The Energetic Metabolism of Societies

Part II: Empirical Examples

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Summary

Part I of this set of articles proposed methods to account for the energetic metabolism of societies. In this second part, the methods explicated in Part I are used to analyze the energy flows of societies with different "modes of subsistence": hunter-gatherers, a contemporary agricultural society in southeastern Asia, and a contemporary industrial society (Austria). The empirical examples are used to demonstrate differences in the "characteristic metabolism" of different modes of subsistence. The energy system of hunter-gatherers can be described as an "uncontrolled solar energy system," based mainly upon harvesting biomass without attending to its reproduction. Hunter-gatherers use only about 0.001% to 0.01% of the net primary production (NPP) of the territory they inhabit. Agricultural societies harness NPP to a much higher extent: Although agriculture often reduces NPP, the amount of biomass that agricultural societies use is much higher (about 20% of potential NPP). Because ecological energy flows are the main source of energy for agricultural societies, NPP strictly limits the energetic metabolism of agricultural societies. Industrial society uses area-independent energy sources (fossil and nuclear energy), which, however, result in new sustainability problems, such as greenhouse gas emissions. By providing methods to account for changes in energy flows, the metabolism approach proves itself to be a useful concept for analyzing society-environment interactions. The article demonstrates the difference between the metabolism approach and conventional energy statistics and discusses the significance of the proposed approach for sustainable development.

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Introduction

Energy use is a prominent theme in many discourses, disciplines, and research fields concerned with sustainable development and with interactions between society and its natural environment. Examples include human ecology, environmental management, ecological economics, and ecological engineering. Data on energy production and consumption are often used as "headline indicators" for environmental pressures exerted by a socioeconomic system, such as a national economy (EEA 1999; Eurostat 1999). Changes in societal energy flows associated with transitions between different modes of subsistence (Sieferle 1997; Smil 1994), such as the transition from agricultural to industrial society, or related to the development of industrial economies (e.g., Cleveland et al. 1984; Hall et al. 1986) are frequently seen as fundamental challenges to be addressed by policies that aim at a more sustainable development.

Interestingly, research on industrial metabolism, focused on materials flow accounting (MFA), has all but neglected the issues of energy in recent years, despite the existence of a rich tradition of energy studies that can be traced back well into the 19th century (Martinez-Alier 1987). In an attempt to bring energy flows back onto the agenda of industrial metabolism research and thereby to industrial ecology, I have proposed an accounting concept for the energetic metabolism of societies in Part I (Haberl 2001) of this set of articles that is compatible with currently used MFA methods and that attempts to utilize, as far as possible, existing notions and methods of conventional energy balances. The main features of the proposed accounting methods are the following:

- In calculating the energy input of a society, all energy-rich materials (or immaterial energy flows as, for example, light and electricity) crossing the boundary between society and environment are considered. In particular, all biomass inputs are accounted for, regardless of the purpose for which they are used. The energy equivalent of combustible materials is assessed on the basis of their gross calorific value.
- The nutrition of humans and domesticated animals is regarded as an energy conversion process and is explicitly accounted for. The food input of humans and working animals is defined as final energy, whereas the food input of all other domesticated animals is accounted for as part of the conversion process of primary energy (plant biomass input) to final energy.
- The work of humans and working animals is accounted for as part of a "useful energy analysis."

The proposed method (figure 1) allows us to trace the flow of energy through a society based upon the following notions: *Total primary energy input* is the total amount of energy mobilized by a society and consists of *direct energy input* (i.e., energy actually entering the society under consideration) and *hidden flows* (i.e., energy mobilized but not crossing the boundary between society and environment). *Domestic consumption* is defined as direct energy input minus exports. *Final energy* is defined as the energy used to produce, in a first step, *useful energy* (i.e., energy actually performing useful work) and, ultimately, *energy services* (i.e., immaterial services for which the energy is actually used).

Here I apply the methods discussed in more detail in Part I to three different kinds of societal organization (Gellner 1988), or "modes of subsistence," namely, a hunter-gatherer society, an agricultural society, and an industrial society (Sieferle 1997). A mode of subsistence can be characterized by a set of society-environment interrelations associated with specific characteristics of societal organization (Fischer-Kowalski and Haberl 1997) (see below). I feel that such a comparative study is not only of historical interest, but is of great significance for understanding the current sustainability problems of industrial society.

Empirical Examples

In this section I discuss the energetic metabolism of different societies. In order to be able to compare the presented data and estimates, I use per capita values, measured as gigajoules per capita and year (GJ/cap·yr).[1]

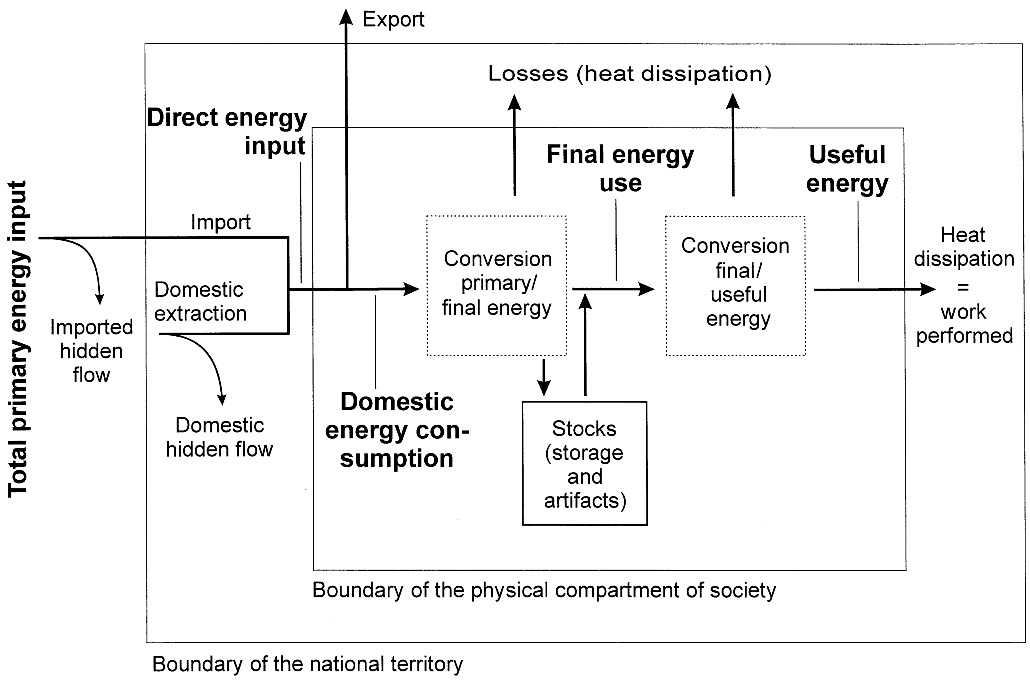

Figure 1 Summary of the accounting concept for the energetic metabolism of society, as discussed in Part I (Haberl 2001).

Hunter-Gatherer Energetics[2]

For more than 99% of their existence, humans were organized as hunter-gatherer societies. These were composed of small groups of usually 20 to 50 people, mostly nomadic, subsisting on the products of photosynthesis, much like any other heterotrophic organism. Hunter-gatherers have existed in many different environments, including tropical and semitropical savannahs, temperate forests, and grasslands. Today, hunter-gatherers persist only in extreme environments not suitable for cultivation.

The energetic metabolism of hunter-gatherers has been described as an "uncontrolled solar energy system" (Sieferle 1997), because hunter-gatherers harvest the biomass they need (edible parts of plants, animal products, fiber, etc.) without caring for the reproduction of these resources (Fischer-Kowalski and Haberl 1997). Of course, an exact appraisal of the energy flows of prehistoric societies is impossible (Smil 1992). Studies exist on the energetics of recent hunter-gatherer societies (e.g., Kemp 1971), but they offer only limited insight into the energetics of ancient hunter-gatherers, on the one hand because contemporary hunter-gatherers tend to live in extreme environments, and on the other hand because they use tools and fuels "imported" from industrial society. Nevertheless I estimate the order of magnitude of the societal energetic metabolism of an "ideal-typical" hunter-gatherer society, drawing from the literature. Of course, this should not be taken as a description of any specific hunter-gatherer society.

Although the question of *what* people eat has been discussed heatedly (Harris 1987; Vayda 1987), it is much easier to estimate *how much* they ingest. Whereas it is important for detailed analyses to take into account such factors as age and sex distribution, body weight, activity level, and ambient temperature (Leslie et al. 1984), I am interested here only in the order of magnitude determined by physiological properties of the human organism. The food energy intake (i.e., final food energy consumption) of hunter-gatherers can be assumed to be something like 10 MJ/day or 3.5 GJ/cap·yr—an amount of energy that Boyden (1992) has called the "human energy equivalent." In order to estimate the primary energy input associated with food provision, losses such as the indigestible parts of animals hunted or plants gathered or food lost during preparation must be accounted for. Some of these materials were presumably used for tools, clothing, fiber, and other nonfood uses. In the absence of better data, the primary energy needed to provide for food and these additional materials may be assumed to be double the amount of ingested food, giving an estimate of 7 GJ/cap·yr. Because prehistoric hunter-gatherers did not domesticate animals (with the possible exception of dogs, in late stages), there is no need to account for this compartment.

The use of fire by early humans is of great significance, as it seems to constitute the only share of final energy use by hunter-gatherers not flowing through the human organism (tools, clothes, etc. are a "nonenergy" use; see Part I) and thus are part of the "exosomatic" (Boyden 1992; Georgescu-Roegen 1971; Lotka 1925) energy flow of early human societies. Probably nobody will ever be able to reconstruct how much firewood any specific prehistoric hunter-gatherer society used. Additionally, the extent of the use of fire would have depended largely on variable local environmental conditions, so that results for any specific study site cannot be extrapolated. In the absence of better estimates, I follow Boyden in assuming rather arbitrarily a value of 3.5 GJ/cap·yr (Boyden 1992, 80). This would, however, obviously be several orders of magnitude higher in cases where hunter-gatherers burn down forests during hunting, thus promoting herbaceous vegetation; there is evidence that some prehistoric hunter-gatherer societies did adopt such behavior (Butzer 1984). Because import and export can be assumed to be close to zero, and hidden flows are of low significance in such a theoretical and inexact calculation, we can consider domestic extraction, total primary energy input, direct energy input, and domestic consumption to all be equal to one another and to have a value of about 10 GJ/cap·yr. "Final energy" would be nutritional energy (3.5 GJ/cap·yr) plus firewood used (3.5 GJ/cap·yr), giving an estimate of 7 GJ/cap·yr.

In estimating the amount of useful energy delivered, one is confronted with the same uncertainties, but this poses no major problem here because I am interested only in determining an order of magnitude. It is a much-debated question whether hunter-gatherers should be regarded as "original affluent societies" (Sahlins 1972) or rather whether they led a hard-working, badly nourished life (Smil 1994). Estimates of the hours of work per capita and day depend upon the point of view on this issue. Although the argument that hunter-gatherers do not manage the resource flows upon which they depend speaks in favor of the former position, the lack of accessible resources could lead to shortages requiring hard work, at least periodically. I follow the low estimate of Marvin Harris of 4 hours of work per capita and day (Harris 1991). Humans can deliver up to 100 watts (W) in continuous work (Smil 1992). This is, however, a maximum; additionally, we have to take losses into account. A continuous delivery of 50 W useful power[3] may be an appropriate guess; this equals about 0.2 GJ/cap·yr (4 hours of work per day). How much of the assumed 3.5 GJ/cap·yr fuel wood can be converted to useful energy depends largely upon the purpose of fire use. Assuming, for example, 20% efficiency of a three-stone open cooking fire (Dutt and Ravindranath 1993), fires would deliver about 0.7 GJ/cap·yr. Useful energy is, therefore, of the order of magnitude of 1 GJ/cap·yr.

Energetics of a Contemporary Agricultural Society

In this section I report data from a field study in Sang Saeng, a predominantly agricultural village in northeastern Thailand that is currently in the process of rapid industrialization. Nevertheless, the economy is still predominantly directed toward subsistence, exploiting local resources. The cultivation of glutinous rice makes up a large part of food consumption. The village was analyzed in a field study carried out by my colleague Clemens M. Grünbühel in 1998 (Grünbühel 1999, 2000; Grünbühel et al. 1999). The results presented here are derived from calculations that I made based upon data collected by Grünbühel in this field study (used with permission).

Table 1 summarizes the energy "production" system in Sang Saeng—that is, the provision of final energy—broken down into four main categories of energy: biomass, fossil fuels, hydro-

Table 1 Per capita energy provision in Sang Saeng, northeastern Thailand, 1998

	Domestic extraction (GJ/cap·yr)	*Domestic hidden flows (GJ/cap·yr)*	*Import (GJ/cap·yr)*	*Imported hidden flows (GJ/cap·yr)*	*Total energy input (GJ/cap·yr)*	*Direct input (GJ/cap·yr)*	*Export (GJ/cap·yr)*	*Domestic consumption (GJ/cap·yr)*	*Final energy (GJ/cap·yr)*
Biomass	48	21	0.4	1	70	48	8	41	27
Fossil fuels	0	0	4	1	5	4	0	4	4
Hydropower	0	0	0	0.04	0.04	0	0	0	0
Electricity	0	0	0.4	0	0	0.4	0	0.4	0.4
Total	48	21	5	3	76	53	8	45	31

Sources: Based on data collected by Grünbühel (1998), used with permission; my own calculations. See text for explanation.

Note: Numbers have been rounded.

power, and electricity. "Domestic" and "imported" are defined with reference to the territorial boundary of Sang Saeng. Domestic extraction is exclusively biomass, including both agricultural biomass and wood harvest for charcoal, cooking, and construction. Domestic extraction data are based upon field study results. Domestic hidden flows are unused agricultural biomass residues. Imports are about one order of magnitude smaller than domestic extraction. About 80% of the imported energy is fossil fuels. Imported biomass consists mostly of living animals. Imported hidden flows were calculated based upon data on Thailand's power system (about 90% thermal power plants, 10% hydropower plants) and literature data on energy losses in fossil energy conversion (refinery, transport of natural gas and liquid fossil fuels) (Fritsche et al. 1997). Data on import flows were calculated from field study data. Exports are mainly rice (90%) and living animals.

Taken together, table 1 shows that the energy input in Sang Saeng is quantitatively dominated by biomass flows. Nevertheless, fossil energy and electricity are decisive for Sang Saeng's energy metabolism. Although biomass accounts for 91% of domestic energy consumption and 87% of final energy consumption, fossil and electric energy is much more important when we look at the useful energy provided (see below). This can be interpreted as an indication that Sang Saeng, although it still exhibits many features of an agricultural society, is already in an early stage of the industrialization process.

Table 2 shows that nutrition amounts to more than 70% of final energy consumption in Sang Saeng, most of this being fodder for working animals. Data on the energy content of human food were calculated from nutrition studies of five households for 1 week each. The fodder consumption of livestock was calculated based upon factors for the per capita nutritional requirements and livestock counts from the field study. The use of charcoal, wood, and gas for cooking, as well as the use of gasoline for vehicles and the use of petroleum and electricity for light, were assessed in the field study. The amount of useful energy delivered by human and animal work was calculated based upon observations during the field study on working time of humans and animals in rice cultivation and other farming activities, using factors from the literature (Fluck 1992; Smil 1992). Useful energy delivered by vehicle motors was calculated assuming an efficiency of 15%; the efficiency of cooking was assumed to be 30% (Dutt and Ravindranath 1993).

Table 2 shows that fossil energy provides about one-half of the total amount of drivepower used in Sang Saeng, that is, about 20% of the useful energy. Additionally, gas is used for activities such as cooking, and petroleum for light. Therefore, the importance of fossil energy in relation to biomass should not be judged solely on the basis of primary energy data.

Calculating an "energy efficiency" of humans or working animals by dividing the useful energy (work) by the nutrition energy input could result in misleading conclusions. Animals are not only

Table 2 Per capita use of final and useful energy in Sang Saeng

Final energy (GJ/cap·yr)		*Useful energy (GJ/cap·yr)*	
Human food (biomass)	5	Human work	0.3
Nutrition of working animals (biomass)	17	Animal work	0.3
Vehicle motors (oil products)	3	Vehicle drivepower	0.5
Process heat (biomass and gas for cooking)	5	Process heat delivered (cooking)	1.4
Light and data processing (oil and electricity)	0.8	Light	0.04
Total	31	Total	2.4

Sources: Based on data collected by Grünbühel (1998), used with permission; my own calculations. See text for explanation.

Note: Numbers are rough estimates and have been rounded.

kept to harness their work force, but they are also important for fertilization (dung). To regard human nutrition only as an input needed to sustain the labor force would also be problematic because nutrition also is necessary for growth, reproduction, and maintenance of body functions. Nevertheless, a comparison of the energy needed to sustain working animals with the amount of work performed shows a remarkably low return. This can be explained by the fact that the animals work only for a short period of the year and stay idle for the rest of the time. In contrast, agricultural machinery does not continuously need energy when it is not working.

The estimates of the size of the energetic metabolism in Sang Saeng presented here are similar to other appraisals of the energy flow in agricultural societies. For example, Fischer-Kowalski and Haberl (1997) estimated the per capita biomass energy input in the alpine village of Törbel in the year 1875 at 65 GJ/cap·yr, based upon detailed data from Netting's Törbel study (Netting 1981). This figure is comparable to the direct input in Sang Saeng (53 GJ/cap·yr). Calculations of the Austrian energy metabolism during the 19th century (Krausmann and Haberl 2000) lead to astonishingly similar results: The per capita direct energy input, calculated according to the definitions discussed in Part I, was approximately 72 GJ/cap·yr in 1830. At that time, Austria's socioeconomic energy metabolism relied almost exclusively on biomass (coal accounted for less than 1%). Although further empirical evidence is desirable, the convergence of these results obtained for communities in very different ecological settings (Sang Saeng/Törbel) and on different levels of social organization (villages/nationwide analysis) supports the notion of a "characteristic metabolic profile" of agricultural societies. It should be noted, however, that all these examples refer to societies at an early state of transition from agricultural to industrial society.

Energy Flows in an Industrial Society: Austria 1995

As an example of the energetic metabolism of an industrial economy I here report calculations for Austria in 1995. Austria is a highly industrialized central European country. Austria's industrial energy system is to some extent atypical: With a share of 70%, hydropower contributes significantly to electricity generation. The contribution of biomass to technical energy provision (about 13%) is also quite high; this can be explained by a high availability of fuel wood because of the high proportion of forest to total area (45%). The use of nuclear energy for electricity generation was forbidden by law following a popular vote in 1978.

Per capita energy provision in Austria in 1995 is shown in table 3. As can be seen, domestic extraction of biomass is astonishingly similar to that in Sang Saeng. Fossil energy—coal, oil, and gas—covers about 60% of the energy input (total energy input, 58%; direct input, 56%; domestic consumption, 60%). Import, mostly of fossil energy, accounts for 58% of the direct input.

It is interesting to compare the figures displayed in table 3 to the data reported in conventional energy statistics. According to the official Austrian energy balance (Bittermann 1999), the

Table 3 Per capita energy provision in Austria in 1995

	Domestic extraction (*GJ/cap·yr*)	*Domestic hidden flows* (*GJ/cap·yr*)	*Import* (*GJ/cap·yr*)	*Imported hidden flows* (*GJ/cap·yr*)	*Total energy input* (*GJ/cap·yr*)	*Direct input* (*GJ/cap·yr*)	*Export* (*GJ/cap·yr*)	*Domestic consumption* (*GJ/cap·yr*)	*Final energy* (*GJ/cap·yr*)
Biomass	59	4	17	4	84	76	13	62	21
Fossil fuels	15	0	107	24	146	122	5	117	75
Hydro plus electricity	18	0	3	0	18	21	4	17	21
Nuclear energy	0	0	0	2	2	0	0	0	0
Heat (district heat)	0	0	0	0	0	0	0	0	4
Total	92	4	127	31	251	219	23	196	121

Sources: Calculated on the basis of the Austrian energy balance (Bittermann 1999), data from the Austrian import/export statistics (ÖSTAT 1998), and extensive analyses of socioeconomic biomass flows (Krausmann 2001a).

Note: All figures are gross calorific values. "Imported hidden flows" refers only to hidden flows of imported energy carriers (no other imported resources or consumer goods considered) and are rough estimations based on data from the literature (e.g., Fritsche et al. 1997).

"total energy supply" in Austria amounts to 141 GJ/cap·yr. This figure is comparable to the direct energy input of 219 GJ/cap·yr (table 3). Thus, direct energy input is 55% higher than the figure reported in energy statistics. A smaller part of this difference is due to the fact that direct energy input was calculated on the basis of the gross calorific value, which for fossil fuels and biomass is 4% to 20% higher than the net calorific value. The largest part of the difference is due to the fact that energy statistics ignore most biomass flows.

The difference between final energy use according to my calculation (121 GJ/cap·yr) and that reported in the energy balance (111 GJ/cap·yr) is much smaller. In this case, the difference results exclusively from the difference between gross and net calorific values and from the addition of human nutrition (about 5 GJ/cap·yr) to the use of technical energy carriers. Because there are practically no more working animals in Austria, it is not necessary to account for their nutritional energy uptake in calculating final energy. The considerable "nonenergetic" use of biomass—for example, wood for pulp and paper or timber for construction and furniture—is not part of final energy use. Use of biomass-derived fuels for the provision of useful energy in technical devices is already accounted for as "final energy" in Austrian energy statistics.

Table 4 shows that nutrition of humans and working animals is not an important part of the final energy use of an industrial country (4%), mostly because of the increase in final energy use and the absence of working animals. Instead, energy used to run machinery and vehicles (stationary and vehicle motors) accounts for an important part of final energy use (34%). Space and water heating is quantitatively even more important (38%), and industrial process heat accounts for 21%.

Table 4 also shows that human work is quantitatively not important for the provision of useful energy in an industrial society. My estimate of the amount of work delivered was based on the number of hours worked in the Austrian economy according to statistical data, and on the assumption that the amount of physical energy delivered per hour is about one-half of that in Sang Saeng, reflecting the fact that a large part of the heavy physical work is done by machinery and many workers are employed in the service sector, which usually requires little physical work. Physical work delivered per capita is markedly smaller than in Sang Saeng, not only because of the assumption that the average worker will deliver less power, but even more so because of the much smaller number of working hours per capita—a result consistent with other analyses (e.g., Giampietro 1997).

Society's Energetic Metabolism and Sustainability

Energy Flows and Society-Ecosystem Relations in Different Modes of Subsistence

One objective for the analysis of the energetic metabolism of societies is to understand the relationship between societies and their natural environment. The energy system of hunter-gatherers has been described as an "uncontrolled solar energy system," because hunter-gatherers utilize suitable and accessible energy resources for nutrition and other purposes more or less in the form in which ecosystems deliver them. Probably no, or no important, systematic and intentional attempts are made to systematically change and control ecosystem processes in order to make them more "productive" in socioeconomic terms. Hence, hunter-gatherers use only a minuscule proportion of the net primary production (NPP) of terrestrial ecosystems they inhabit that is accessible and suitable for their needs. Boyden (1992, 80) estimates that hunter-gatherers utilize less than 1/10,000 to 1/100,000 of the NPP of the regions they inhabit.[4] That is, the energy throughput of hunters-gatherers using the NPP of terrestrial vegetation either directly (through gathering) or indirectly (through hunting or fishing) and relying exclusively upon biomass, is only a very small percentage of ecological energy flows. In the words of Boyden: Hunter-gatherers "fit into their habitats in much the same way as other omnivorous species" (Boyden 1992, 80). This is the reason why hunter-gatherers reach only low population densities (0.02 to 0.2 persons per square kilometer), despite their low per capita energy requirements.

Table 4 Per capita use of final and useful energy in Austria in 1995

Final energy (GJ/cap·yr)		*Useful energy (GJ/cap·yr)*	
Human food (biomass)	5	Human work	0.05
Stationary motors[a]	11	Drivepower stationary motors	9
Vehicle motors (mostly oil products)	30	Drivepower vehicle motors	4
Process heat[b]	26	Process heat delivered	18
Space and water heating[c]	46	Heat delivered for space / water heating	31
Light and data processing[d]	3	Light delivered	0.1
Total	121	Total	63

Sources: Calculated on the basis of the energy flow diagram published by the Austrian Energy Agency (EVA 1997) and other statistical data (ÖSTAT 1998).

Note: Numbers are estimates and have been rounded.

[a] Mostly electricity.

[b] Mostly industrial, but also including residential process heat, cooking, and so forth; all kinds of final energy carriers are used.

[c] All kinds of final energy carriers are used.

[d] Almost exclusively electricity.

Agriculture leads to a fundamentally different type of relation between a society and its natural environment (Vasey 1992). This type of society-nature interrelation is not only characterized by a considerably higher throughput of energy and materials than that of hunter-gatherers, but also by a kind of behavior that involves the intentional transformation of parts of the natural environment in a way that renders it more useful for societal needs. This has been termed "colonization of natural systems" (Fischer-Kowalski and Haberl 1997; Fischer-Kowalski et al. 1997). Colonization includes activities to alter and control important parameters of natural systems, often with the goal of producing materials (e.g., biomass) or releasing energy (e.g., hydropower). Colonization can also aim at creating certain physical conditions (e.g., construction of roads). Colonization requires planned interventions into natural systems, usually requiring know-how, societal organization, and work.

Agriculture involves the colonization of various natural systems on different levels of biological organization, examples being domestication of animals and plants, and interventions into terrestrial ecosystems such as the control of species composition and nutrient or water flows. Agriculture is associated with a considerable increase in per capita energy flows; patterns of an agricultural ecosystem's primary production are influenced by agricultural societies so that a higher percentage of the NPP can be used for societal purposes. Livestock, usually regarded as a societal compartment with respect to material and energy flow analyses (see Part I), consumes about ten times more plant biomass energy than it delivers in the form of products (meat, milk, eggs, furs, etc.)—this being the most important reason for the increase in total energy throughput of agricultural societies as compared to hunter-gatherers.[5]

Nevertheless, the energetic metabolism of agricultural societies is limited by the biological productivity of their territory. Although agricultural societies can influence the NPP of the regions they inhabit—this being an important aspect of technological change in agricultural societies (see below)—they are usually not able to increase the NPP above the level of the NPP of potential vegetation (i.e., the vegetation that would emerge if human interventions stop). One reason for this is that in agricultural societies that have no area-independent sources of energy at their disposal, many options to increase productivity per unit area require increases in the amount of human or animal work, both of which are in short supply (Netting 1993). Therefore, the aboveground NPP of potential vegetation of the region agricultural societies inhabit is an upper limit for the growth of the energetic metabolism of agricultural societies. Sang Saeng is an excellent example. Based on the data of Grünbühel's field study (Grünbühel 1999, 2000; Grünbühel et al. 1999) it can be calculated that about 56% of the current aboveground NPP on Sang Saeng's territory is harvested by humans or consumed by human livestock. Moreover, the productivity of the currently prevailing vegetation is considerably (47%) lower than that of the potential vegetation (tropical rain forest), probably due mostly to low nutrient availability.

Such changes in ecological energy availability resulting from human activities (land use, land cover change, biomass harvest) can be analyzed by using an indicator that has been termed "human appropriation of net primary production" (HANPP) (Haberl 1997; Haberl et al. 2001; Vitousek et al. 1986). HANPP can be defined as difference between the potential NPP and the part of the NPP actually remaining in ecological cycles (Haberl 1997). In other words, the calculation reported above shows that the people living in Sang Saeng appropriate about 70% to 80% of the aboveground NPP on their territory;[6] a strong indication that this community lives very close to its ecological limits, at least with the technology currently available to this community. The same kind of calculation was performed for Austria in 1830 by Krausmann, showing that the aboveground productivity in Austria was 39% lower than that of the potential vegetation. At the same time, 34% of the actual vegetation's aboveground NPP was harvested, resulting in a HANPP value of 59% (Krausmann 2001a).[7] Although lower than the corresponding figure in Sang Saeng, this is probably also close to the maximum possible at that time, because Austria's mountainous terrain limits crop production and makes types of land use other than forestry difficult or even impossible in large parts of the country.

Although further evidence would be desirable, these case studies already lead to the tentative conclusion that agricultural societies reduce the overall NPP on their territory, while at the same time maximizing the proportion of NPP that can be utilized by society. Much of the evidence discussed by Netting (1993) suggests that the development of agricultural societies over time, from slash-and-burn agriculture to permanent, intensive cropping, leads to more refined colonization strategies, enabling agricultural societies to exploit a greater proportion of the production potential of their territory, but at the cost of an increasing demand for agricultural labor—eventually leading to a demand for labor that seems to be close to a physiologically tolerable maximum, in some cases up to 4,000 hours per worker and year (Netting 1993).

The main sustainability problem of agricultural societies seems to be the maintenance of the often fragile balance between the productivity of their colonized ecosystems, the supply of human and animal labor to keep these systems productive, and population density. That is, one may speculate, the maximum population density of agricultural societies depends not passively on the characteristics of their habitat, but rather on an interplay between natural conditions and societal colonization of natural processes. Nevertheless, the productivity of the potential vegetation seems to represent an upper limit for the energetic metabolism of agricultural societies that cannot be surpassed in a larger region; for example, in a whole country. The limit for the energetic metabolism of an agricultural society is probably significantly lower than the potential aboveground NPP of its territory. For example, the Austrian direct energy input in 1830, almost exclusively biomass, was 21% of the potential aboveground NPP, and the figure for Sang Saeng (19%) is practically identical. The reason is that, without fossil energy subsidies, average agricultural ecosystems are considerably less productive than potential vegetation in terms of aboveground NPP.

According to Sieferle, the transition from the controlled solar energy system of agricultural societies to an energy system powered by area-independent fossil energy and later supported by large-scale hydropower and nuclear energy was a prerequisite for the industrial revolution (Sieferle 1982, 1997). Although cause and effect may be debatable, we know for certain that the transition toward industrial society is associated with a fundamental change in the patterns of societal energy use (Smil 1992, 1994), resulting in an industrial energy system that is no longer constrained by the productivity of terrestrial ecosystems.

Table 5 presents a comparison between the energy provision systems of hunter-gatherers,

Table 5 Comparison of the per capita energy input of hunter-gatherers (order of magnitude), an agricultural society in an early stage of transition toward becoming an industrial society (Sang Saeng, northeastern Thailand), and an industrial society (Austria, 1995)

	Total energy input				*Domestic consumption*			
	Total (GJ/cap·yr)	*Biomass (%)*	*Fossil (%)*	*Others (%)*	*Total (GJ/cap·yr)*	*Biomass (%)*	*Fossil (%)*	*Others (%)*
Hunter-gatherers	10	100%	0%	0%	10	100%	0%	0%
Sang Saeng 1998	76	93%	7%	0%	45	91%	8%	1%
Austria 1995	251	33%	58%	8%	196	32%	60%	9%

Sources: See tables 1–4.

Sang Saeng, and Austria in 1995, based upon the calculations discussed in the last sections. It shows leaps in the per capita energy flows between the three different modes of subsistence by factors of between 4 and 7. Patterns of societal energy supply change from the uncontrolled solar (biomass) energy system of hunter-gatherers to the controlled solar (biomass) energy system of agricultural societies, to the fossil energy system of industrial society, the latter relying strongly on imported energy. The simple fact that the total primary energy input of Austria in 1995 of more than 2,000 PJ/yr (1 PJ $= 10^{15}$ J) surpasses the aboveground NPP of potential vegetation (1,480 PJ/yr) by 35% demonstrates that industrial energy metabolism is independent of ecological energy flows. Of course, as is well known, the industrial patterns of energy use cause new sustainability problems such as depletion of nonrenewable resources, the release of greenhouse gases caused by fossil fuel combustion, and toxic emissions. These sustainability problems are, however, fundamentally different from those experienced by agricultural societies, and this difference depends, to a large extent, on the size and pattern of the energetic metabolism of agricultural and industrial societies.

This discussion is quite relevant for the interpretation of the "human appropriation of NPP," or HANPP. The famous result of Vitousek and colleagues (1986) that global HANPP amounted to about 40% in the early 1980s has sometimes been misinterpreted as an indication for limits to human population growth. The argument runs as follows: If we appropriate 40% of NPP today, a doubling of world population will inevitably lead us to a level of 80% HANPP in about 40 or 50 years—and this is seen as already too close to the margin of 100% HANPP which is neither possible nor desirable (Meadows et al. 1992; Costanza et al. 1998). This has stimulated a response by "technological optimists" who argued that HANPP was not a valid concept for determining ecological limits, essentially for two reasons: (1) Agriculture can raise the productivity of the vegetation to higher levels than those of the potential vegetation, and (2) Vitousek's notion of "appropriation" or "co-option" of biomass counts all productivity of strongly human-influenced ecosystems, above all, agro-ecosystems, as "co-opted."[8] The amount of biomass actually consumed is much lower than the amount of biomass "appropriated"; therefore, HANPP is not a valid indicator for biomass scarcity (Davidson 2000; Sagoff 1995).

The results presented here and, above all, a time series for HANPP in Austria for 1830–1995 (Krausmann 2001a) confirm this argument to some extent, although they do not necessarily support the optimism of the adherents of a "no limits" hypothesis. The quoted evidence shows that it is indeed possible to increase the NPP of agro-ecosystems quite substantially. For example, from 1830 to 1995 the NPP of Austria's vegetation increased by some 40% from 860 to 1,200 PJ/yr. The average productivity (NPP per unit area and year) of cropland increased by a factor of about 2.8, the productivity of grasslands by a factor of 2.3. Moreover, because harvest indices—the ratio of economically useful product to aboveground NPP—increased considerably for most crops, a much larger percentage of the aboveground NPP of cropland was useful harvest. Overall, Austria was able to increase its biomass harvest by some 70% from 1830 to 1995, supporting a growth of population from 3.5 to 8 million, whereas HANPP decreased from about 59% to 51% in the same period of time (Krausmann 2001a).

Whereas this discussion clearly shows that it would be overly simplistic to equate population growth or economic growth—Austria's GDP grew by a factor of 28 from 1830 to 1995—with a growth in HANPP, I would be hesitant to interpret the Austrian example as "progress toward sustainability." It is essential to acknowledge that the "delinking" that occurs between HANPP and biomass harvest during the transition from agricultural to industrial society is only possible because new, area-independent sources of energy, above all fossil fuels, become available, resulting in new sustainability problems (e.g., global warming). According to as yet unpublished calculations by Krausmann (2001b), the relation of outputs to inputs in the Austrian agriculture sector changed from 6:1 in 1830 to 0.8:1 in 1995,[9] essentially transforming agriculture from the largest socioeconomic source of net energy (Cleveland et al. 1984; Hall et al. 1986) in 1830 to a sector that, from a societal perspective, consumed net energy instead of delivering it in 1995 (cf. Pimentel et al. 1973). In addition, a host of environmental problems such as nitrogen leaching, soil erosion, biodiversity loss, and others, were related to this change in agricultural practice.

Moreover, whereas Davidson (2000) and Sagoff (1995) argued that the NPP of agroecosystems can surpass that of natural vegetation, we find that this is rather unlikely for larger regions, although it is certainly possible on a small scale.[10] I Austria, the productivity of many crops already seems to approach limits set by morphological and physiological constraints of plants; still the productivity of the actually prevailing vegetation is, on the average, some 14% smaller than that of the potential vegetation. One of the reasons for this is the relentless growth of built-up areas, another the fact that most (but not all) agro-ecosystems are still less productive than potential vegetation. That is, although there is the possibility to increase the "efficiency of area use," this normally reduces the energy efficiency of the agricultural sector, which is only possible if area-independent sources of energy become available. Moreover, it is plausible that there exist biological limits to this optimization process, although we currently do not know where exactly they might be.[11]

Implications for Sustainability Strategies of Industrial Society

One concrete recommendation is that indicators derived from the accounting concept derived in this pair of articles should be used as "headline indicators" for society's energy throughput, instead of using indicators such as "primary energy consumption" taken from conventional energy balances that are used in current environmental reports (e.g., EEA 1999; Eurostat 1999). That is, I argue that socioeconomic energy throughput, as assessed with the concepts presented here, is a better proxy for the aggregate environmental pressures on the environment exerted by a given national economy than conventional measures of energy use derived from energy statistics. Many reasons for this should have become apparent in the preceding section (see also Part I).

A central implication of this is that a strategy to reduce the total energy throughput of a society—as measured by the indicators proposed in this article—is an essential element of sustainable development.[12] This also means 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 in order to reduce carbon dioxide (CO_2) emissions. Even if the HANPP argument may not yield a straightforward measure for ecological limits, as discussed above, it is still valid that HANPP has significant ecological implications. By definition, HANPP reduces the amount of biomass energy available to ecological food webs—thus potentially contributing to biodiversity loss (Wright 1990)[13]—and it has implications for carbon storage in terrestrial ecosystems. As is well known (Houghton 1995), the conversion of forests to agroecosystems is not only associated with an increase in HANPP, but also with net releases of carbon into the atmosphere that contribute to global warming.

For these reasons, we should view policies that aim to reduce CO_2 emissions through a substitution of biomass for fossil fuels with caution, at least if they contribute to an increase in HANPP. This is the case if they entail an increase in logging or increases in cropland areas at the expense of forests. On the other hand, strategies of a "cascade utilization of biomass" that aim at the reuse and "energetic recycling" of biomass residues and wastes would allow an increase to the contribution of biomass to energy provision without leading to an increase in HANPP (Haberl and Geissler 2000). Concrete examples for this are the use of crop residues or dry, solid biomass wastes for energy generation. These materials can be used in combined power and heat plants to deliver electricity and heat. A large spectrum of wet biomass residues and wastes—for example, manure, kitchen wastes, wastes from the food industry, and maybe wet crop residues—can be used in biogas plants, which can again deliver fuel for combined power and heat plants. When elaborated to sufficient detail, accounting schemes such as those presented in Part I of this pair of articles can be useful for deriving the potentials for a cascade utilization of biomass. As has been shown elsewhere, there are significant energy potentials that could be mobilized by such a strategy (Haberl and Geissler 2000).

Another important point refers to the interpretation of carbon sinks related to terrestrial vegetation in industrialized countries that play a major role in current negotiations on the implementation of the Kyoto Protocol (IPCC 2000). Calculations for Austria (Erb 1999; Haberl et al. 2001) show that Austria's current aboveground vegetation component stores about 633 megatons (Mt) less carbon (1 Mt = 10^6 t) than its potential vegetation—that is, the vegetation that would be expected to evolve if human impact ceased to exist—would store in its aboveground compartment. For comparison, this amounts to about 40 times the current annual carbon emissions in Austria from fossil fuel combustion.

Because of the changes associated with the transition from agricultural to industrial society discussed in the previous section, we are currently experiencing an increase in forested areas, which is associated with a net carbon sink in the vegetation (i.e., vegetation soaks up carbon from the atmosphere). That is to say that there must have been a minimum of carbon storage in Austria's vegetation that can be suspected to have occurred some 200 years ago, just before Austria's industrialization began (Krausmann 2001a).

The reason for this is obviously Austria's transition from an agricultural to an industrial energy system. Because the energy system of agricultural society relied practically exclusively on biomass, and had little energy available for increasing the productivity of its agro-ecosystems, it used as much area as possible to generate energy inputs for society, resulting in high HANPP and low energy availability in ecosystems. Thus, little biomass remained in ecosystems that could be used to build up and maintain biomass (i.e., carbon) stocks. This changed as fossil energy became available, providing an area-independent energy source that could be used to increase the productivity of agro-ecosystems, allowing a reduction in cropland and grassland areas in favor of forests (and urban areas). In other words, the emergence of carbon sinks in vegetation in Austria—and other industrial countries (IPCC 2000) as well—is a consequence of the environmental history of industrialized countries that involved (1) deforestation and other changes in biomass stocks in terrestrial ecosystems in the past followed by (2) a partial reversal of this depletion of biological carbon stocks due to the availability of fossil fuels during the industrialization process.[14]

Therefore, the credibility of schemes that entail carbon credits for land-cover changes that create carbon sinks is not only undermined by issues of uncertainties surrounding the magnitude and stability of carbon sinks.[15] From the point of view elaborated in the above discussion, the very concept to offer industrialized countries carbon credits that allow them to emit more CO_2 from fossil fuel combustion in return for changes in land cover that are (1) a continuation of land-use trajectories that are currently observed in almost all industrialized countries (i.e., growth in forest areas) and (2) are based upon the very feature of the industrial energy system that causes most of the problem—that is, fossil fuel combustion—appears fundamentally flawed.[16]

Conclusions

The approach toward the analysis of the "energetic metabolism" of societies explicated in this set of articles uses energy flow accounting as a tool for analyzing the interactions between societies and their natural environments. It seeks to describe the energy flows through mostly regionally (e.g., nationally) defined socioeconomic units. It aims at an accounting system for society and the economy in physical terms ("physical economy") that can be used to analyze the biophysical structures of a society as an ecosystem component.

The empirical calculations presented in this article suggest that transformations between different "modes of subsistence" (hunter-gatherers, agricultural societies, industrial society) have been associated with qualitative and quantitative leaps in societal energy metabolism. Analyzed as per capita flows, these transformations were associated with an increase in the amount of energy drawn by societies from their natural environments and an even higher increase in the amount of useful energy available to perform work. For example, while energy inputs increased by factors of between 3 and 6 from agricultural to industrial society, available useful energy increased by a factor of between 20 and 30 (tables 3 and 5). Although I would be reluctant to equate this observation with "cultural progress" (e.g., Ostwald 1909) or an improvement of the quality of life or the satisfaction of human needs and wants (e.g., Giampietro and Pimentel 1991), it seems undeniable that this increase in energy availability was associated with dramatic increases in the complexity of social organization. Further research into the significance of changes in societal energy metabolism for society and the economy (e.g., Rosa et al. 1988; Sieferle 1997; Smil 1992) is, therefore, desirable.

Whereas discussion of the relation between societal energy flows and social organization or other general sociological theorizing will probably remain hotly debated for some time to come, the usefulness of appraisals of societal energetic metabolism for analyzing the interactions between societies and their natural environments seems to be less contested. As the empirical examples have shown, changes in patterns and amounts of per capita energy throughput are intimately linked to sustainability problems of human societies. In this respect it is essential to measure the "total amount of energy 'metabolized' by society" (Giampietro 1997, 96) with the methods described in Part I, because conventional energy balances—while otherwise methodologically similar to the concepts presented here—fail to take into account important inputs, especially biomass. Nevertheless, as has been discussed, these flows are highly significant for society-environment interrelations and sustainable development. In particular, including these flows is essential to the understanding of the relation between land use and socioeconomic metabolism, which has so far been neglected in most land-use research as well as in practically all materials flow analysis work. This field of inquiry is especially significant for the study of sustainability problems related to the transition from agricultural subsistence economies to the industrial mode of subsistence that currently takes place in large parts of the so-called developing countries. This approach seems, therefore, important for analyzing global sustainability issues.

Using the accounting methods proposed in this article, it is possible to describe the relations between the "biophysical structures of society" and ecosystems in much the same way as systems ecologists describe ecosystem components. This offers us the possibility of exploiting ecological concepts and methods—above all those of systems ecology—to place human activities in an ecological context. An example of this is the concept of human appropriation of NPP (Haberl 1997; Haberl et al. 2001; Vitousek et al. 1986). On the other hand, societal metabolism can be related to social activities—for example, economic activities or the use of technologies. Therefore, the societal metabolism approach is both a theoretically appropriate and an empirically promising strategy for analyzing the relations between human societies and their natural environments—a core field of inquiry in industrial ecology, ecological economics, and human ecology, especially in the context of sustainable development. I hope to have demonstrated here as well that, in order to fully exploit the potential of the metabolism approach for industrial ecology, material and energetic aspects of societal metabolism both must be taken into account, because they are essentially two complementary aspects of the same thing.

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Notes

1. $1 GJ = 10^9$ J (SI) $= 2.39 \times 10^5$ kcal $= 9.48 \times 10^5$ BTU = 23.9 toe.
2. The figures discussed here demonstrate only the order of magnitude of energy flows of hunter-gatherer societies. I mostly follow data derived by Boyden (1992). Studies of modern hunter-gatherers that have fossil fuels at their disposal (e.g., Kemp 1971) do, of course, differ from these ideal-typical calculations.
3. By this I mean the rate of useful energy flow "produced" by physical human work (see Part I).
4. For hunter-gatherers who used fire for hunting, the amount of biomass burned per capita could have been dramatically larger. Although I would be reluctant to regard this as "exosomatic energy input" of these hunter-gatherer societies, it should probably be taken into account when calculating the "human appropriation of NPP" (see text in section "Society's Energetic Metabolism and Sustainability" and note 7), resulting in considerable human appropriation of net primary productivity (HANPP) values for these societies. Note, however, that the controlled use of fire was not a feature of all hunter-gatherer societies, and that large-scale fires were probably not used by all hunter-gatherers who could control fire for hunting.
5. When hunter-gatherers hunt animals, the energy these animals need for metabolism takes place outside the boundary of the hunter-gatherer society (because the animals are not domesticated, they are not being fed, etc.). Therefore, this energy flow is not regarded as an input of hunter-gatherer societies. Conversely, agricultural societies domesticate and feed their livestock. According to the accounting scheme discussed in Part I these processes take place within the boundaries of the "biophysical structures" of the society and have to be accounted for when calculating the energy input.
6. The HANPP value of 70% to 80% is calculated as follows: The productivity of actual vegetation is 47% lower than that of potential vegetation; that is, it amounts to 53% of potential vegetation. A bit more than half (56%) of this 53% is harvested, which amounts to 30% of potential NPP. That is, of the 100% potential NPP, 47% is foregone because actual vegetation is less productive than potential vegetation and 30% is harvested, resulting in a total HANPP of (about) 77%.
7. NPP of actual vegetation was 39% lower than potential NPP (100%), that is, it amounted to 61% of potential NPP. Of this 61% about one-third (34% of actual NPP or about 21% of potential NPP) was harvested. That is, HANPP amounted to 39% (reduction in productivity) plus 21% (harvest), giving a total of about 60%.
8. The definition of "NPP appropriation" used here—and in other work of our group (Haberl 1997; Haberl et al. 2001; Krausmann 2001a)—uses a different definition: We define HANPP as the difference between the NPP of the potential vegetation and the amount of NPP actually remaining in ecosystems after human harvest. That is, HANPP amounts to about 95% on cropland (because we also regard straw harvested as "appropriated") and about 60% to 75% on grassland (we regard only the biomass grazed by livestock or harvested by humans as "appropriated"); both categories of land are regarded as having a HANPP of 100% by Vitousek.
9. Calculated as the relation of "socioeconomic inputs into agriculture" to "socioeconomic outputs of agriculture." Inputs include hidden flows of fertilizer production, imported feedstuffs, fuels, and so forth. Outputs are plant and animal products in the form in which they leave the agriculture sector, that is, as primary produce.
10. Arid regions might be a notable exception. In these regions, adding water can increase NPP by large margins. Substantial sustainability problems

are associated with this, however, for example, exhaustion of water supplies that are often nonrenewable in these regions, and soil salinization.

11. For example, modern crops have harvest indices between 0.5 and 0.6, indicating that at the time of harvest 50% to 60% of the biomass has been allocated to the grain. Because plants need shoots to carry the leaves for photosynthesis, there are clearly limits to the "optimization" of crop plants. Moreover, light availability, the efficiency of photosynthesis, and other factors that cannot easily be influenced by society limit aboveground NPP.
12. That should not mean that other aspects—for example, materials throughput or fossil-fuel-related CO_2 emissions—were not important "headline indicators."
13. On-going research by my colleagues and me at the Department of Social Ecology confirms this assertion in an empirical study that relates HANPP to species diversity data for seven taxonomic groups on 38 plots measuring 600 $\times$ 600 meters. These as yet unpublished results indicate that, although the relation between HANPP and species diversity may be nonlinear, high HANPP values are significantly associated with low species diversity.
14. Another aspect of carbon sinks is that enhanced CO_2 levels stimulate forest growth, potentially also leading to a carbon sink (e.g., Chambers et al. 2001). Considerable doubts exist, however, concerning the stability of these carbon sinks. For example, a large part of the increase in forest NPP is allocated to short-lived components such as leaves and other biomass that are quickly remineralized, so that the additional carbon fixed is, to a considerable extent, released into the atmosphere in few years (Schlesinger and Lichter 2001). Moreover, rising temperatures are likely to increase remineralization rates in general and, thus, carbon releases from terrestrial ecosystems. Model calculations show that this effect of global warming could even lead to net releases of carbon from terrestrial ecosystems (Sarmiento 2000).
15. Several reports by the International Institute for Applied Systems Analysis (e.g., Obersteiner et al. 2000) argued that uncertainties concerning the magnitude and stability of vegetation-related carbon sinks that are probably—the detailed regulations still have to be negotiated—accounted for under the Kyoto Protocol are large enough to make verification all but impossible.
16. That is not to say that keeping carbon in the biota—for example, by decreasing deforestation rates—or creating carbon sinks has to be a bad thing. But, for the discussed reasons, and, above all because there is not enough land to create sufficient carbon sinks to offset emissions from fossil fuel combustion, carbon sinks cannot solve the problem of fossil-fuel-related carbon emissions.

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