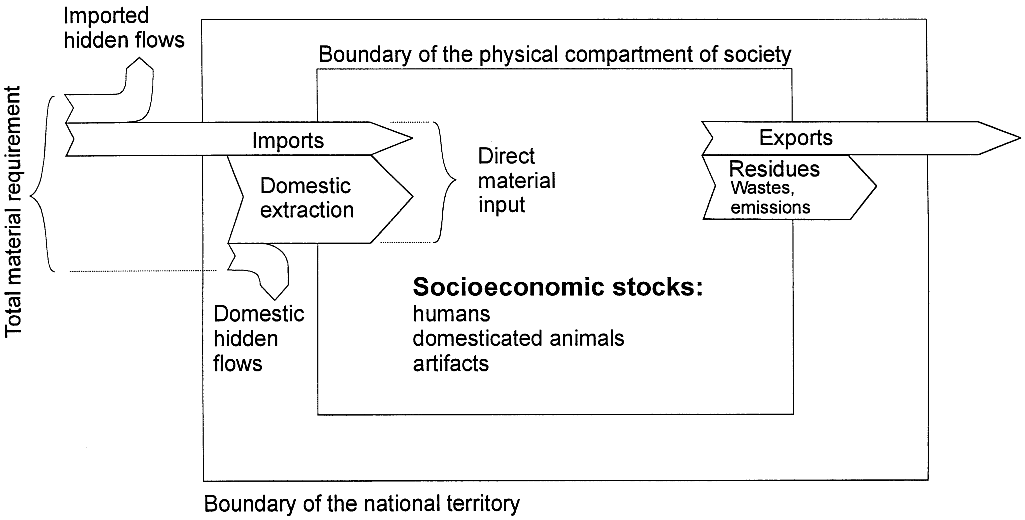


Figure 1 Schematic diagram of a national materials flow analysis. Although the terminology contained in this figure is gradually being accepted internationally, there is not yet a generally accepted scheme for considering internal materials flows in society.

How to Account for Society's Energetic Metabolism

Energy Statistics and Energy Balances

Energy balances are commonly used in economics to describe and analyze societal energy flows. In this context, it is important to distinguish between energy statistics and energy balances. Energy statistics report collected data on the energy flow of defined socioeconomic energy sectors or conversion processes (e.g., IEA 1992; UN 1997). They do not necessarily provide a consistent picture of the energy flow through an economy. In contrast, energy balances trace the flow of commercial energy through the economy in a consistent manner. Contrary to energy statistics, energy balances also contain values calculated from statistical data—for example, for energy conversion processes—based upon equations that guarantee that for every conversion process the energy inputs and outputs are equal, in accord with the first law of thermodynamics (Bittermann 1999; IEA 1995).

There are different methodologies for deriving energy balances from statistical data, and different statistical agencies use different terminologies. Figure 2 represents an attempt to describe an "ideal typical national energy balance" derived from Austrian (Bittermann 1999) and international (IEA 1995) energy balances—which rely on internationally agreed-upon conventions (IFIAS 1974)—based upon the following notions:

- "Primary energy supply" is usually defined as the energy supplied in the form in which it is extracted from the natural environment, for example, extracted energy-rich materials (biomass, fossil fuels), harnessed flows of mechanical energy (hydropower, wind power, etc.), nuclear energy transformed to heat, or radiant solar energy used to produce heat or electricity; however, because the economies of many industrialized countries rely to a relatively great extent on imported energy carriers that may already have been processed, it is not, strictly speaking, the primary energy supply that is accounted for in energy balances. Instead, the energy input measured in an energy balance should be termed the "total energy supply." Total energy supply consists of domestically extracted primary energy carriers and imported energy carriers, which may be either raw materials (crude oil, coal, etc.) or products derived from primary energy (gasoline, light oil, coal briquettes,

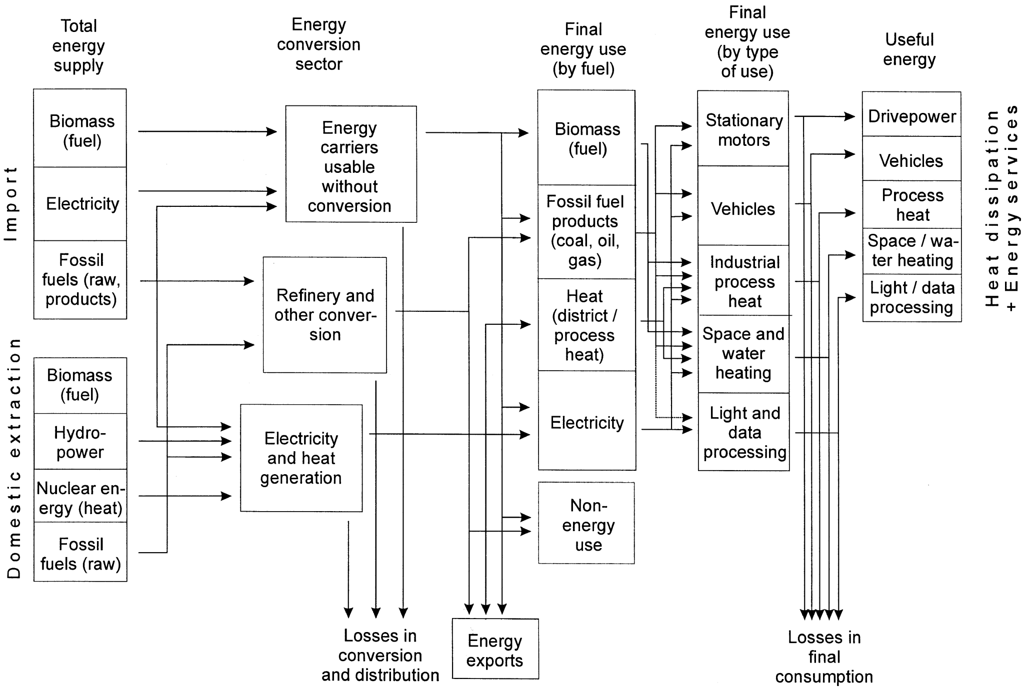


Figure 2 Energy flows usually covered in national energy balances. For reasons of clarity, stock changes (which usually are of minor importance quantitatively) have been omitted. Derived from the Austrian energy balance (Bittermann 1999) and the International Energy Agency energy balances (IEA 1995). Note: As an alternative to the procedure shown here (as used in the Austrian energy balance), total energy supply may also be calculated on a net basis, that is, including only the balance of imports and exports (as is done by the International Energy Agency).

electricity, etc.). Conceptually, the notion of total energy supply is similar to that of "direct material input" as used in MFA.

- "Energy conversion" is assessed by calculating conversion balances for the most important processes in which primary energy is converted into final energy (see below). In contemporary industrial societies, the most important conversion processes are usually electricity and heat generation, oil refining, and coal-related conversion processes.
- "Final energy use" is usually defined as the energy sold to final consumers. A final consumer is any economic entity buying energy in order to generate energy services (Lovins 1977) for production or consumption. Energy services are immaterial services obtained by using energy. Examples include conditioning the climate in a room, moving persons or commodities from point A to point B, and shaping a workpiece. Excluded from the notion of final energy is that energy used to produce other energy carriers, for example, heating oil used for electricity generation.
- On the right side of figure 2, the energy use of final consumers is further specified. This part of the energy flow analysis, called "useful energy analysis," is not available for all countries, and even where available, it is generally based on random sampling surveys and technical extrapolations of low accuracy.[9] Final energy use is broken down into the categories of stationary motors/drivepower, vehicles, industrial process heat, space and water heating, and light and electronic data processing.

This description of conventional energy balances reveals what industrial society considers to be its main energy problem: the use of fossil fuels, hydropower, and nuclear energy for technical processes in the economy. This perspective obviously derives from the fact that energy statistics were established to serve as an economic accounting tool, not as a provider of human ecological or environmental data.

For reasons of clarity, the fact that the use of renewable energy sources has recently been included in many energy balances (e.g., IEA 1995; UN 1997) has been omitted from figure 2. As a consequence of this change in practice, many countries now account for solar energy, wind power, ambient heat gained with heat pumps, and biomass used for heat or electricity provision. The inclusion of these energy carriers into an energy balance is conceptually straightforward.

Figure 2 reveals, however, that energy statistics do not account for the provision of nutritional energy, either for humans or for domesticated animals. This practice stands in sharp contrast to that of ecological energetics and most human ecological studies on energy flows, both of which usually prominently account for physiological energy flows.

Energy Conversion Processes

Table 1 gives an overview of 13 main energy conversion processes usually accounted for in energy statistics, demonstrating the wide variety of energy conversions making up the energetic metabolism of industrial societies. The discovery of new forms of energy conversion (that is, of technologies to tap new energy potentials or to use known energy sources in new ways) has often been described as an important aspect of technological development with far-reaching consequences for society, the economy, and society-nature interrelations (e.g., Sieferle 1997b; Smil 1992; Smil 1994).

For industrial societies, combustion—that is, the conversion to heat of energy stored chemically in energy-rich materials—is usually the most important energy conversion process in quantitative terms. Combustion is so important that it is common to refer without further consideration to the calorific value of a combustible material as its "energy equivalent." That is, energy balances generally convert materials flows to energy flows only in reference to the respective technological processes involved. The flow of materials that chemically store energy—that is, that react with oxygen in an exothermic chemical reaction—is converted into energy units by calculating the amount of heat that can be produced in combustion. Unfortunately, there exist two conventions: net and gross calorific value. The net calorific value (lower heating value) is the amount of heat produced by burning a fuel excluding the latent heat of water vapor produced during combustion. In contrast, the gross calorific value (higher heating value) includes the energy released by the condensation of the water vapor contained in the waste gases. Most energy balances use the net calorific value to convert tons of fuel to energy (IEA 1995), which is presumably a reflection of the predominant technologies used.

The Trophic-Dynamic Aspect of Ecological Energetics

One of the aims of the metabolism approach is to bridge the gap between the social sciences and the natural sciences, in particular between sociology and economics on the one hand and ecology on the other. Therefore, it is useful to compare societal with ecological energy flows. To use the full communicative value of the metabolism approach, accounting methods for the societal energy flows should treat human society as an ecosystem component (McDonnell and Pickett 1997); that is, they should consider societal energy flows in the broader context of ecological energetics.

Because a review of ecological energetics is part of any modern ecological textbook, I discuss main features of ecological energetics only briefly here (see Wiegert 1976). Solar radiation is by far the most important energy source of all ecosystems in quantitative terms. Most of the incoming solar energy drives the hydrological cycle, the climate system, and so on. A small part of the energy is assimilated by autotrophic organisms (e.g., green plants and cyanobacteria) in the process of photosynthesis.[10] This process of primary production is the energetic basis for all heterotrophic food chains, or food webs, that is, heterotrophic processes that consume the chemically stored en-

Table 1 Energy conversion processes usually accounted for in energy statistics

Energy conversion process	*Technological processes*	*Energy carriers*
Electromagnetic energy → thermal energy	Thermal solar collector	Solar energy
Electromagnetic energy → electrical energy	Solar cell	Solar energy
Chemical energy → chemical energy	Refinery, other chemical processing	Fossil fuels
Chemical energy → thermal energy	Combustion (open fires, furnaces, stoves, etc.)	Biomass, fossil fuels
Nuclear energy → thermal energy	Nuclear fission (nuclear power plants)	Fission of uranium or plutonium
Thermal energy → thermal energy	Heat pump, heat exchanger	Heat derived from environmental media or combustion
Thermal energy → mechanical energy	Steam engine, internal combustion machine, Stirling motor	Heat derived from combustion of fossil fuels or biomass, nuclear fission, or solar energy
Mechanical energy → mechanical energy	Conversion of water or wind power into rotational energy (e.g., hydropower turbines), power transmission through crankshafts, etc.	Hydropower, wind power, etc.; power transmission through all kinds of mechanical machinery
Mechanical energy → electric energy	Electric generator	Mechanical power derived from water, wind, or wave power, etc., or mechanical energy from steam engines or internal combustion machines
Electric energy → mechanical energy	Electric motor	Electricity
Electric energy → thermal energy	Resistance heating	Electricity
Electric energy → electromagnetic energy	Electromagnetic radiation, electroluminescence	Electricity
Electric energy → chemical energy	Electrolysis	Electricity

Sources: Derived from Smil 1992; Bittermann 1999; IEA 1995.

ergy made available through primary production. Examples are herbivores eating plants, first-order carnivores eating herbivores, and so on, and finally, detritivores consuming both the excreta and the carcasses of heterotrophs and autotrophs. The basic process underlying these energy flows is the oxidation of energy-rich biological materials through a variety of metabolic pathways. These two energy conversions involve energy flows through living organisms and are often referred to as the "trophic-dynamic" aspect of ecological energetics. This schema of the trophic aspect of ecological energetics is summarized in figure 3.

Two main parameters are used to characterize primary production: gross primary production (GPP), the total amount of radiant energy converted to energy-rich substances by plants, and net primary production (NPP), which is defined as GPP minus the amount of energy used by the plant for its own metabolism. NPP is thus the total increase in plant tissue during a given period of time. Although GPP is difficult to measure on large spatial and temporal scales—for ex-

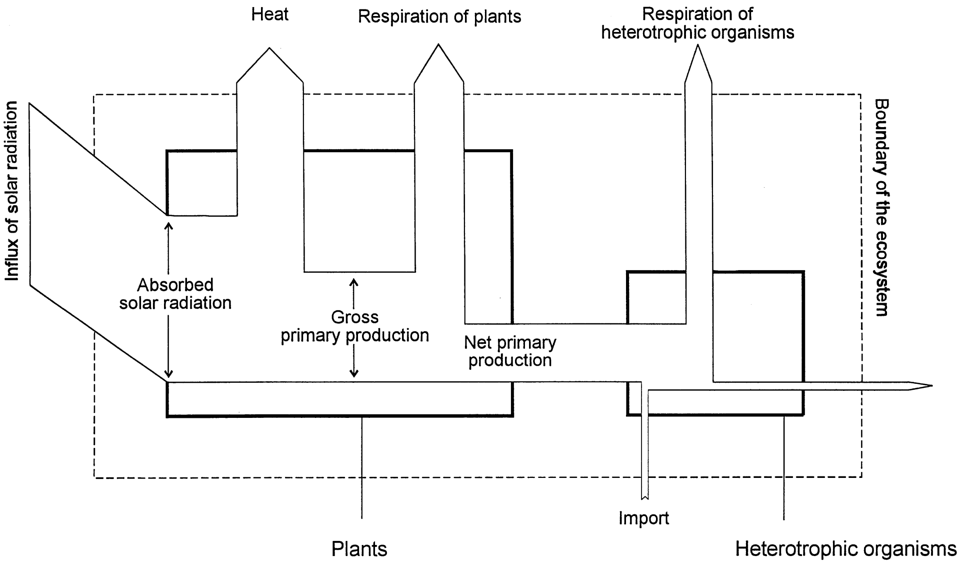


Figure 3 The trophic-dynamic aspect of ecosystem energetics. Absorbed solar energy not lost as heat is transformed into gross primary production (GPP). GPP minus plant respiration yields net primary production (NPP). NPP, measurable as biomass flow or as energy flow, is the input to food webs of heterotrophic organisms: herbivores, carnivores, detritivores (i.e., animals, fungi, and microorganisms). The breakdown of heterotrophic food webs (consumers of first-, second-, third-, and higher-order carnivores, detritivores, etc.) can be highly complicated and has been omitted for reasons of clarity.

ample, at the landscape level—NPP can be determined even on this scale with reasonable accuracy.

Because the trophic structure of terrestrial ecosystems reflects existing food webs, there is an intimate relation between energy flows and materials flows. From their very beginnings (Lindemann 1942, Hutchinson 1959), studies of ecological energetics involved measuring the flow of biomass through various compartments of ecosystems (Odum 1969, 1971). These flows are usually assessed as materials flows, measured as the (dry) mass or carbon content of biomass. The energy equivalent of biological materials is usually assessed separately. To capture the maximum amount of energy that could in principle be gained by an organism from its nutrition, the energy equivalent of biological materials is generally assessed as gross calorific value. As a consequence, this is the value used in ecological studies to convert materials flows to energy flows (Golley 1961).

The biosphere is a closed-cycle system with respect to materials; that is, chemical elements are recycled in the so-called grand biogeochemical cycles (carbon, nitrogen, sulfur, etc.), driven by a continuous flow of solar energy. The fundamental difference between the flow of energy and the flow of materials in ecosystems, namely, that materials are recycled whereas energy is not, was pointed out very early (MacFadyen 1948) and stands in sharp contrast to societal metabolism, which is a throughput system with respect to both energy and materials.

Deriving Energy Metabolism from Energy Statistics

When comparing the concepts used in MFA and in conventional energy balances, it becomes obvious that energy balances account only for the inputs used to produce, maintain, and utilize but one of the three kinds of societal stocks considered in MFA, namely, artifacts. The energy requirements of humans and domesticated animals are not accounted for in energy balances. An accounting scheme for societal energy metabolism, on the other hand, should include these flows of nutritional energy.

For several reasons, the energetic metabolism of societies should be based upon the gross calorific value of energy-rich materials (biomass, fuels, or whatever). First, using the gross calorific value makes ecological and societal energy flow analyses comparable. Second, the energetic value of food and fodder is usually assessed as gross calorific value, resulting in inconsistencies where net calorific values are used for technical energy conversions. Third, new technologies (condensing furnaces) have been developed that can utilize the latent heat of water vapor in the waste gases, resulting in an efficiency rating above 100% where the energy equivalent of the fuel is calculated as net calorific value. As a result, there are proposals to use gross calorific values also for conventional energy balances.[11]

Energy balances do not describe only the energy input of a society. They describe the energy flow in several steps: energy supply, conversion, final consumption, and in some cases, useful energy. That is to say, energy balances also analyze the purpose for which energy is being used. The generation of drivepower is an important example. Drivepower is essential for all production processes, and the substitution of drivepower generated by inanimate prime movers for human and animal labor is a key aspect of industrialization. Similarly, the substitution of animal labor for human labor was a key aspect of the Neolithic revolution and of changes in agricultural technology. Moreover, drivepower is essential for transport processes that are of key importance for patterns of societal resource use (see Sieferle 1997b; Smil 1994). Although the importance of humans and animals as prime movers in industrial society may be negligible compared to the amounts of power delivered by motors, turbines, and so on, accounting for animate prime movers is decisive when comparing different modes of subsistence (Fischer-Kowalski and Haberl 1997; see also Part II of this set of articles). Thus, analyses of societal energy metabolism should take into account the drivepower delivered by draft animals and humans.

Hence, traditional energy balances must be enhanced by two aspects to be able to account for the energetic metabolism of a society: nutritional energy should be considered, and human and animal-derived drivepower should be included. Both requirements pose methodological problems that are discussed below.

Energy Conversions and Energy Flow Accounting

The flow of energy through a society usually involves several steps, for example, the import of crude oil through a pipeline, production of different oil products in a refinery, transportation of the products to final consumers, or energy conversion processes such as those in oil-fired power plants. That is, the energy flow consists not only of energy conversion processes but also of transport processes, including the transport of energy-rich materials. These “energy transfers,” as I call them, take place between economic actors, and in them no energy conversion occurs beyond that of the energy needed for transportation itself (this latter energy should be assessed separately). Energy transfers can involve the flow of energy-rich materials, but they need not be immediately related to a materials flow. Examples include electricity transmission through power lines and the transmission of power through a crankshaft. Energy transfers involving flows of combustible materials are treated by considering the gross calorific value of the material transferred.

The treatment of other energy conversions and transfers is less straightforward. For example, hydropower harnesses the potential and kinetic energy of water. In energy statistics, several approaches are used. It was long common to calculate the amount of fuel that *would have been used* in a thermal power plant to generate the same amount of electricity (usually assuming an efficiency of 33%). One may of course use any arbitrarily assumed efficiency to extrapolate the water power utilized from the amount of electricity generated. For example, the United Nations energy statistics (UN 1997), the IEA energy balances (IEA 1995), and the European Union–wide rules for harmonizing energy balances assume the primary energy used to be equal to the amount of electricity produced (efficiency 100%).[12] An alternative approach, which is used in no officially published energy balance to my knowledge, however, would be to try to reflect the physical processes at hand. The amount of water energy used could be calculated based upon the efficiency of turbine and generator, both between 95% and 99%.

The second significant case is nuclear energy. Here it is a reasonable solution to assess the amount of heat generated through nuclear fission (the thermodynamic efficiency of nuclear power plants is usually about 30%). For example, UN energy statistics calculate the primary energy used in nuclear electricity generation (which is called quite misleadingly "primary electricity") by assuming a plant efficiency of 33% (UN 1997).

An additional problem to be solved arises from what in energy statistics is usually termed "nonenergy" use. Energy statistics usually include under this heading mainly the use of oil derivatives for chemical syntheses (the production of synthetic materials, asphalt, etc.). Nonenergy use, thus, means that some material that also *could* be used as a source of energy is used for a purpose not regarded as energy flow because a part or all of a material's energy content remains in the product.[13] At first glance, this looks like a minor problem that can easily be solved pragmatically either by including or not including these flows, but the problem can in fact be intriguing. For example, consider the energy gained from the incineration of wastes such as the synthetic materials produced from fossil fuels. In this case, appropriate treatment of the flows is essential to avoid double counting. Matters become even more complicated when we turn to biomass, where complex utilization chains abound (Hall 1984). In energy balances, this biomass problem does not arise because energy balances usually include only the biomass used for combustion but none of the biomass used for other purposes, including nutrition. For analyses of societal energy metabolism, there are two alternative solutions to these problems:

1. One could argue that energy flow analysis should reflect the socioeconomic utility of the respective flows. If a material is not being used for energy provision then its energy value can be regarded as irrelevant. From society's point of view, it may be largely unimportant whether a particular material has an energy value or not. The energy value may be even a nuisance, as most people would probably prefer noninflammable buildings or furniture.
2. On the other hand, one could regard all flows of energy-rich materials as energy flows, irrespective of the purpose for which they are being used. This can be argued on the grounds that, for assessing the environmental impact of the harvest of a particular kind of biomass on the ecosystem from which it is taken, it is largely irrelevant for which purpose society uses the biomass. Therefore, from an ecological point of view, it is preferable to regard all flows of energy-rich materials as societal energy flows.

I argue in favor of the second approach, at least where comprehensive accounts of societal energy flows are at issue. No a priori reason exists to regard one materials flow (e.g., crude oil in a pipeline) as energy flow just because most of it will probably be used to generate energy, and exclude another materials flow (e.g., the construction of a wooden house) because the timber probably will not be burned in the next decades. By analogy, MFA does not ask if a material will be used for a durable product or for combustion. Therefore, we should regard the construction of a wooden house as an input to a societal *stock* of energy that can be released later on. In fact, the idea of recovering energy from used-up materials when they cannot be recycled as raw materials anymore is advocated as a strategy for the more efficient use of biomass (Haberl and Geissler 2000).

Moreover, there remains the problem of tractability. If the same material can be used for different purposes, it is impossible to *measure* at any particular stage of analysis (e.g., extraction or import of crude oil) for which purpose it will actually be used. Although it may in some cases be possible, given sufficient data for the process chain, to *calculate* the amount used for energy and nonenergy purposes on every level of interest, this can be a demanding or practically impossible task if process chains are complex or poorly documented.

Direct Energy Input and Total Primary Energy Input

For energy flow analyses to be compatible with MFA (figure 1), I propose defining an equivalent to the "direct material input," which could accordingly be termed "direct energy input." The direct energy input can be defined as the total amount of energy actually entering the socioeconomic compartment under consideration, either by domestic extraction or by import. Domestic extraction can be calculated by adding the energy content of all biomass that is harvested domestically and enters the economy, to the data on technical energy input that can be derived from energy statistics. Data on biomass can be taken from agricultural and forestry statistics and converted to energy flows using gross calorific values. What is usually not accounted for, but should be included, is livestock grazing.[14] For imports we should consider the import of all energy-containing materials, not only that of energy carriers. Trade statistics usually cover trade data in considerable detail; however, including all energy-containing final products would necessitate the assessment of the gross calorific value of all imported goods, which is a rather imposing task. A reasonable proxy[15] can be obtained by restricting the analysis to imported raw materials of major interest (e.g., feedstuffs, food, timber, paper, petrochemicals, etc.).

The equivalent of the "total material requirement" could be termed *total primary energy input* and defined as direct energy input plus hidden energy flows (see figure 1). In order to avoid double counting, imported derived energy carriers (e.g., electricity) have to be subtracted.[16] Hidden flows can be either domestic—that is, biomass harvested but not used such as the crop residues plowed back into the soil—or imported. At least for all energy flows included in energy statistics, these hidden flows are a well-researched issue (e.g., Fritsche et al. 1992; Spreng 1995) and can be assessed with reasonable accuracy. It is more difficult to account for hidden biomass flows, but it is certainly feasible. The calculation of imported hidden flows should also include the energy embodied in imported raw materials and goods. In short, defining and empirically assessing the energy input of a society is conceptually rather straightforward, although it can be quite demanding to actually assess all of the relevant flows, especially the hidden flows.

Internal Societal Energy Flows

Energy balances allow one to trace energy flows through a society in considerable detail, using internationally comparable notions such as final energy and useful energy. The analysis of societal energy metabolism can, therefore, draw upon a wealth of available data although it should also consider those flows not accounted for in energy balances. In this section, I propose an accounting scheme that leaves the general structure of energy balances intact, but allows for the inclusion of these missing flows.

Two interrelated problems must be solved: a) How should the flow of nutritional energy be accounted for? b) How can we treat the provision of drivepower by draft animals and humans? Whereas nutritional energy is quantitatively relevant even in industrial society, accounting for animate power could be regarded for an industrial metabolism as an academic problem. An upper limit for this energy flow can be derived as follows: a (very) hardworking individual can deliver up to 100 watts for 8 hours per day (0.8 kWh/day).[17] Even assuming 300 working days per year, this is less than 1 GJ/y—a small amount of energy compared to the 100–200 GJ/y of commercial final energy that the average member of an industrialized country uses (Smil 1992). For comparisons between different modes of subsistence (discussed in Part II), however, exactly these processes matter.

To tackle these problems, we must identify the most important energy conversion processes and assign them to the steps of energy conversion in an energy balance as described in figure 2. These conversion processes are (1) the conversion of animal fodder, both into human foods such as meat, milk, eggs, and so on and into other biomass products such as wool, leather, and the like, and (2) the conversion to power (work) of the biomass ingested by humans and domesticated animals.[18] Energy balances usually differentiate between two stages of energy conversion (1) the conversion of primary energy to final energy and (2) the conversion of final energy to the useful energy needed to produce energy services (figure 2).

For human metabolism there are two possible solutions. The first, the trophic-dynamic approach, regards the food consumed by humans as final energy so that human-derived power has to be defined as useful energy. The second, the "work-as-final-energy" approach, regards human food as intermediate energy (regarding it as primary energy would not be consistent with the definition of livestock as a part of society). Physical power delivered by humans can then be defined as final energy being converted to power (useful energy) through mechanical devices.

How the animal compartment is treated depends upon the choice between these two alternatives (figure 4):

1. In the trophic-dynamic approach there are two logically consistent possibilities. In the first (approach a1), animals are bioconverters that convert ingested biomass into human food and work, which are both regarded as final energy. In the second (approach a2), the animal compartment is hypothetically split up into two subcompartments performing two different processes: livestock (animals 1) as converters of nutritional energy, on the one hand, and domesticated animals (animals 2) as consumers of feedstuffs (final energy) and deliverers of power (useful energy), on the other hand.
2. In the work-as-final-energy approach (approach b), animal work has to be regarded as final energy (as is human work). The animal compartment is treated as one compartment performing the two processes "conversion of nutritional energy" and "power production."

The three approaches are described in figure 4. The advantage of the first approach (a1) is its simplicity and tractability; however, its shortcoming is that it treats animal work and human work at different levels of energy conversion. Whereas energy losses between power delivered by the draft animal and useful power derived from it are explicitly accounted for (the transmission mechanism is a separate conversion process), in the human compartment the transmission mechanism is lumped into the conversion balance of food to useful power.

The second approach (a2) avoids these shortcomings. It distinguishes two different processes: The conversion between different kinds of biomass is treated as a "primary to final" energy conversion, and the conversion of food to work is considered a "final to useful" energy conversion. In this case, the work of both animals and humans is treated symmetrically and transmission losses are aggregated into these conversion processes. (This is usual in energy balances. The conversion balance of electricity generation, for example, lumps together cooling losses, friction, generator losses, the plant's own electricity consumption, etc.) Paid physical work, however, could be regarded as final energy; in this case the scheme is unsatisfactory. In addition, splitting up the animal sector to perform these calculations can pose problems in tractability, especially if the same animals are used for both purposes (e.g., eating the meat of draft animals).

The third approach (b) avoids these problems. Human and animal work are accounted for as final energy converted to useful energy through a transmission mechanism that is then separately accounted for. But this approach generates other problems. The trophic-dynamic aspect of societal energy flows is lumped into a complex conversion balance, seemingly only serving the purpose of generating human and animal work. Important societal flows such as human nutrition do not feature prominently as part of an important aggregate parameter (final energy), but only as intermediate flows. Moreover, the notion that human nutrition is only an intermediate process serving the purpose of generating work, which is insinuated by this concept, is problematic. A large part of human food is needed for growth, reproduction, and maintenance of the organism. Moreover, only about 4% to 10% of the total human time in a population is allocated to physical work (Giampietro 1997). In the course of industrialization, human (and animal) physical work is becoming ever less important quantitatively for the production pro-

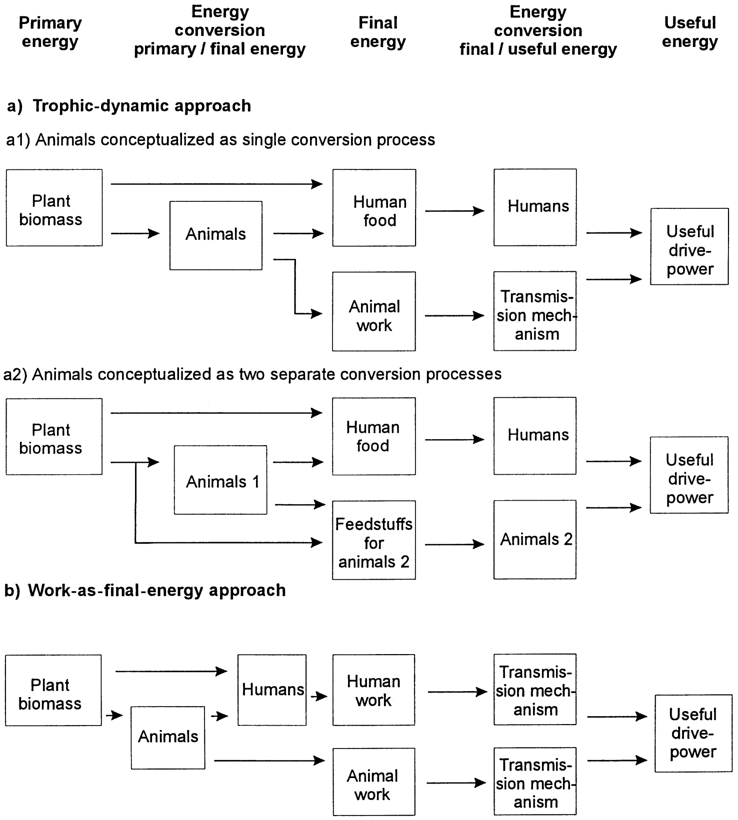


Figure 4 Alternatives for conceptualizing nutritional energy and work delivered by draft animals and humans in energy flow analysis. Dissipative losses and outflows of energy-rich materials (e.g., manure) have been omitted for reasons of clarity. See text for further explanation.

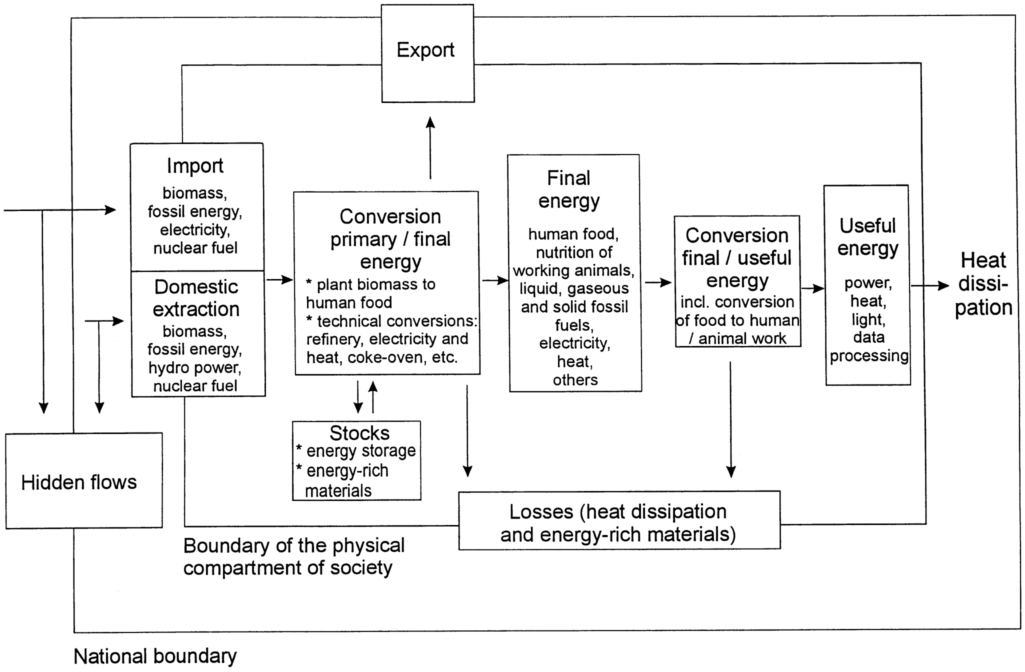
cess, whereas changes in nutritional habits (e.g., consumption of animal versus plant products) are increasingly determining societal biomass flows.[19]

As a result of these considerations, I propose to follow approach a2, that is, to follow the trophic-dynamic approach and differentiate between animals as converters between different kinds of biomass on the one hand, and working animals on the other hand.

The problem of nonenergy use can be solved by introducing a new kind of stock. Although the notion of stocks in energy balances usually refers to energy stored for future use (e.g., natural gas storage, crude oil storage), the inclusion of all energy-rich materials requires the introduction of an energy stock consisting of energy-rich products (buildings, furniture, libraries, etc.). Eventually, as these products become wastes, their energy potential can be tapped. On the other hand, if they are deposited, this should be regarded as an energy output flow back to nature.

Conclusions

A summary of the proposed methodology is presented in figure 5, summarizing the accounting concepts discussed in previous sections. The energy input of a society can be described as direct energy input and as total primary energy input. Although the direct energy input contains only the amount of energy actually entering the societal compartment under consideration—most prominently a national economy—the total primary energy input also considers hidden flows. These hidden flows are energy flows mobilized to procure the direct input but not crossing the boundary of the societal compartment under consideration, either because they take



Direct energy input = import + domestic extraction
Total primary energy input = direct energy input + hidden flows - double counting (derived energy carriers)
Domestic energy consumption = direct energy input - export

Figure 5 Summary of the proposed methodology.

place abroad or because the energy flow takes place outside the boundary of the societal compartment. By subtracting exports from direct energy input, it is possible to calculate the domestic energy consumption.[20] Energy entering society will usually be transformed in various ways into other forms of energy, eventually ending up as final energy, which is energy directly used to provide energy services. Animals used to provide food for humans are considered as part of this conversion process, whereas human nutrition and the nutrition of draft animals is regarded as final energy. A part of the energy input is not used for energy provision but is put in stock as energy-rich materials in durable installations.

Final energy is defined as the energy used to produce useful energy and finally energy services. Final energy also includes the nutritional energy consumed by humans for their sustenance and activity, as well as the nutritional energy consumed by working animals. Nonenergy use is not considered to be final energy use. Useful energy is defined as the physical energy equivalent of the work actually performed in providing energy services (Lovins 1977). By definition, however, energy services cannot be accounted for in terms of energy units and are, therefore, very difficult to account for on an aggregated level (e.g., for a society or an economy as a whole). What can be done is to follow the flow of energy through a society from energy input to useful energy. Examples of useful energy are the flux of light produced by a bulb, the power delivered to mechanical devices by crankshafts, the heat delivered by a radiator, and so on.[21] Basically, there are four categories of useful energy: power, heat, light, and data processing. Whereas the latter two are usually each treated as a unit in energy balances, types of power and heat are sometimes differentiated (e.g., power for vehicles versus power delivered by stationary motors, and industrial process heat versus space and water heating).

Using these concepts, it is possible to develop an accounting system that can monitor the energy flow through a defined socioeconomic compartment, such as a national economy, a city, or a village. Some of the properties discussed depend on the size of the system under consideration. For example, the per capita direct input and domestic consumption are smaller in a small town importing most energy as final energy carriers than for the average inhabitant of the country in which the town is located, because energy losses in conversion (e.g., electricity production) take place outside the system's boundary. The advantage of the domestic consumption parameter is that it mirrors the energy throughput of a regionally defined system of production and consumption; therefore, it can be linked to economic indicators describing the economic activity in this region (e.g., the system of national accounts). On the other hand, total primary energy input depends mainly on consumption patterns in the population under consideration, and less on the level of aggregation. Because exports are not subtracted in calculating primary energy input, however, there can be considerable distortions when energy-exporting regions are assessed.

Final energy and useful energy refer only to energy conversions taking place within the system boundaries of the socioeconomic system under consideration. Final energy use can also be directly linked to economic accounting systems and the activity of different sectors of the economy. Final and useful energy, however, are less directly linked to the interaction between a society and its natural environment than energy input is, because quite a considerable proportion of the initial energy is usually lost in conversion processes from primary to final energy, or is used for other than energetic purposes. On the other hand, the utility a society is able to draw from its energetic metabolism largely depends upon the energy services it is able to derive from energy inputs. Although it remains an unsatisfactory approximation, the amount of useful energy spent is, at present, probably the best available measure for the amount of energy services that are at a society's disposal.

Part II of this series will apply these concepts to different kinds of societal organization or modes of subsistence (hunters and gatherers, agricultural society, and industrial society) and compare the concepts proposed here to conventional energy balances. To give an idea of the order of magnitude of differences between energy statistics and the metabolism concept, consider the case of Austria: According to the official energy balance, Austria's total energy supply in 1995 amounted to 141 GJ/(capita yr) (Bittermann 1999). The corresponding figure for the same year based upon the metabolism approach, the direct energy input, was 219 GJ/(capita yr) or about 55% higher. Most of this difference is due to the fact that conventional energy balances ignore most biomass inputs—although biomass use is certainly highly relevant for sustainable development (see practical examples in Part II). Therefore, I advocate the use of the metabolism approach when attempting to develop headline indicators for the total environmental impact (Giampietro 1997) of societies.

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Notes

1. It has become difficult to stay ahead of this quickly evolving and very productive field of inquiry. Seminal statements quite similar to the modern approach toward national materials flow analysis include those by Ayres and Kneese (1969) and Boulding (1973). Examples of national materials flow analyses include those by Schütz and Bringezu (1993) and Hüttler et al. (1997). For overviews see work by Adriaanse et al. (1997), Ayres and Simonis (1994), Erkmann (1997), Fischer-Kowalski (1998), and Fischer-Kowalski and Hüttler (1998).
2. The article does not focus on issues of modeling; however, accounting is a prerequisite for modeling: What is not accounted for is usually neglected in models too. See also note 3.

3. An important strand of the analysis of energy flows is current economic energy models such as IMAGE, MARKAL, EFOM, MESSAGE, and many others. These models analyze interrelations between technical energy conversions, the economy, technological change, and the environment. They are mainly used for optimization and forecasting (e.g., Richels and Sturm 1996). However useful and policy-oriented these models may be, they are based upon energy data derived from conventional energy statistics that do not consider many of the aspects of societal energy use discussed in this paper, above all, the links between energy use and land use (see Part II of this set of articles).
4. Contrary to this recent focus of the MFA researchers, energy is often used as a headline indicator in life-cycle analysis and other types of environmental analysis.
5. The rationale behind the idea of regarding societies as consisting of both symbolic and biophysical elements—that is, both culture (comprising institutions, social organization, communication, etc.) and the physical compartments of society—is to devise means to analyze the interrelations between societies and their natural environment. This seems to be one of the most important gaps in scientific understanding for spelling out strategies of sustainable development. An alternative approach is the concept of a human ecosystem (Force and Machlis 1997; Machlis et al. 1997) encompassing a so-called human social system (i.e., social institutions, social cycles, and social order) and critical resources (i.e., natural resources such as energy, land, flora, fauna, water; socioeconomic resources such as capital, labor, population; and cultural resources). This concept, largely derived from the Chicago school of human ecology, can lead to comparable empirical approaches, for example, the analysis of energy flows through and between compartments quite similar to those proposed here (Axinn and Axinn 1984). Although a worthwhile issue, correlations between the human ecosystem concept and the metabolism approach are not dealt with in this article.
6. The question of how to treat so-called hidden flows—that is, materials moved but not used by society, such as soil plowed over or soil, gravel, and rocks excavated at one place and dumped at another—is intensively discussed. Materials that actually enter a national economy and are economically valued are termed "direct input" (e.g., Adriaanse et al. 1997; Bringezu et al. 1997; Fischer-Kowalski and Hüttler 1998).
7. For the analysis of the energy flow of a Nepali rural community, plants have also been included as a component of the human ecosystem (Axinn and Axinn 1984; see note 5).
8. I do not elaborate here on the question of comparing different products or technological options to provide various kinds of services. In this field, methods that are more closely related to the second approach are used, such as the material input per service approach (Schmidt-Bleek 1994).
9. Useful energy can be defined as the energy that actually performs work used to provide energy services (Lovins 1977).
10. Besides organisms capable of photosynthesis (photoautotrophs), some microbes can use chemical energy from exothermic chemical reactions to synthesize biological material from inorganic compounds (chemolithoautotrophs).
11. For fossil fuels, the difference between net and gross calorific value is between 5% and 20%, depending on the hydrogen content of fuels. That is, converting energy flows as assessed in conventional energy balances into energy flows in an analysis of socioeconomic metabolism as proposed here simply means to multiply fossil-energy flows by an appropriate factor between 1.05 and 1.2, depending on the type of fuel.
12. Losses that result from using off-peak electricity to pump water upward into reservoirs to produce peak-load electricity in pumped storage power plants are considered separately. Before Austria adopted the European Union rules, hydropower use was extrapolated from hydroelectricity generation on the basis of an assumed efficiency of 80% (Bittermann 1999).
13. Chemical syntheses usually are exothermic and/or endothermic reactions and thus involve energy flows; however, in many chemical syntheses involving substances derived from fossil fuels, a significant part of the potential energy remains in the product. Therefore, chemical syntheses—those that are not intended to deliver energy, but serve other purposes—are usually accounted for in energy statistics as nonenergy use. If, however, the products are burned in waste incineration plants, this will be accounted for in energy statistics.
14. Another energy input that could be included is passive solar energy captured by south-oriented windows. This is a significant energy input not accounted for even in advanced conventional energy balances. A very rough estimate for Austria suggests that this might amount to some 15% of energy used for space heating (in Austria this

would be about 3% to 5% of technical primary energy input).

15. Note that whether any such proxy is reasonable depends on the research question. For example, when comparing the United States and Japan, the level of detail that has to be considered to obtain significant results might be higher than for comparisons between countries with similar patterns of imports and exports.
16. The formula "total primary energy supply = direct input + hidden flows" leads to double counting when an energy carrier included in the direct input has been derived from other forms of energy. Consider imported electricity produced in a thermal power plant. In this case, the entire energy input of the plant is counted as hidden flow, whereas the imported electricity is part of the direct input. To avoid double counting, only the energy used to produce the electricity should be taken into account.
17. Throughout this article, I use the SI units "joule" (J) for energy, "watt" (W) for power, and occasionally the derived unit "kilowatt-hour" (kWh; 1 kWh = 3.6 MJ), together with suitable prefixes indicating order of magnitude. 1 kcal = 4.1868 kJ; 1 kJ = 0.9478 Btu; 1 Btu = 1.0551 kJ; 1 toe = 41.8 MJ.
18. In agricultural societies, other conversion processes can be important, too; one example is the utilization of heat dissipated by humans and livestock for space heating (by placing the living room of a farm house over the stable). A significant part of ingested food is used for growth, reproduction, and maintenance of the body functions of humans and domesticated animals, not for power delivery. Because this is not a physical energy output of this compartment, however, it cannot be counted as a flow of useful energy. On the other hand, this means that we should be cautious about interpreting the ratio of work output to food input as a measure of the efficiency of this conversion process.
19. If nutritional biomass flows are treated in this way, losses that accrue to the conversion of plant biomass to meat or other animal products will be treated as conversion losses of primary to final energy (human food). It should be noted, however, that sustaining the workforce is surely not the only purpose of food in industrial society.
20. It is also possible to calculate the total primary energy consumption of a country by subtracting all exports (including the respective hidden flows) from the total primary energy input. In general, though, data accuracy is worse for hidden flows than for economically highly valued flows. Therefore, all calculations involving hidden flows introduce a lot more uncertainty and errors. In cases where hidden flows have to be included (e.g., if we want to deal with the issue of shifting energy-intensive production to less developed regions), it is therefore essential to make sure that uncertainty can be kept low enough not to hamper the conclusions being drawn from the analysis.
21. It is important to note, however, that it can be possible to produce the same energy service (e.g., a well-heated room) with different amounts of useful energy (e.g., by using better insulation). Equally important is that it may be very difficult or even technically impossible to reduce some losses in converting primary energy to useful energy, as in cases where thermodynamic laws make further efficiency improvements impossible.

References

Adriaanse, A., S. Bringezu, A. Hammond, Y. Moriguchi, E. Rodenburg, D. Rogich, and H. Schütz. 1997. *Resource flows: The material basis of industrial economies*. Washington, DC: World Resources Institute.

Axinn, G. H. and N. W. Axinn. 1984. Energy and food relationships in developing countries: A perspective from the social sciences. In *Food and energy resources,* edited by D. Pimentel and C. W. Hall. Orlando, FL: Academic Press.

Ayres, R. U. and L. W. Ayres. 1998. *Economy-wide applications of mass-balance principles to materials and waste*. Accounting for resources, Vol. 1. Northampton: Edward Elgar.

Ayres, R. U. and A. Kneese. 1969. Production, consumption and externalities. *American Economic Review* 59(3): 282–297.

Ayres, R. U. and U. E. Simonis. 1994. *Industrial metabolism: Restructuring for sustainable development*. Tokyo: United Nations University Press.

Bittermann, W. 1999. Energiebilanzen 1993–1997. [Energy balances 1993–1997]. *Statistische Nachrichten* 54(7): 567–578.

Boulding, K. E. 1973. The economics of the coming spaceship earth. In *Towards a steady state economy,* edited by H. E. Daly. San Francisco: Freeman.

Boyden, S. 1992. *Biohistory: The interplay between human society and the biosphere*. Paris: UNESCO and the Parthenon Publishing Group.

Bringezu, S., M. Fischer-Kowalski, R. Kleijn, and V. Palm. 1997. *Regional and national material flow ac-*

counting: From paradigm to practice of sustainability. Wuppertal special report no. 4. Wuppertal, Germany: Wuppertal Institute for Climate, Environment, Energy.

Bringezu, S., R. Behrensmeier, and H. Schütz. 1998. Material flow accounts indicating the environmental pressure of economic sectors. In *Environmental accounting in theory and practice*, edited by K. Uno and P. Bartelmus. Dordrecht: Kluwer.

Cook, E. 1971. The flow of energy in an industrial society. *Scientific American* 224(3): 135–144.

Daly, H. E. 1992. Is the entropy law relevant to the economics of natural resource scarcity? Yes, of course it is! *Journal of Environmental Economics and Management* 23: 91–95.

Erkmann, S. 1997. Industrial ecology: An historical view. *Journal of Cleaner Production* 5(1–2): 1–10.

Fischer-Kowalski, M. 1998. Society's metabolism: The intellectual history of materials flow analysis. Part 1. 1860–1970. *Journal of Industrial Ecology* 2(1): 61–78.

Fischer-Kowalski, M. and H. Haberl. 1997. Tons, joules, and money: Modes of production and their sustainability problems. *Society and Natural Resources* 10(1): 61–85.

Fischer-Kowalski, M. and W. Hüttler. 1998. Society's metabolism: The intellectual history of materials flow analysis. Part 2. 1970–1998. *Journal of Industrial Ecology* 2(4): 107–137.

Fischer-Kowalski, M. and H. Weisz. 1999. Society as hybrid between material and symbolic realms: Toward a theoretical framework of society-nature interrelation. *Advances in Human Ecology* 8: 215–251.

Fischer-Kowalski, M., H. Haberl, W. Hüttler, H. Payer, H. Schandl, V. Winiwarter, and H. Zangerl-Weisz. 1997. *Gesellschaftlicher Stoffwechsel und Kolonisierung von Natur: Ein Versuch in Sozialer Ökologie*. [Socioeconomic metabolism and colonization of nature: Approaches to social ecology]. Amsterdam: Gordon Breach Fakultas.

Force, J. E. and G. E. Machlis. 1997. The human ecosystem. Part 2. Social indicators for ecosystem management. *Society and Natural Resources* 10: 369–382.

Fritsche, U., J. Leuchtner, F. C. Matthes, L. Rausch, and K. H. Simon. 1992. *Gesamt-Emissions-Modell Integrierter Systeme (GEMIS), Version 2.0*. [Total emission model of integrated systems (TEMIS), version 2.0]. Wiesbaden: Hessisches Ministerium für Umwelt, Energie und Bundesangelegenheiten.

Geller, H. S. 1989. Implementing electricity conservation programs: Progress towards least-cost energy services among U.S. utilities. In *Electricity: Efficient end-use and new generation technologies, and their planning implications*, edited by T. B. Johansson et al. Lund: Lund University Press.

Giampietro, M. 1997. Linking technology, natural resources, and the socioeconomic structure of human society: A theoretical model. *Advances in Human Ecology* 6: 75–130.

Godelier, M. 1986. *The mental and the material: Thought economy and society*. London: Blackwell Verso.

Goldsmith, E. and N. Hildyard. 1984. *Overview*. The social and environmental effects of large dams, Vol. 1. Camelford, U.K.: Wadebridge Ecological Centre.

Golley, F. B. 1961. Energy values of ecological materials. *Ecology* 42(3): 581–584.

Haberl, H. 1997. Human appropriation of net primary production as an environmental indicator: Implications for sustainable development. *Ambio* 26(3): 143–146.

Haberl, H. and S. Geissler. 2000. Cascade utilization of biomass: How to cope with ecological limits to biomass use. *Ecological Engineering* 16(Suppl.): S111–S121.

Hall, C. W. 1984. Energy sources and conversions relating to food. In *Food and energy resources*, edited by D. Pimentel and C. W. Hall. Orlando, FL: Academic Press.

Harris, M. 1987. Comment on Vayda's review of good to eat: Riddles of food and culture. *Human Ecology* 15(4): 511–517.

Hutchinson, G. E. 1959. Homage to Santa Rosalia, or why are there so many kinds of animals? *The American Naturalist* 93: 145–159.

Hüttler, W., H. Payer, and H. Schandl. 1997. *National material flow analysis for Austria 1992*. Vienna: IFF (Institute for Interdisciplinary Studies of Austrian Universities), Department of Social Ecology.

IEA (International Energy Agency). 1992. *Energy statistics of OECD countries 1989–1990*. Paris: International Energy Agency, Organisation for Economic Co-Operation and Development.

IEA. 1995. *Energy balances of OECD countries 1992–1993*. Paris: International Energy Agency, Organisation of Economic Co-Operation and Development.

IFIAS (International Federation of Institutes for Advanced Study). 1974. *Energy analysis workshop on methodology and conventions*. Stockholm: International Federation of Institutes for Advanced Study.

Jänicke, M. 1995. Tragfähige Entwicklung, Anforderungen an die Umweltberichterstattung aus der

Sicht der Politikanalyse. [Sustainable development. Requirements for environmental reporting from the point of view of policy analysis]. In *Neue Ansätze der Umweltstatistik, Ein Wuppertaler Werkstattgespräch,* edited by S. Bringezu. Berlin: Birkhäuser Verlag.

Kemp, W. B. 1971. The flow of energy in a hunting society. *Scientific American* 224(3): 105–115.

Leslie, P. W., J. R. Bindon, and P. T. Baker. 1984. Caloric requirements of human populations: A model. *Human Ecology* 12(2): 137–162.

Ligon, P. and T. Votta. 2001. Strategic contracting increases waste prevention and materials recycling. *Resource Recycling* March: 1–4.

Lindemann, R. L. 1942. The trophic-dynamic aspect of ecology. *Ecology* 23(4): 399–418.

Lovins, A. B. 1977. *Soft energy paths: Toward a durable peace*. Cambridge: Ballinger.

Luhmann, N. 1984. *Soziale Systeme, Grundriß einer allgemeinen Theorie*. [Social systems, an outline of a general theory]. Frankfurt am Main: Suhrkamp.

MacFadyen, A. 1948. The meaning of productivity in biological systems. *Journal of Animal Ecology* 17: 75–80.

Machlis, G. E., J. E. Force, and W. R. Burch. 1997. The human ecosystem. Part 1. The human ecosystem as an organizing concept in ecosystem management. *Society and Natural Resources* 10: 347–367.

Martinez-Alier, J. 1987. *Ecological economics. Energy, environment and society*. Oxford: Basil Blackwell.

Matthews, E., C. Amann, S. Bringezu, M. Fischer-Kowalski, W. Hüttler, R. Kleijn, Y. Moriguchi, C. Ottke, E. Rodenburg, D. Rogich, H. Schandl, H. Schütz, E.v.d. Voet, and H. Weisz. 2000. *The weight of nations: Material outflows from industrial economies*. Washington, DC: World Resources Institute.

McDonnell, M. J. and S. T. A. Pickett. 1997. *Humans as components of ecosystems: The ecology of subtle human effects and populated areas*. New York: Springer.

Meyer, W. B. and B. L. Turner. 1994. *Changes in land use and land cover: A global perspective*. Cambridge: Cambridge University Press.

Moran, E. F. 1993. Ecosystem ecology in biology and anthropology: A critical assessment. In *The ecosystem approach in anthropology, from concept to practice,* edited by E. F. Moran. Ann Arbor: University of Michigan Press.

Nishioka, Y., Y. Yanagisawa, and J. D. Spengler. 2000. Saving energy versus saving materials. *Journal of Industrial Ecology* 4(1): 119–135.

Odum, E. P. 1969. The strategy of ecosystem development. *Science* 164: 262–270.

Odum, H. T. 1971. *Environment, power, and society*. New York: Wiley-Interscience.

Rappaport, R. A. 1971. The flow of energy in an agricultural society. *Scientific American* 224(3): 117–133.

Richels, R. and P. Sturm. 1996. The costs of CO_2 emission reductions: Some insights from global analyses. *Energy Policy* 24(10/11): 875–888.

Schandl, H., W. Hüttler, and H. Payer. 1999. Delinking of economic growth and materials turnover. *Innovation* 12(1): 31–45.

Schandl, H., H. Weisz, and B. Petrovic. 2000. Materialflussrechnung für Österreich 1960 bis 1997. [Material flow accounts of Austria 1960 to 1997]. *Statistische Nachrichten* 55(2): 128–137.

Schmidt-Bleek, F. 1994. *Wieviel Umwelt braucht der Mensch? MIPs, Das Maß für ökologisches Wirtschaften*. [How much environment does man need? MIPs, the measure for ecological housekeeping]. Basel: Birkhäuser Verlag.

Schütz, H. and S. Bringezu. 1993. Major material flows in Germany. *Fresenius Environmental Bulletin* 2: 443–448.

Sieferle, R. P. 1997a. Kulturelle Evolution des Gesellschafts-Natur-Verhältnisses. [Cultural evolution of society-nature interrelations]. In *Gesellschaftlicher Stoffwechsel und Kolonisierung von Natur, Ein Versuch in Sozialer Ökologie*, edited by M. Fischer-Kowalski et al. Amsterdam: Gordon and Breach Fakultas.

Sieferle, R. P. 1997b. *Rückblick auf die Natur: Eine Geschichte des Menschen und seiner Umwelt*. [Looking back on nature: A history of man and his environment]. München: Luchterhand Verlag.

Smil, V. 1992. *General energetics, energy in the biosphere and civilization*. New York: Wiley.

Smil, V. 1994. *Energy in world history*. Boulder, CO: Westview Press.

Spreng, D. 1995. *Graue Energie, Energiebilanzen von Energiesystemen*. [Embodied energy, energy balances of energy systems]. Zürich: vdf Hochschulverlag, Teubner.

Stahmer, C., M. Kuhn, and N. Braun. 1997. *Physische Input-Output-Tabellen (PIOT) 1990*. [Physical input output tables (PIOT) 1990]. Wiesbaden: Statistisches Bundesamt.

Starr, C. 1971. Energy and power. *Scientific American* 224(3): 37–48.

Townsend, K. N. 1992. Is the entropy law relevant to the economics of natural resource scarcity? (comment). *Journal of Environmental Economics and Management* 23: 96–100.

UN (United Nations). 1997. *Energy statistics yearbook 1995*. New York: United Nations, Department for Economic and Social Information and Policy Analysis, Statistics Division.

Vayda, A. P. 1987a. Explaining what people eat: A review article. *Human Ecology* 15(4): 493–510.

Vayda, A. P. 1987b. Reply to Harris. *Human Ecology* 15(4): 519–521.

Vellinga, P. and N. Herb. 1999. *Industrial transformation: Science plan*. IHDP report no. 12. Bonn, Germany: International Human Dimensions of Global Environmental Change Programme.

Vitousek, P. M., P. R. Ehrlich, A. H. Ehrlich, and P. A. Matson. 1986. Human appropriation of the products of photosynthesis. *BioScience* 36(6): 368–373.

Wiegert, R. G. 1976. *Ecological energetics*. Stroudsburg, PA: Dowden, Hutchinson and Ross.

Wright, D. H. 1990. Human impacts on the energy flow through natural ecosystems, and implications for species endangerment. *Ambio* 19(4): 189–194.

Young, J. T. 1991. Is the entropy law relevant to the economics of natural resource scarcity? *Journal of Environmental Economics and Management* 21: 169–179.

Young, J. T. 1993. Entropy and natural resource scarcity: A reply to the critics. *Journal of Environmental Economics and Management* 24: 210–213.

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