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The process of industrialization from the perspective of energetic metabolism Socioeconomic energy flows in Austria 1830–1995

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Abstract

This paper empirically analyzes the socioeconomic energy metabolism of Austria in the period 1830–1995. During this period Austria underwent a transition from being a largely agricultural society to being an industrial society. We describe the changes associated with this transition in terms of the 'physical economy,' or more precisely, in terms of changes in the throughput of energy, assessed in physical units (J per year). In accordance with currently used methods of material flow accounting (MFA), we define the indicators 'direct input' and 'domestic consumption' with respect to socioeconomic energy flows. Using these indicators, we analyze the transition from 1830, at which time biomass provided more than 99% of Austria's domestic energy consumption (DEC), to 1995, when biomass accounted for 30% and fossil energy for 60% of DEC. Total DEC in Austria increased by a factor of 6 in this period. The paper discusses the relevance of these changes for processes of interaction between society and its natural environment, focusing on the interrelations between energy metabolism and changes in land use.

Keywords: Socioeconomic metabolism; Energy flow accounting (EFA); Land use and land cover change; Human appropriation of net primary production (HANPP); Biophysical indicators

1. Introduction

Conceptualizing the economy as a physical process is a central aim of the emerging interdisciplinary field of ecological economics. For example, in his seminal book *Ecological Economics* Joan Martinéz-Alier heavily criticized the 'chrematistic' orientation of the current economic mainstream and pleaded for an approach that takes the material and energetic aspects of economic processes into account (Martinez-Alier, 1987). A predominant approach to analyzing the physical economy is the concept of 'socioeconomic metabolism' (more narrowly termed 'industrial metabolism'; Ayres and Simonis, 1994). The basic idea of socioeconomic metabolism can be traced back to Marx; today, the metabolism concept is a cornerstone of research into the 'human

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dimensions' of environmental change (for reviews, see Fischer-Kowalski, 1998; Fischer-Kowalski and Hüttler, 1998). Prominent economists, including Kenneth Boulding and Robert Ayres, re-invented the concept in the late 1960s and early 1970s and elaborated the first empirical analyses of the material flows of a national economy (Ayres and Kneese, 1969; Boulding, 1973). Today, international standards for national material flow accounting (MFA) are being developed (e.g. Adriaanse et al., 1997; Bringezu et al., 1997; Matthews et al., 2000, Eurostat, 2001).

Analyses of socioeconomic energy flows figure prominently in the work leading up to today's metabolism research (Martinez-Alier, 1987). In contrast, material flows build the focus of current metabolism studies. This may be due to the fact that socioeconomic energy flows are commonly reported in energy statistics, so that the need for research has seemed less urgent in this field. However, the energy statistics published by national statistical offices (e.g. Bittermann, 1999) or international bodies (IEA, 1992, 1995; UN, 1997) cover only the energy used in 'technical' energy conversions—that is, the production of heat, power and light in technical processes (e.g. internal combustion machines, furnaces, electric devices). Neither the uptake of nutritional energy by humans and domesticated animals, nor the production of energy by their muscular activity are accounted for in energy statistics (Haberl, 1997a). In other words, biomass is accounted for in energy statistics only if it is used as fuel for heat or electricity production.

The shortcomings of such an approach become evident in analyses of agricultural societies, which rely strongly on muscular energy for the provision of mechanical energy, with the noteworthy exceptions of the use of windmills, water-mills and sailboats (Smil, 1992, 1994). Human ecologists, ecological anthropologists and the economists whom Martinez-Alier (1987) describes as the forerunners of modern ecological-economical thought have been using such a broader notion of socioeconomic energy flows for a long time (e.g. Boyden, 1992; Giampietro and Pimentel, 1991; Giampietro et al., 1992; Giampietro and Pimentel, 1990; Kemp, 1971; Odum, 1971; Pimentel et al., 1973). In analyzing the energy system's transition in the course of industrialization, it must then be seen as insufficient to restrict the analysis to heat and power production (e.g. Fouquet and Pearson, 1998). However well researched such analyses may be, their narrow focus covers up rather than clarifies the relevant transition processes at hand.

Therefore, we will first propose a method to account for the energetic metabolism of societies, and in a second step we will use this method for an appraisal of energy flows in the Austrian economy during the last 170 years. This empirical analysis will form the basis for a discussion of shifts in sustainability problems during the transition from a largely agricultural economy to the still quickly industrializing Austrian economy of today.

In this discussion, we are guided by the following questions: how did socioeconomic energy metabolism and the significance of biomass in the socioeconomic energy system change during this transition process? What can we learn from the historical process for future development? We address these questions based upon empirical evidence and an analysis of important aspects of the development of the socioeconomic energy metabolism. We will present a quantitative analysis of the socioeconomic energy metabolism of Austria (in its current boundaries) in a time series from 1830 to 1998, and relate these results to figures for the development of domestic energy consumption (DEC) in Austria. In addition, we will use these figures to discuss the significance of the changes in Austria's energy metabolism for society-environment interrelations—especially with respect to land use—during industrialization.

2. Concepts and methods

2.1. The concept of socioeconomic metabolism

In analogy to the biological notion of metabolism, the concept of socioeconomic metabolism describes physical exchange processes (i.e. material and energy flows) between human societies and their natural environment as well as internal material and energy flows of human societies (Ayres and Simonis, 1994; Fischer-Kowalski, 1998). In the metabolism approach, socioeconomic systems are conceived of as systems depending upon a continuous throughput of material and energy. Socioeconomic systems extract raw materials from their natural environment and subsequently transform these materials as part of the economic process. Materials are accumulated for certain periods of time (forming material stocks) or they are more or less readily released into ecosystems as wastes and emissions. The analysis of society-nature relations with the concept of socioeconomic metabolism, therefore, allows us to address two types of environmental (or sustainability) problems: (a) problems occurring on the input side of the socioeconomic system—for example, scarcity of resources; and (b) problems occurring on the output side—for example, problems related to pollution or emissions.

Currently, international standards to be used in accounting for socioeconomic metabolism are being developed (Eurostat, 2001; Matthews et al., 2000). The methodology of 'MFA' has proven to be useful in providing suitable biophysical headline indicators.[1] In recent years, the concept and methodology of MFA have, in fact, increasingly been adopted by national statistical offices to generate biophysical headline indicators (Gerhold and Petrovic, 2000; Steurer, 1998a,b). Furthermore, the concept provides a research agenda that can be tackled in interdisciplinary projects. While social scientists can study socioeconomic patterns of material and energy flows, natural scientists can analyze, for example, the consequences of these flows for natural processes (Schandl and Schulz, 2000).

[1] The necessity of grounding ecological-economical analyses of sustainability problems on biophysical assessment and the necessity of having suitable biophysical headline indicators have both been stated many times, for instance, in a series of contributions to an *Ecological Economics Forum* entitled 'Why sustainability analysis must include biophysical assessments' (Wackernagel, 1999), and most recently by Charles Hall and others in *BioScience* (Hall et al., 2001).

2.2. Socioeconomic energy metabolism

Material 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. We will use an accounting concept for the energetic metabolism of societies that might be called 'energy flow accounting' (EFA). This concept was developed by one of the authors and is described in more detail elsewhere (Haberl, 1997a, 2001, 2002). The basic idea of EFA is to establish an account of socioeconomic energy flows that uses the same basic concepts and system boundaries as MFA, with energy instead of matter as the unit of analysis. That is, EFA uses current MFA concepts (e.g. Matthews et al., 2000) to obtain measures of the total energy throughput of society in order to provide biophysical headline indicators for the investigation into the development of society-nature interactions that are complementary to the indicators derived from MFA. Additionally, EFA employs, as far as possible, existing notions and methods of conventional energy balances (abbreviated as CEBs; for more on methodological details of CEBs, see Bittermann, 1999; IEA, 1995; IFIAS, 1974; UN, 1997) in order to trace the flow of energy through an economy and obtain indicators for the amount of energy a society is able to harness for its purposes.

2.3. The EFA method we use relies on the following basic concepts:

- In calculating the energy input of a society, all energy-rich materials and immaterial energy flows (e.g. electricity, light) 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 (contrary to CEBs, which use net calorific values to convert tons of fuel to energy values). We do not use 'quality

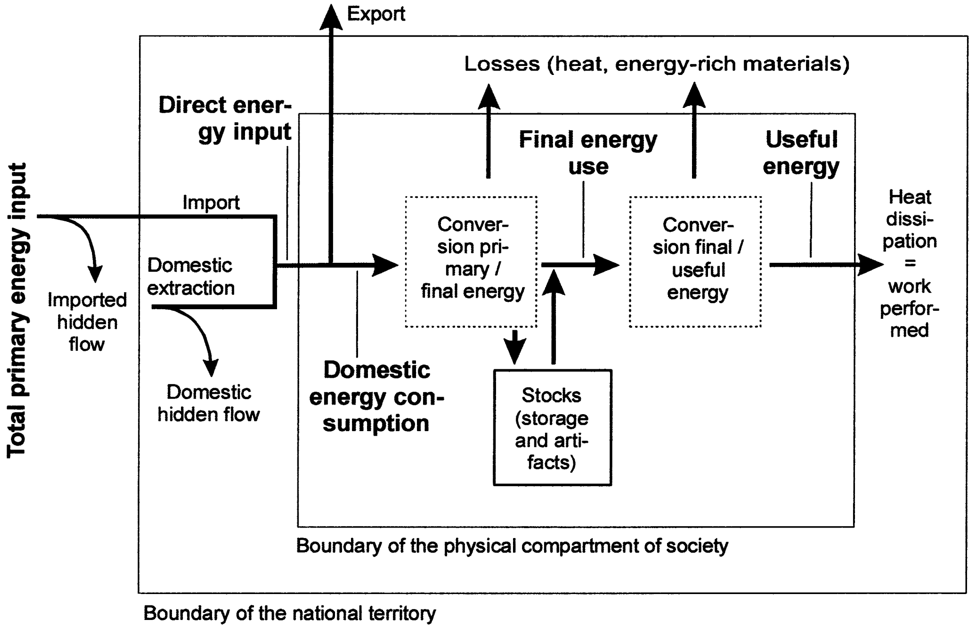

Fig. 1. Summary of the accounting concept for society's energetic metabolism used in this paper. Source: adapted from Haberl 2001a.

factors' to reflect differences in economic value between different kinds of fuel (e.g. Cleveland et al., 1984, 1998) or concepts such as exergy that consider differences between energy sources in their ability to do work (see Ayres, 2001; Fraser and Kay, 2001; Hall et al., 1986). Moreover, we do not account for 'embodied' energy (Odum, 1996).[2]

- The nutrition of humans and domesticated animals is regarded as an energy conversion process within society and is explicitly accounted for. The food input of humans and working animals is defined as final energy, whereas the food input of all domesticated animals that are used to produce human food 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'.

We describe two main aspects of the 'energetic metabolism' of the socioeconomic system in Austria: energy input and socioeconomic energy use ('useful energy analysis'). To characterize energy input (Fig. 1) we empirically calculate direct energy input (DEI) and DEC. DEI is defined as domestic energy extraction plus imports. DEC is defined as DEI minus exports. Note that imports and exports should in principle also include the calorific value of all imported materials and products. Due to data restrictions, we were able to include only those material flows that are most important from an energetic point of view; that is, for example, food, feedstuffs, and paper. Whereas it would also be interesting to calculate the total primary energy input (see Fig. 1), this has not been feasible due to the great amount of data it would require to assess hidden flows—i.e. the energy that is mobilized but does not cross the boundary of the socioeconomic system.

[2] Using quality factors or accounting for embodied energy would be a valuable next step in the analysis of socioeconomic metabolism over long periods of time. What we are mainly aiming at is a basic accounting framework that can also be useful in deriving such indicators. This, however, must be left to future research.

Final energy is usually defined in CEBs as the energy sold to final consumers; that is, all economic actors who use the energy to produce energy services (and not to convert it into another form of energy—as is the case in electricity production). Energy services are immaterial services for the procurement of which the energy is actually used. Examples are the transportation of a person or a good from A to B or the provision of air-conditioned rooms or a well-lighted workplace, etc. (Lovins, 1977). Useful energy can be defined as the energy equivalent of the work actually performed in the process of providing energy services. Examples are the amount of heat released by a heating system into a room to be kept at a desired temperature, the drivepower actually applied to accelerate a vehicle, the light emitted by a lamp, etc. Useful energy can be calculated from data on final energy use by multiplying the amount of final energy used for a certain appliance or process by the efficiency of this process. For example, if a heating system releases 80% of the energy equivalent of the fuel into the rooms to be heated and dissipates 20% with the flue gas, useful energy delivered is 80% of the fuel put into this heating system. Since energy services can, by definition, not be measured in energy units but have to be defined using a variety of different parameters, we were not able to develop a sensible measure to quantify them in such a long time series. Therefore, we will focus on useful energy in order to have some indication for the utility society is able to derive from using energy.

2.4. Human appropriation of net primary production

To relate socioeconomic energy flows to ecosystem processes and to assess their impact on ecological energy flows we use a concept originally developed by Peter Vitousek and others which has been called 'human appropriation of net primary production (NPP)' and is often abbreviated as HANPP (Haberl, 1997b; Krausmann, 2001a; Martinez-Alier, 1998; Vitousek et al., 1986; Wright, 1990). This notion refers to the observation that humans alter ecological energy flows by using the land. Agriculture and forestry, for example, harness biomass energy for socioeconomic purposes and thereby reduce the amount of (NPP)—i.e. they reduce the net amount of biomass energy accumulated by green plants in the process of photosynthesis over a defined period of time, usually 1 year. NPP is the amount of energy yearly available as an energy input to all heterotrophic food chains and it is, therefore, an important ecological parameter for describing ecosystems. Thus HANPP can be used to assess the effect of land use on the availability of biomass energy in ecosystems. HANPP measures essentially two processes[3]:

1. Changes in productivity induced by human land use; e.g. impacts on NPP of the conversion of natural ecosystems to agro-ecosystems or other kinds of land cover.
2. The reduction of energy availability in ecosystems caused by human harvest of biomass.

Socioeconomic energy flows are related to land use in various ways: as we will show, biomass is a significant component within the socioeconomic energy system. Furthermore, socioeconomic energy flows are important driving forces for changes in land use and in the agricultural production system. Therefore, HANPP provides a useful concept to relate socioeconomic energy flows to ecosystem processes.

2.5. The spatial reference system

The spatial reference system of the data set is the territory of modern Austria, which has existed as an administrative unit only since 1918. Before the end of World War I the territory of today's Austria was spread over several provinces of the Austro-Hungarian Empire. Five of the Austro-Hungarian Empire's provinces (*Kronländer*) were approximately identical to modern provinces (*Bundesländer*). These five provinces (counted today as six, including the city of Vienna, which is

[3] HANPP is formally defined as NPP_0-NPP_t where NPP_0 is the NPP of potential vegetation (i.e. the vegetation that would prevail in the absence of human intervention) and NPP_t the fraction of NPP remaining in ecosystems after human harvest has taken place. For conceptual issues see Haberl, 1997b.

now a separate province in administrative terms) account for almost 60% of Austrian territory today. Two other provinces, Tyrol and Styria (35% of Austrian territory today), covered a considerably larger territory before 1918.

All data we report for the time period before 1910 refer to a territory of 86 000 km^2, of which almost 95% are within Austria's borders today. 6000 km^2 of this territory are part of Italy and Slowenia today. Furthermore, the ninth modern Austrian province of Burgenland is not considered pre-1910 because it was not possible to get data for this province for the 19th century. Burgenland has a total area of 3900 km^2 (4.7% of the current Austrian territory) and was under Hungarian administration until 1918. All data for the period 1918–1995 include Burgenland and refer to today's Austrian territory of about 84 000 km^2.

2.6. Data sources

Domestic extraction of fossil energy carriers (coal, oil, natural gas) has been recorded and published on a regional level by official mining statistics since the early 19th century (e.g. K.K.Ackerbauministerium, 1874; BMWA (ed.), 1995). We used data compilations (Hain, 1852; Turetschek, 1979) in addition to the original sources. Data on hydropower generation and electricity imports and exports were taken from the statistics published by the Austrian load management administration (Bundeslastverteiler, 1995), which go back to the beginnings of electricity production in Austria. Data on the import and export of biomass and fossil energy carriers were taken from official foreign trade statistics (e.g. Bundesamt für Statistik, 1930; ÖSTAT, 1995). For the period prior to the First World War no official import–export data are available because until then the territory of modern Austria was part of the Austro-Hungarian empire.

We assume that prior to 1850 imports and exports did not play a significant role in terms of physical quantities since no efficient means for long distance transportation (mainly railroads) were available at that time. With the expansion of the railroad system in the Austro-Hungarian empire and steam navigation on the Danube during the second half of the 19th century, imports of coal increased rapidly, and in the years prior to World War I they even exceeded the values from the 1920 and 1930s. For 1910 we used published data for coal imports (KAAW, 1925; Berl, 1921) and interpolated these values for 1874, assuming that coal imports started in 1850.

Austria has a long tradition of land use surveys and agricultural statistics, with the first reliable and comparable data dating back to the late 18th century. To generate a time series of land use in Austria, various statistical sources were compiled. For the 19th century, cadastral survey data (stable cadaster/*stabiler Kataster* 1817–1835 and land tax regulation/*Grundsteuerregelung* 1869–1883) were used. These land surveys were performed with high accuracy and were combined with detailed estimations of agricultural yields (Inama-Sternegg, 1884; k.k.Finanz-Ministerium, 1858; Sandgruber, 1978a). Additionally, land-use data compiled by official agricultural statistics (mostly based on cadastral data) were used. For the 20th century, our calculations relied upon data aggregated from official Austrian agricultural statistics.

Domestic extraction of biomass was calculated according to agricultural and forestry statistics on a disaggregate level for 20 to 30 different land use categories. The cadastral survey of 1830 provides regionalized data of average yields which are considered to be quite reliable (Sandgruber, 1978a; Schneller, 1978, 1978). Beginning in 1869 the Ministry of Agriculture *(k.k. Ackerbauministerium)* published yearly estimations of the yields of all agricultural crops and meadows at a regional level. After 1918 these publications were continued by the Austrian Statistical Office. For land-use types not recorded in agricultural statistics (pastures, alpine pastures), harvested biomass had to be estimated according to specific yield values for Austria compiled by extensive literature reviews (Böhm, 1995; Brugger and Wohlfahrter, 1983; Zoepf, 1885).

The harvest of wood has been recorded at irregular intervals by official statistics since the beginning of the 20th century and published yearly since 1940. Since the official figures tend to underestimate the harvest of wood, corrected yearly data were used, compiled by two detailed studies on the supply and demand of wood in Austria (Bundesholzwirtschaftsrat, 1980; Gerhold, 1992). For data on the harvest of wood in the 19th century, we used historical estimates and calculations based on estimates of wood demand in households and industry as well as on estimates of yearly increments (Hain, 1852; Wessely, 1853; for details see Krausmann 2001b).

Unfortunately, imports and exports of biomass could not be considered for the period prior to World War I since no reliable data were available. In the 19th century the food supply of the population living on today's Austrian territory, and especially in the rapidly growing City of Vienna, was dependent to a certain degree on grain and oxen imported from other parts of the Austro-Hungarian empire, above all from Hungary. If we assume that domestic agriculture could supply only 75% of the population's food demand, this would result in a yearly biomass import of only 5–10 PJ between 1830 and 1910—compared with a domestic biomass extraction of 260–320 PJ. Furthermore, we expect exports of biomass (mostly wood) to be on the same order of magnitude. Therefore, not including biomass imports and exports for the period 1830–1910 does not pose a major problem and should not lead to serious distortion in our results of DEI and DEC (see Krausmann, 2001b).

Primary data on domestic extraction imports and exports of fossil fuels and biomass were converted to calorific values using standard tables on the gross calorific value of the materials under consideration (for details see Krausmann (2001b)). Data on electricity production from hydropower and imported electricity were converted into primary energy by assuming an efficiency (units electricity per unit primary energy) of 95%. A compilation of the primary data on domestic extraction, imports and exports for primary energy carriers on an aggregate level is given in Table 4, as well as an overview of the corresponding conversion factors (gross calorific values) (Table 5).

3. Austria's energetic metabolism 1830–1995

3.1. Overview: energy input

In Table 1, we present data on domestic extraction, import, DEI, export, and DEC for 13 years between 1830 and 1995. These years were selected largely based on data availability.

Over the whole period, DEI increased by a factor of 6.9 and DEC increased by a factor of 5.9. In 1830, biomass accounted for more than 99% of energy supply—in 1995, the contribution of biomass decreased to 36% of the direct input and 31% of the DEC. The role of fossil energy increased dramatically over the whole period: from less than 1% in 1830, it rose to 54% of the DEI and 60% of the domestic consumption. However, the dominance of fossil fuels is less impressive than one would expect from statistical data on technical energy use: according to the Austrian energy balance, fossil energy accounted for 76% of the Austrian 'total DEC' in 1995 (Bittermann, 1999). This figure is comparable to the 'DEC' calculated in Table 1, but includes only technical energy conversions.

The importance of energy imports increased dramatically over the whole period: in 1995 imports accounted for 58% of the DEI. This is considerably higher than the importance of imports for the Austrian materials throughput: imports accounted for only about 29% of the direct material input in 1995 (Amann et al., 2000). 81% of the imported energy are fossil fuels. Total DEC according to the official Austrian energy balance (Bittermann, 1999)—that is, the technical energy use in the Austrian economy measured as net calorific value—amounted to 1.136 PJ per year in 1995; that is, 27% less than the DEC calculated on the basis of the above-presented methods.

Per capita values of Austria's energy input are presented in Table 2. Austria's population rose from about 3.6 million to 8.1 million (or by a factor of 2.3) throughout the period under consideration. The increase in per capita energy throughput is significantly lower than the increase in total socioeconomic energy input. DEI increased by a factor of 3, DEC by a factor of 2.6. However, while per capita biomass use remained

Table 1
Socioeconomic energy metabolism in Austria 1830–1995—energy inputs of the Austrian socioeconomic system

		1830	1874	1910	1926	1930	1936	1950	1960	1970	1980	1986	1990	1995
Population	[Mio.]	3.6	4.7	6.6	6.6	6.7	6.8	6.9	7.1	7.5	7.6	7.6	7.8	8.1
Domestic extraction	[PJ]	263	318	305	341	366	355	469	684	748	775	752	794	754
Biomass	[PJ]	261	298	269	293	313	302	294	389	420	486	499	537	487
Fossil energy	[PJ]	1	19	34	43	46	45	156	249	248	179	133	134	121
Hydropower	[PJ]	1	1	1	5	7	8	19	45	80	110	120	123	146
Import	[PJ]	n.d	43	286	178	177	118	179	261	557	853	875	950	1061
Biomass	[PJ]	n.d	n.d	n.d	28	27	21	17	29	54	91	112	132	173
Fossil energy	[PJ]	0	43	286	150	149	97	161	230	498	750	742	794	862
Imported electricity	[PJ]	0	0	0	0	0	0	0	2	5	11	21	25	26
DEI	[PJ]	263	361	590	519	543	473	648	945	1306	1628	1627	1744	1815
Biomass	[PJ]	261	298	269	320	340	323	311	418	474	577	611	668	660
Fossil energy	[PJ]	1	62	320	193	196	142	317	479	746	929	874	928	983
Hydro/imp. electricity	[PJ]	1	1	1	5	7	8	19	47	85	122	142	148	172
Export	[PJ]	n.d	n.d	n.d	36	34	25	29	102	89	134	171	197	251
Biomass	[PJ]	n.d	n.d	n.d	30	31	23	23	44	57	98	119	154	174
Fossil energy	[PJ]	0	n.d	n.d	6	2	0	3	49	8	10	25	16	41
Electricity	[PJ]	0	0	0	0	0	1	3	9	24	26	27	26	35
Domestic consumption	[PJ]	263	361	590	483	509	448	619	842	1216	1493	1455	1547	1564
Biomass	[PJ]	261	298	269	291	309	299	288	374	418	479	491	514	486
Fossil energy	[PJ]	1	62	320	187	193	142	314	430	737	918	849	912	942
Hydro/imp. electricity	[PJ]	1	1	1	5	6	7	16	38	61	96	115	121	137

n.d., no data.

Table 2
Per capita socioeconomic energy metabolism in Austria 1830–1995—per capita energy inputs of the Austrian socioeconomic system

		1830	1874	1910	1926	1930	1936	1950	1960	1970	1980	1986	1990	1995
Population	[Mio]	3.6	4.7	6.6	6.6	6.7	6.8	6.9	7.1	7.5	7.6	7.6	7.8	8.1
Domestic extraction	[GJ/cap]	73.1	68.2	46.0	51.5	54.6	52.6	67.6	96.5	99.8	102.4	98.9	101.6	93.5
Biomass	[GJ/cap]	72.7	63.8	40.7	44.2	46.7	44.7	42.4	55.0	56.0	64.2	65.7	68.7	60.4
Fossil energy	[GJ/cap]	0.2	4.2	5.2	6.5	6.9	6.7	22.5	35.2	33.1	23.6	17.4	17.2	15.0
Hydropower	[GJ/cap]	0.3	0.2	0.1	0.8	1.0	1.2	2.7	6.4	10.7	14.6	15.8	15.8	18.1
Import	[GJ/cap]	n.d.	9.2	43.2	26.9	26.4	17.4	25.8	36.9	74.3	112.7	115.2	121.6	131.7
Biomass	[GJ/cap]	n.d.	n.d.	n.d.	4.2	4.1	3.1	2.5	4.0	7.2	12.1	14.7	16.8	21.5
Fossil energy	[GJ/cap]	0	9.2	43.2	22.7	22.3	14.3	23.2	32.5	66.4	99.1	97.6	101.6	106.9
Imported electricity	[GJ/cap]	0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.7	1.5	2.8	3.2	3.3
DEI	[GJ/cap]	73.1	77.3	89.2	78.3	80.9	70.0	93.4	133.3	174.1	215.0	214.1	223.3	225.2
Biomass	[GJ/cap]	72.7	63.8	40.7	48.4	50.8	47.8	44.9	59.0	63.2	76.3	80.4	85.5	81.9
Fossil energy	[GJ/cap]	0.2	13.3	48.4	29.1	29.2	21.0	45.8	67.6	99.4	122.7	115.1	118.8	121.9
Hydro / imp. electricity	[GJ/cap]	0.3	0.2	0.1	0.8	1.0	1.2	2.7	6.7	11.4	16.1	18.6	18.9	21.3
Export	[GJ/cap]	n.d.	n.d.	n.d.	5.4	5.0	3.7	4.2	14.4	11.9	17.7	22.5	25.2	31.1
Biomass	[GJ/cap]	n.d.	n.d.	n.d.	4.5	4.6	3.5	3.4	6.2	7.6	13.0	15.7	19.8	21.6
Fossil energy	[GJ/cap]	0	n.d.	n.d.	0.9	0.3	0.0	0.4	7.0	1.1	1.4	3.3	2.1	5.1
Electricity	[GJ/cap]	0	0	0	0.0	0.1	0.2	0.4	1.3	3.3	3.4	3.5	3.4	4.4
Domestic consumption	[GJ/cap]	73.1	77.3	89.2	72.9	75.9	66.3	89.2	118.9	162.1	197.3	191.5	198.0	194.1
Biomass	[GJ/cap]	72.7	63.8	40.7	43.9	46.1	44.3	41.5	52.8	55.7	63.3	64.7	65.8	60.3
Fossil energy	[GJ/cap]	0.2	13.3	48.4	28.3	28.8	21.0	45.3	60.7	98.3	121.3	111.8	116.7	116.9
Hydro / imp. electricity	[GJ/cap]	0.3	0.2	0.1	0.8	0.9	1.0	2.4	5.4	8.1	12.7	15.1	15.5	17.0

n.d., no data.

in the same order of magnitude over the whole period (DEI: 40.7–85.5 GJ per capita year, DEC 40.7–72.7 GJ per capita year), the overall increase in energy metabolism was made possible by a surge in fossil energy and hydropower use. Interestingly, per capita biomass energy consumption decreased from 1830 to 1910 by more than 40%, and in 1995 reached a level similar to that of 1830. That is, most of the increase in total biomass use seems to be related to population growth, but the increase in overall energy use resulted from changes in the energy system during the transition from agricultural to industrial society. Most of this increase was covered by fossil fuels. Hydropower supplied about 10% of the DEI in 1995.

Fig. 2 graphically displays the total (Fig. 2a) and per capita (Fig. 2b) DEC of Austria 1830–1995. This figure shows that DEC starts to in-

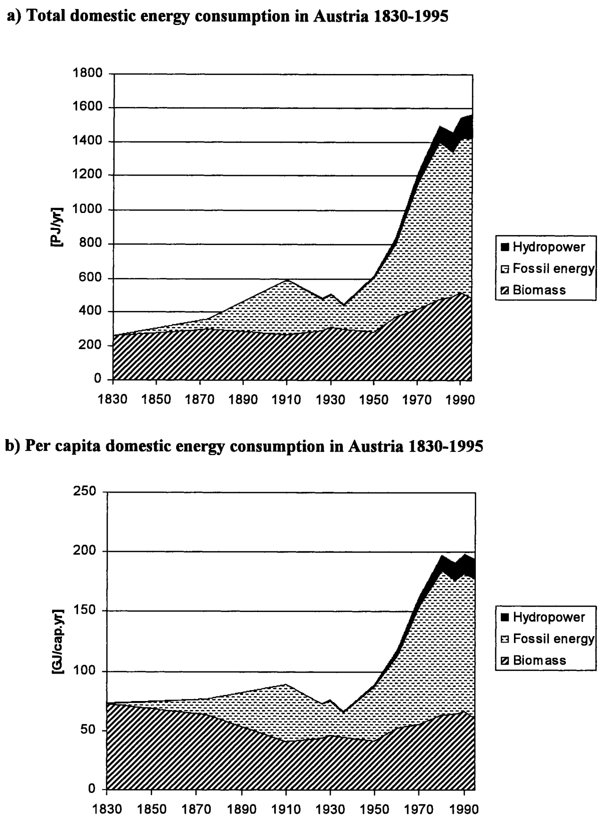

Fig. 2. Total DEC and per capita DEC in Austria 1830–1995.

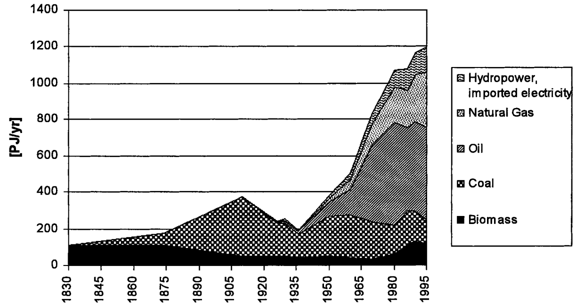

Fig. 3. 'Technical' DEC in Austria 1830-1995. By 'technical' DEC we mean energy use as assessed in CEBs, including only the biomass used for combustion. Figures are gross calorific values.

crease significantly in the second half of the 19th century and reaches a peak before World War I. After the war the newly formed Republic of Austria was cut off from the former Monarchy's large coal districts and domestic fossil energy consumption does not reach the level of the pre-war period again until the 1950s.[4] The figure shows that the increase in total DEC equals population growth between 1830 and 1950, since per capita DEC only slightly increases during the 19th century. Even if the DEC was probably lower during and shortly after the two World Wars (1914–1918 and 1939–1945, respectively), this constancy is a remarkable result: it suggests that in the beginning,

[4] During the 19th century Austria—i.e. the territory described by modern Austria—developed into one of the industrial centers of the Austro-Hungarian Empire, with a concentration of energy-intensive iron industry. Austria was and still is very rich in woodlands, and until the 1850/1870s the energy supply needs of these industries were met to a high degree by wood and charcoal. Only with the expansion of the railroad system was coal rapidly substituted for biomass. Before World War I a large proportion of this coal was provided by the large coal regions of the Austro-Hungarian empire outside Austria's current borders (e.g. from the region of Bohemia in today's Czech Republic). After the war the new Republic of Austria faced an oversized and damaged heavy industry complex and a severe energy crisis, since domestic coal resources were limited. Consequently, (1) a restructuring of the industrial complex with a reduction of the energy-intensive iron industry, (2) significant increases in the energy efficiency of industrial technology, and (3) the economic crisis of the 1930s, worked together to result in low values of DEC between 1918 and 1938—compared with the peak in 1910 (Sandgruber, 1978b; Bachinger and Matis, 1974; Berl 1921).

industrialization supported more people with less biomass and a slowly increasing overall amount of energy per capita. Throughout this period, per capita biomass use declines and fossil energy appears to be substituted for biomass. After 1950, per capita energy input increases quickly until about 1980 and remains more or less stable afterwards. Since the increase in population in this period from 1950 to 1995 was only about 17%, almost all of this surge in energy consumption must be attributed to structural changes in society and the economy.

3.2. 'Technical energy': hydropower and fossil energy

Fig. 3 presents a time series of the 'technical' DEC in Austria of 1830, broken down into the categories 'biomass', 'coal', 'oil', 'natural gas', and 'hydropower plus net imported electricity'. These data would be largely identical to a time series of total energy input according to a CEB, with the exception that we use gross calorific values whereas CEBs are calculated on the basis of net calorific values of all materials.

'Technical' DEC rose by a factor of 10.6 from 1830 to 1995. That is, the increase in 'technical' energy use was considerably higher than that of total DEC (which rose by a factor of 5.9). In 1830 hydropower and fossil energy each provided about 1% of technical DEC; the remaining 98% were covered by firewood. In 1995, nearly 80% of the technical DEC were supplied by fossil energy carriers, the remainder by hydropower (plus the import/export balance of electricity) and biomass[5].

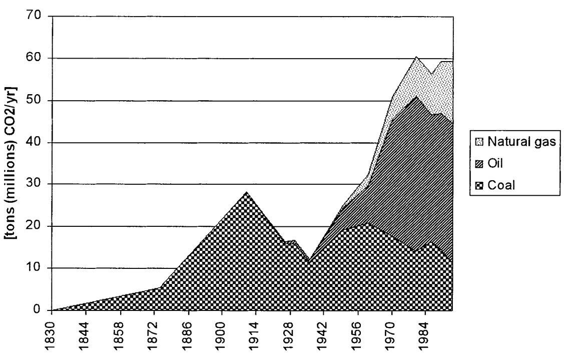

Fig. 4. Fossil-energy related CO_2 emissions in Austria 1830–1995 (excludes CO_2 emissions from industrial processes, biomass combustion, and waste incineration plants).

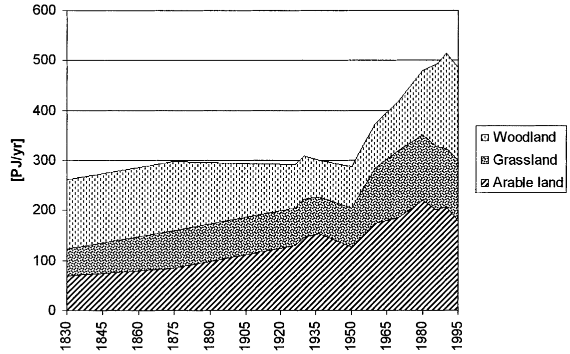

Fig. 5. Biomass DEC in Austria 1830–1995 broken down to the main land-cover classes from which the biomass is derived.

3.3. Fossil-energy-related CO_2 emissions

In Fig. 4, we used the data reported in Table 1 to calculate fossil-energy-related CO_2 emissions in Austria between 1830 and 1995, using emission factors from the Austrian Federal Ministry of

[5] The data for biomass use are, unfortunately, rather unreliable. For 1830 and 1874 we estimated firewood consumption according to calculations from Wessely (1853) and other regional historical studies. For 1926–1960 we used figures from the Austrian timber balances (e.g. Bundesholzwirtschaftsrat, 1980; Gerhold 1992). For 1970–1995 we used firewood data derived from timber balances and estimates for other biomass energy (biogas, biomass-derived wastes, wood chips, etc.) from the official Austrian energy balances (Bittermann, 1999; Bittermann, pers.comm.). These sources probably underestimate the use of biomass for combustion for the period 1926–1970 because in this period the use of wood for combustion was not an important issue in energy policy (and was, therefore, also underrepresented in energy statistics). After the first oil price increase in 1973, the use of wood was promoted as a 'domestic and renewable' energy carrier in order to reduce Austria's dependence on oil imports from abroad; however, this probably led not only to increased use of biomass for energy provision, but also to better statistical coverage. Therefore, the increase in biomass use for technical energy generation after 1970 is probably overestimated. The underestimation of firewood should not lead to a serious distortion of the overall trend of increasing substitution of fossil energy for biomass, but we assume the decrease in firewood consumption as shown in Fig. 3 to be too steep.

Economic Affairs (BMwA, 1990). Prior to World War II, nearly all CO_2 emissions are caused by the combustion of coal. The surge in CO_2 emissions after 1950 is caused mainly by the use of oil and, later on, natural gas. CO_2 emissions rise steeply until 1980 and remain almost constant afterwards at a level of 60 million tons per year. Note that these data do not include CO_2 emissions from industrial processes such as cement production, and that they do not include any carbon sources or sinks related to land-use changes.

3.4. Biomass

Fig. 5 analyzes the DEC of biomass in Austria 1830–1995, broken down to the main land-cover categories from which biomass is harvested; that is, arable land, grassland, and woodland (forests). Biomass DEC grows slowly from 1830–1874 and is nearly constant afterwards until 1950. From 1950 to 1995, biomass DEC increases by 69%. Biomass DEC from arable land increases by a factor of 2.62 from 1830 to 1995, grassland-derived biomass by a factor of 2.2, and forest biomass by a factor of 1.35. While forest biomass accounted for more than half of total biomass DEC in 1830, this dropped below 30% in the early 20th century. After 1973, when wood use was promoted as a renewable and domestic energy carrier, the proportion of forest biomass to total biomass DEC increased again and was 38% in 1995.[6]

Both imports and exports of biomass grow considerably over the whole period, but the balance of imports and exports is small in energetic terms, compared with DEC or Domestic Extraction. In general, in the early 20th century (as well as during the 19th century, as noted before) Austria imports biomass products derived from arable land and exports a similar amount of biomass energy from forests. After 1970, Austria's imports and exports of products from arable land nearly equal one another (almost no net imports in energetic terms), and Austria still tends to export slightly more forest products than it imports. In 1995, total import and export flows of biomass energy are both about one-third of domestic biomass energy extraction, but the balance of imports and exports is close to zero. Changes in land use associated with the changes in biomass energy flows are discussed below.

[6] For the reasons discussed in Footnote 5, the increase in wood consumption between 1970 and 1980 was probably overestimated in Fig. 4.

3.5. A tentative useful energy analysis for 1830 and 1995

Whereas the previous sections have described the energy input of Austria from 1830 to 1995 in some detail, we analyze in this section the amount of useful energy that could be derived from that energy input. Even modern useful energy analyses, based upon statistical surveys and random sampling surveys, give only rough estimates; therefore, we have to stress that the calculations, we describe below can serve to illustrate only orders of magnitude of the processes. We estimate the following margins of error: final energy 1830, +50/−30%; final energy 1995, +/−10%; useful energy 1830, +100/−50%; useful energy 1995, +/−20%. Nevertheless, even if we assume such margins of error, differences between 1830 and 1995 are large enough to allow a meaningful discussion of the changes in energy availability during industrialization (Table 3).

In order to estimate the food intake of humans in 1830, we assume a value of 10 MJ per capita day (3.65 GJ per capita year), based upon the literature (Ensminger et al., 1994; Freudenberger, 1998; Smil, 2000). A multiplication of this figure with the 1830 Austrian population results in an estimate of human food consumption of 13.1 PJ per year. This figure fits well with our calculation of the production of primary plant products (15.5 PJ per year) and animal products (4.1 PJ per year) for human consumption because we have to assume that about one-third of primary produce for human consumption is lost during food preparation (losses in corn mills, stapling losses, inedible parts of animals, processing losses, etc.). Human

Table 3
A tentative useful energy analysis for Austria 1830 and 1995

	Austria total [PJ]		Per capita [GJ per capita year]	
	1830	1995	1830	1995
Final energy consumption				
Human nutrition	13.1	37.0	3.65	4.59
Nutrition of working animals	30.8	0.0	8.57	0.00
Final energy for vehicle motors (Total final energy for traction and transport)	0.0	245.4	0.00	30.45
	(30.8)	(245.4)	(8.57)	(30.45)
Final energy for stationary mechanical appliances	0.9	89.8	0.25	11.14
Industrial process heat	47.6	211.1	13.25	26.19
Space and water heating	70.4	374.7	19.59	46.49
Light and data processing	n.d.	27.0	0.00	3.35
Total	162.7	984.9	45.30	122.20
Useful energy production				
Human work	1.2	0.3	0.39	0.04
Animal work (mostly draft energy)	1.1	0.0	0.29	0.00
Useful energy delivered by vehicle motors (Total useful energy traction and transport)	0.0	34.8	0.00	4.32
	(1.1)	(34.8)	(0.29)	(4.32)
Stationary mechanical work	0.4	69.0	0.12	8.56
Useful industrial process heat energy	11.0	147.0	3.05	18.24
Useful energy for space/water heating	17.6	252.0	4.90	31.27
Light	n.d.	1.0	0.00	0.12
Total	31.5	504.1	8.76	62.55

n.d., no data. Sources and calculation discussed in the text.

food consumption in 1995 is based upon an estimate of 12.6 MJ per capita day (3000 kcal per capita day, 4.6 GJ per capita year), derived from statistical data (e.g. Elmadfa and Godina-Zarfl, 1994; Elmadfa, 1998). Work energy output (mechanical energy) for 1830 is based on the assumption that 63% of the population work 2900 h per year with an average power delivery of 50 W (Smil 1992). Human work output for 1995 is based upon statistical data of hours worked in the Austrian economy (ÖSTAT, 1998) and the assumption that the average power delivery is half of that in 1830 because machine power has been substituted for most heavy physical work. The results reported in Table 3 show that human work output was 9% of food energy input in 1830, but less than 1% in 1995. Since about 20–30% of humans' food intake can potentially be converted to work (Stout, 1990), the work load in 1830 must have been near the physiologically tolerable maximum for a large proportion of the total population. In 1995 a much smaller proportion of the total population was performing physical work than in 1830.[7]

Our estimate of draft animals' feedstuff consumption is based on statistical livestock data from 1830. Based on an estimate of the body weight of these animals in 1830 and an estimate of their species-specific dry-matter feedstuff consumption, we calculate the feedstuff consumption of working animals as 30.8 PJ per year.[8] Work

[7] Note that in the context of a biophysical analysis human work is reduced to energy output. Therefore the proposed methodology does not allow us to analyze a shift from physical work to 'thinking power'.

[8] We made the following assumptions according to literature reviews (for details see Krausmann 2001b): 90% of all horses, 80% of all oxen and 20% of all cows are used as working animals. Since cows are mainly used for milk and meat production, we regard only one-third of their feedstuff uptake as an energy input to this compartment. Live weight of draft animals: horses 460 kg, oxen 390 kg, cows 270 kg. Animal-specific dry matter consumption: cows: 8 kg dry matter [DM] per year for 1 kg body weight; oxen: 7.7 kg DM per year for 1 kg body weight; horses: 6.6 kg DM per year for 1 kg body weight; (Hitschmann and Hitschmann, 1906).

Table 4
Aggregated primary data on domestic extraction, import and export of primary energy carriers (fossil fuels, biomass and hydropower/electricity)

		1830	1874	1910	1926	1930	1936	1950	1960	1970	1980	1986	1990	1995
Domestic extraction														
Brown coal	[1000 t]	33	1400	2484	2958	3063	2897	4308	5973	3670	2865	2969	2448	1249
Hard coal	[1000 t]	8	42	74	157	216	244	183	132	0	0	0	0	0
Oil	[1000 t]	0	0	0	0	0	7	1703	2448	2798	1475	1117	1149	1035
Gas	[10^6 m^3]	0	0	0	0	0	1	470	1469	1897	1903	1112	1288	1482
Biomass (arable land)	[1000 t DM]	3761	4696	5244	5953	7037	7524	6195	8719	9447	11 520	11 180	11 442	9390
Biomass (grassland)	[1000 t DM]	3068	4132	4020	4145	4095	4117	4406	6123	7527	7423	7091	6601	6796
Biomass (woodland)	[1000 t DM]	7077	6856	5263	5681	5812	4742	5336	6344	5915	7444	8684	10 816	9923
Hydropower	[GWh]	250	250	250	1463	1842	2297	5238	12 507	22 358	30 621	33 347	34 202	40 502
Import														
Brown coal	[1000 t]	n.d.	812	5418	556	444	175	412	475	553	496	695	572	326
Hard coal	[1000 t]	n.d.	1108	7392	4648	4452	2787	5267	5077	5067	3978	4818	4398	3678
Oil	[1000 t]	0	0	n.d.	169	315	296	58	1705	6801	11 278	9635	10 111	11 152
Gas	[10^6 m^3]	0	0	0	0	0	0	0	3	992	3122	4089	5219	6361
Vegetable biomass	[1000 t FW]	n.d.	n.d.	n.d.	1617	1669	1313	1011	1600	1565	2109	2326	2754	3485
Animal biomass	[1000 t FW]	n.d.	n.d.	n.d.	308	235	126	30	67	71	92	91	121	178
Wood (-products)	[1000 t FW]	n.d.	n.d.	n.d.	187	151	96	81	419	1943	4407	5591	6519	8575
Hydropower	[GWh]	0	0	0	0	0	2	29	641	1371	3164	5962	6839	7287
Export														
Brown coal	[1000 t]	n.d.	n.d.	0	50	6	1	19	27	20	19	8	0	0
Hard coal	[1000 t]	n.d.	n.d.	0	160	48	0	1	2	1	2	3	0	0
Oil	[1000 t]	0	0	n.d.	14	18	3	58	1083	177	210	553	367	905
Gas	[10^6 m^3]	0	0	0	0	0	0	0	13	5	18	8	0	15
Vegetable biomass	[1000 t FW]	n.d.	n.d.	n.d.	384	389	224	85	430	793	1425	2499	2981	3360
Animal biomass	[1000 t FW]	n.d.	n.d.	n.d.	24	43	7	8	96	124	194	277	250	470
Wood (-products)	[1000 t FW]	n.d.	n.d.	n.d.	1902	2014	1515	1593	2800	3193	5380	5492	7552	8587
Hydropower	[GWh]	0	0	0	30	120	341	720	2544	6785	7136	7426	7298	9757

For data sources see text, section *data sources*. .n.d., no data; DM, dry matter; FW, fresh weight (i.e. weight given in statistical source); t, tons; m^3, cubic meter; GWh, Gigawatthours; MJ, Megajoules (10^6 J); TJ, Teraloules (10^{12} J).

Table 5
Number of items aggregated to each category of aggregated primary data as presented in Table 4 and corresponding gross calorific values (range of all items within each category and range of yearly averages for each category of primary data as presented in Table 4

	Number of items aggregated	Gross calorific value: range of aggregated items	Gross calorific value: yearly averages of categories
Domestic extraction			
Brown coal	1	13.0 MJ/kg	
Hard coal	1	29.1 MJ/kg	
Oil	1	44.7 MJ/kg	
Gas	1	39.6 MJ/kg	
Biomass (arable land)	15–20	17.9–18.3 MJ/kg DM	17.9–18.3 MJ/kg
Biomass (grassland)	3–8	17.9 MJ/kg DM	
Biomass (woodland)	1	19.5 MJ/kg DM	
Hydropower	1	3.6 TJ/GWh	
Imports and exports			
Brown coal	3	13.0–21.2 MJ/kg	13.0–21.1 MJ/kg
Hard coal	2	29.1–31.4MJ/kg	29.3–31.4 MJ/kg
Oil	17	42.5–45.2 MJ/kg	42.5–44.2 MJ/kg
Gas	1	39.6 MJ/kg	
Vegetable biomass	42	1.5–38.0 MJ/kg	5.6–16.3 MJ/kg
Animal biomass	6	3.0–32.0 MJ/kg	7.4–13.7 MJ/kg
Wood (-products)	7	13.5–18.0 MJ/kg	14.1–16 MJ/kg
Hydropower	1	3.6 TJ/GWh	

For sources see text, section *data sources*.

output of draft animals in 1830 is based upon estimates of the number of work days per year and specific values of power delivery per animal.[9] For 1995, we assume that the amount of work performed by domesticated animals was negligible. Work output of draft animals in 1830 was about 4% of their feedstuff input. Since most of the work of draft animals was used for traction (plowing) and transport, it is probably useful to compare their food input and work output to the consumption and output of vehicle motors for a comparison of 1830 and 1995. Our estimate of the energy input of motor vehicles (cars, trucks, tractors, airplanes, trains and other means of public transport) is based upon data from the Austrian energy flow diagram published by the Austrian Energy Agency (E.V.A., 1997); in calculating the useful energy output estimate we assumed an average efficiency of 15%.[10] The results reported in Table 3 show that per capita useful energy provision (figures in brackets) was more than 10

[9] Assumptions about the number of work days: horses and oxen 250 days per year, cows 150 days per year; estimated according to Hitschmann and Hitschmann 1906. Power delivery: horses 500 W, oxen 250 W, cows 150 W; sources: Smil, 1992, 1994).

[10] The official Austrian energy balance assumes an efficiency of about 30%, but vehicle motors can work at this efficiency only under optimal conditions. Our assumption reflects changing load conditions and losses during vehicle standstills.

times higher in 1995 than it was in 1830, although final energy input grew by a factor of only about 3.6, reflecting the higher average efficiency of internal combustion machines. This is mainly due to the fact that machines need no energy when they are not being used, and it is also an indication of the high cost in energetic terms of animal work in 1830.

Our estimate of the final and useful energy of 'stationary mechanical appliances' in 1830 includes water-mills, both for milling grain (flour mills) and for industrial purposes. In 1830 there were about 11 500 flour mills in Austria. Since no better data was available, we assumed that the number of other mills equaled that of flour mills. In order to calculate final energy input and useful energy output of mills, we assumed an average power output (3.7 kW/unit) and efficiency (50%)—both based upon data from Smil (1992)—and the number of working hours per year (2800 h per year). We cross-checked our results for flour mills as obtained by this calculation with an estimate of the energy needed to grind the amount of grain used in Austria and arrived at reasonably similar figures. Final energy input and useful energy output of stationary motors in 1995 were taken from the energy flow diagram published by the Austrian Energy Agency (E.V.A., 1997). The results reported in Table 3 show an increase in the per capita availability of mechanical energy by a factor of about 70, giving some indication of the extent to which the availability of efficient means for the technical provision of drivepower has increased the demand for mechanical energy.

Our estimate of the final energy used in 1830 for industrial process heat as well as space and water heating is based upon data on fuel wood consumption, charcoal production, and consumption and industrial coal consumption. In order to estimate the useful energy provided, we assumed values for efficiencies[11] based upon data from the literature. Final energy for industrial process heat increased about fourfold for Austria as a whole and twofold per capita. Useful energy increased by a factor of about 13 for Austria as a whole and 6 per capita. Final energy for space and water heating per capita more than doubled, and useful energy for space and water heating per capita increased more than six-fold.

Total per capita final energy consumption rose by a factor of 2.7, total per capita useful energy provision increased by a factor of 7. This again shows the increase in the efficiency with which final energy is converted into useful energy: in 1830, useful energy provision was 19% of final energy consumption, whereas in 1995 the corresponding figure was 51%. This increase in efficiency was caused by increases in the efficiency of technologies (e.g. more efficient machinery), the substitution of machine power for human- and animal-derived power, both of which are energetically inefficient due to the energy consumed during non-work-periods, and the increased quality of available fuels (e.g. natural gas and oil can be used more efficiently than coal or biomass). On the other hand, our analysis shows that gains in the efficiency of energy conversion were by far outweighed by the increased consumption of useful energy caused by the utilization of new appliances that became available during the industrialization process, suggesting that increases in efficiency alone are unlikely to lead to sustainable development because efficiency gains often lead to increased consumption of the services produced at lower cost (e.g. Haberl and Krausmann, 2001; Schipper, 2000).

4. Energy metabolism, land use, and sustainable development

The data discussed in the previous section support the notion that the process of industrialization can be characterized by fundamental changes in the energetic metabolism of society (Sieferle, 1982, 1997): whereas the energy system of agricul-

[11] Assumptions on efficiencies according to Dutt and Ravindranath, 1993; Leach and Gowen, 1987; Smil, 1992, 1994: efficiency of industrial wood stoves 30%, efficiency of household wood stoves 25%, efficiency of coal stoves 40%, efficiency of charcoal production 35%, efficiency of charcoal stoves 40%. Data for 1995 were taken from the Austrian energy flow diagram (E.V.A., 1997).

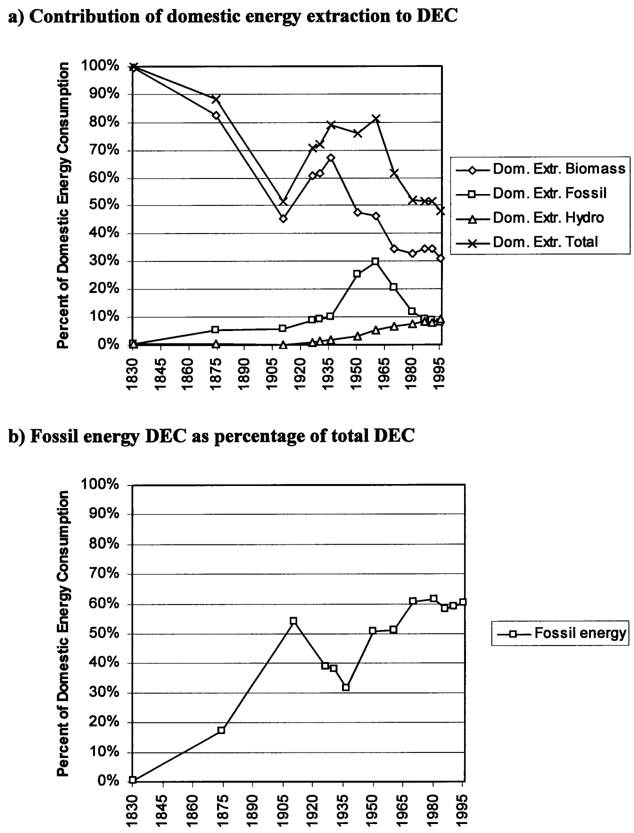

Fig. 6. Domestic extraction of energy and fossil-energy DEC as percentage of DEC Austria 1830–1995.

tural societies relies more or less exclusively on biomass, industrial transformation is accompanied by sweeping changes in the energetic basis of the economic process, leading to a fundamental change in the relation between socioeconomic development and land availability (Hall et al., 2000). However, while the importance of energy for economic development has long been recognized and is discussed in historical studies of energy policy and energy economics (e.g. Podobnik, 1999; Fouquet and Pearson, 1998), these studies employ a notion of socioeconomic energy use that includes only technical energy conversions. As the data presented in the last section show, however, such an approach—derived from current patterns of socioeconomic energy use—considerably underestimates the socioeconomic energy flows of agrarian societies because it fails to take into account essential parts of agrarian societies' socioeconomic energy metabolism—that is, the energy metabolized by humans and domesticated animals. Therefore, it is essential to adopt a broader notion of socioeconomic energy use in order to understand changes in the sustainability problems associated with the industrialization process.

Fig. 6a shows the percentage of DEC derived from domestic extraction. Whereas domestic extraction of biomass provides 99% of DEC in 1830 and still as much as 83% in 1874, its contribution to Austrian DEC then falls quickly to less than 50% in 1910. In the period between the two World Wars the share of biomass gains again in relative importance.[12] After the Second World

[12] The increase in the contribution of biomass to total DEC in the 1920 and 1930s is due to a decrease in total DEC while the level of biomass extraction/consumption hardly changes at all.

War it decreases again to about one-third in the 1970s, at which approximate level it remains until today. The contribution of fossil energy to total DEC (Fig. 6b) grows rapidly in the 19th century and reaches a peak before World War I at about 54%. After the war, the Austrian economy was cut off from the coal regions of the former Austro-Hungarian Empire and the share of fossil energy dropped to 30–40% in the 1920s and 30s. Only after the Second World War does it climb to reach about 60% in 1970, after which time it remains stable at approximately that level.

Domestic extraction of biomass is intimately related to Austrian land-use patterns. In Fig. 7, land-use patterns in Austria in 1830 and in 1995 are analyzed from the perspective of socioeconomic energy metabolism.[13] Interestingly, the area used to produce human food (vegetable food as well as meat and milk production) accounts for about 40% of the total Austrian territory both in 1830 and in 1995. However, whereas in the early 19th century domestic food production was hardly sufficient to feed the Austrian population, in 1995 Austrian agriculture produced food for more than twice the population of 1830 plus considerable (net) exports of agricultural produce. In 1830, more than 30% of the territory was used

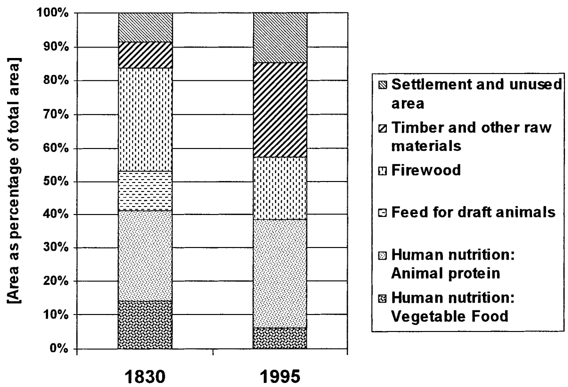

Fig. 7. Functional classification of land use in Austria 1830 and 1995.

[13] Due to the difficulties connected with a functional classification of land use (e.g. multiple use of land in the 19th century), the results shown in Fig. 6 should be regarded as rough estimations.

to produce firewood and charcoal and more than 10% of the land (i.e. almost a quarter of the agricultural land) was necessary to provide feed for draft animals. In 1995, fossil fuel-driven machines had replaced draft animals altogether and the demand for firewood had decreased significantly due to the substitution of coal, oil and gas for biomass. In total, the area used to produce biomass as primary energy carrier has decreased by more than 30% since 1830 and accounts for 56% of the total territory in 1995.

In other words, our figures support the notion that the socioeconomic energy supply has become more independent of area-dependent sources, while they also show that biomass today is still far more relevant for the total socioeconomic energy throughput than the figures for technical energy use suggest (compare Figs. 2 and 3).

Our analysis highlights two basic sustainability problems related to energetic metabolism: (1) land-use related problems of biomass supply; (2) problems related to fossil energy supply and consumption—that is, resource scarcity and CO_2 emissions (see Fig. 4). From this perspective, industrialization can be seen as a process that succeeds—at least temporarily—in overcoming the first problem at the expense of aggravating the second one. In the next section of our paper we will focus on the first aspect.

4.1. Energy metabolism and land use: a HANPP analysis

The significance of biomass use can be discussed from at least two perspectives: a socioeconomic perspective and an ecological one. From the point of view of society, the problem is to secure an appropriate yearly supply of biomass inputs for socioeconomic use. To this end, natural ecosystems are replaced by agro-ecosystems and managed forests, a process that can be termed 'colonization of terrestrial ecosystems' (Fischer-Kowalski and Haberl, 1993, 1997; Haberl and Schandl, 1999). From an ecological point of view, colonization changes numerous important structures and functions of ecosystems, thereby eventually inducing changes in ecosystems that are often regarded as detrimental; examples include species loss, habitat loss, net carbon releases from ecosystems into the atmosphere, human-induced changes of nitrogen cycles, etc. (Diamond, 1989; Ehrlich and Wilson, 1991; Houghton, 1995; Vitousek et al., 1997).

From an economic point of view, we find that domestic extraction of biomass in Austria increases by 87% from 1830 to 1995 (Table 1, Fig. 5). This increase in biomass harvest—and not an increase in net biomass imports—is the reason why an average Austrian is able to consume nearly as much biomass energy in 1995 as in 1830 even though population increased from about 3.6 to 8.1 million people (Table 2).

In order to elucidate the impact of this surge in biomass extraction, we will also discuss the process from an ecological point of view. The socioeconomic colonization of energy flows in ecosystems can be evaluated with the indicator 'human appropriation of NPP', often abbreviated as HANPP (Fischer-Kowalski et al., 1997; Haberl et al. 2001).

Given the impressive increase in biomass harvest discussed above, one might suspect a surge in HANPP in Austria 1830–1995. Interestingly, an empirical analysis of human appropriation of aboveground.[14] NPP in Austria 1830–1995 yielded the opposite result (Krausmann, 2000, 2001a). Fig. 8 further analyzes this counterintuitive finding. The key factor is that the aboveground NPP of Austrian vegetation (NPP_{act}) increased by 342 PJ per year (+40%), which more than compensates for the increase in biomass harvest. Nevertheless, even in 1995 the aboveground NPP of actual vegetation was still 14% smaller than that of potential vegetation; in 1830 the corresponding figure had been 39%. As a consequence, the relation between biomass harvest and HANPP fell from 1: 2.9 in 1830 to 1: 1.4; that is, biomass harvest increased from about 35% of HANPP in 1830 to over 70% in 1995 (Fig. 8).

The analysis presented elsewhere in more detail by Krausmann (2000, 2001a) shows that increases in commercial yields *and* the NPP per unit area of agro-ecosystems (agricultural land and managed grasslands) were the main driving forces behind the increase in NPP_{act}. Increases in yields were not only associated with an increase in aboveground NPP, but led also to a decrease in the agricultural area needed, allowing an increase in forested area, which accordingly grew by 22% from 1830 to 1995. Fig. 9 analyzes this process on an aggre-

[14] Since data on belowground NPP are quite uncertain, we restrict our analysis to aboveground processes.

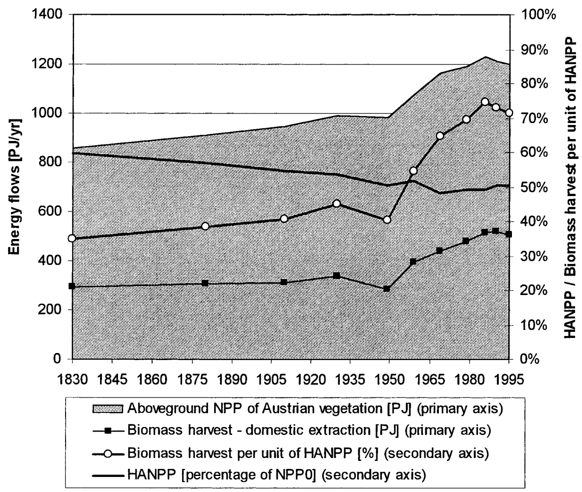

Fig. 8. Aboveground NPP of Austrian vegetation 1830–1995 [PJ per year]; Biomass harvest Austria 1830–1995 [PJ per year]; Human appropriation of aboveground net primary production (HANPP) in Austria 1830–1995 [% of aboveground NPP of potential vegetation]; biomass harvest per unit of HANPP [%]. Original figure; data source: Krausmann, 2001a.

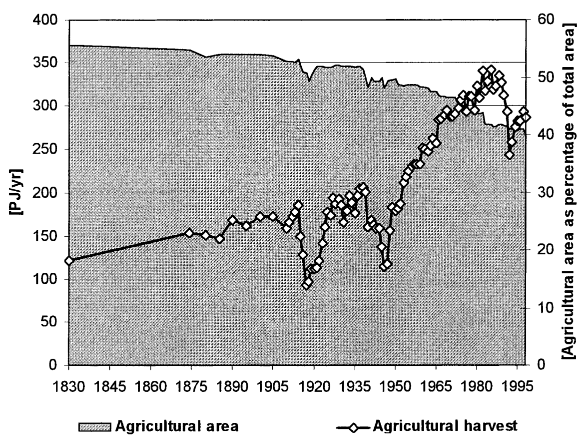

Fig. 9. Agricultural area [% of total area of Austria] and biomass harvest on agricultural area [PJ per year] for Austria 1830–1995. Original figure; data source: Krausmann 2001b.

gated level. The area of agricultural land (arable land and managed grasslands) fell from 56% of Austria's total area in 1830 to 41% in 1995; at the same time, agricultural biomass harvest surges from about 121 PJ in 1830 to 287 PJ in 1995, eventually reaching more than 300 PJ per year in the 1980s. The yields of main crops rose by factors of between 4 (rye) and 6, 7 (corn). This was only possible, of course, because of an enormous increase in the use of agricultural inputs (mineral fertilizer and other agro-chemicals, fossil fuels, electricity, etc.), probably leading to a considerable decrease in the energy efficiency of agriculture (Pimentel et al., 1990).

Summing up, we find that an increase in (fossil) energy input into agro-ecosystems led to a considerable increase in yields (and NPP). This made possible a 'delinking' between biomass harvest and HANPP (that is, an increase in the 'efficiency of area use'), while the energy efficiency of agriculture probably fell considerably (Fluck, 1992; Pimentel et al., 1990). This increase in energy inputs into agro-ecosystems was only possible due to the availability of area-independent energy, above all, mechanical energy (tractors and other machinery) and the energy needed to produce agro-chemicals. Therefore, doubts are warranted on whether it would be sensible to regard the observed decrease in HANPP as an increase in land use sustainability in Austria, although it is a clear indication of the diminishing importance of the availability of land area for the energetic metabolism of industrial societies. Moreover, these results call into question the making of simple extrapolations of current global HANPP levels on the basis of population figures with the goal of indicating limits to population growth (e.g., Meadows et al., 1992).[15]

The discussion in the previous section, however, warrants some caution regarding the potential of strategies that promote a large-scale substitution of biomass for fossil energy in order to reduce fossil-based CO_2 emissions. Currently, Austria's DEC exceeds the aboveground NPP of Austria's potential vegetation by about 6% and that of actually prevailing vegetation by about 13%. Obviously, therefore, even if it were possible to use 100% of the aboveground NPP, the current Austrian DEC could not be sustained on that basis. A large-scale substitution of biomass for fossil energy would, therefore, be impossible without a surge in HANPP, with potentially detrimental impacts on terrestrial ecosystems, including changes in land cover (deforestation) that could also trigger a net carbon release into the atmosphere (Houghton, 1995).[16]

5. Conclusions

We use the approach of a socioeconomic 'energy metabolism' to empirically analyze changes in the socioeconomic energy system and the consequences these changes have for the relation of a socioeconomic system to its natural environment and to other economies. Our results support Sieferle's (1982, 1997) hypothesis that industrial modernization can be understood as a transition

[15] In their famous book, Meadows et al. (1992) used Vitousek's calculation of global HANPP to demonstrate the biophysical limits of socioeconomic growth: *If the* 40% *figure* (global HANPP on terrestrial ecosystems according to Vitousek et al. 1986) *is even approximately correct*, *it poses some interesting questions about the next doubling of human population and economic activity*, *only* 20 *to* 30 *years away*, *What would the world be like if humans co-opted* 80% *of the NPP? Or 100%?* Since then, this argument has been used often and prominently by ecological economists (e.g. Daly, 1992; Costanza et al., 1998). A more thorough treatment of this subject can be found in a forthcoming article by one of the authors (Haberl, 2002).

[16] The promotion of the energetic use of 'renewable domestic' biomass is one major part of Austrian policies to combat Global Warming and to fulfill the Kyoto protocol. For example, current proposals by the 'Austrian Biomass Association' (Österreichischer Biomasse-Verband, 2000) to meet the requirement of the European 'White Paper' on renewable energy (COM(97) 599 of 26 November 1997) mostly by increasing biomass harvest for energy production would drive cropland area up by 15% and would increase HANPP by about 4–5 % points to preindustrial levels. The proposal includes measures to increase wood harvest by 43 PJ per year, to plant rape seeds on 900 km^2, and maize on 500 km^2 to gain biofuels, as well as to plant other energy crops on 440 km^2, leading to a total increase in primary biomass harvest of about 66 PJ per year (gross calorific value)—i.e. 7% of Austria's current fossil DEC.

process from the area-based solar energy system of agricultural society to an industrial energy system based, to a large extent, upon area-independent energy sources (fossil energy, nuclear energy, large-scale hydropower). Our results also support the notion that the industrialization process leads to a more efficient conversion of primary energy into useful energy (e.g. Ostwald, 1909; Giampietro, 1997; Giampietro et al., 1997); while the per capita energy input—DEI or DEC—increased by a factor of about 2.6 to 3, the per capita availability of useful energy increased by a factor of approximately 7 from 1830 to 1995.

Note that imports are far more important for the energetic metabolism of Austria than they are for sustaining Austria's material flows. While imports accounted for 'only' 30.2% of Austria's Direct Material Input in 1995 (Amann et al., 2000), in the same year 58.5% of Austria's DEI were imported (Table 1). This also shows that, although MFA and EFA consider essentially the same flows, they differentiate between different functions of these flows for socioeconomic processes.

For some it may come as unexpected to discover the quantitative importance of land-derived energy for industrial metabolism; agricultural and forestry-derived biomass accounted for about one-third of the energy input of Austria in 1995, whereas they supplied only about 13% of 'technical' primary energy. This order of magnitude of land-derived energy flows greatly exceeds the level the importance of these sectors as assessed in purely monetary terms; in 1995, agriculture and forestry contributed all of 1.5% to Austria's GDP (ÖSTAT, 1997). One reason for the oversight of biotic resources continued role in the economy is that members of industrial societies do not necessarily perceive human and animal nutrition and labor as energy-transformation processes.

Our results allow us to analyze the changing role of land use for the socioeconomic system. In 1830 agriculture and forestry were almost the only energy source available. Therefore, a positive relation between the amount of energy gained per unit of energy invested into agriculture or forestry was an essential condition for socioeconomic survival at that time. Scarcity of energy that could be used to increase agricultural yields seems to have been an important limiting condition for agricultural output, and thus for population density. As area-independent sources of energy became available, this constraint was relieved and other criteria such as productivity per unit area (i.e. yields) and labor productivity (Boserup, 1965; Netting, 1993) became more important during industrialization.

This development has led to an increase in energy input into agriculture. As a consequence, as many studies have shown, the relation between energy input and energy output in agriculture fell quite dramatically during industrialization (e.g. Fluck, 1992; Pimentel et al., 1973). For example, while about 10 J could be gained for every Joule of energy input in pre-industrial US corn farming around 1700, the output of corn per Joule of energy input in the United States had fallen to about 2.3 J by around 1975 (Pimentel et al., 1990). In Spain, the relation between energy inputs into the agricultural sector and energy incorporated in all agricultural products fell from 1:6.9 to 1:0.75 from 1950 to 1977 (Martinez-Alier, 1987), and calculations for the Austrian agricultural production system show basically the same results (Krausmann, 2001c). In other words, in the late 1970s agriculture had become an essentially energy-consuming instead of an energy-producing sector.

We conclude that the role of agriculture changes fundamentally during industrialization, from being the most important energy-providing economic activity—the energy efficiency of which was decisive for the survival of society—to an economically marginalized sector in which energy efficiency is no major criterion, whereas labor productivity and area productivity are optimized. This is reflected in an increase in the 'efficiency of area use' or, in other words, the improvement of the relation between HANPP and biomass harvest from 2.9:1 in 1830 to 1.4:1 in 1995. This shows that HANPP *per se* is no useful indicator for ecological limits (e.g. Meadows et al. 1992) because HANPP can, in principle, be decoupled from biomass harvest and population growth, as the present case study shows. However, it returns us to the question of how to sustainably achieve high agricultural yields—and we doubt that many would regard today's industrialized agriculture with heavy nitrogen leaching, impoverishing agricultural soils, and high fossil energy inputs, to name but few problems, as 'sustainable' (see Hall et al., 2000 for an in-depth discussion of this issue).

Our results also suggest that indicators for a society's energy input like those discussed in this paper—DEI, DEC—are suitable 'headline indicators' (EEA, 1999) that can be used for the strategic orientation of policies aimed at restructuring the economy for sustainable development. The proposed methodology and the derived indicators are fully consistent with currently used indicators for socioeconomic material flows, and they allow us to link the metabolism approach to land use and ecosystem processes. Problems associated with socioeconomic energy flows—e.g. land use and global changes in carbon cycles—are at the heart of the challenge posed by the political aim of sustainable development. The interrelation between land-use-related carbon sinks and sources and the changes in fossil energy consumption that take place during industrial transformation as discussed above are only one example of this.

Therefore, we conclude that a broad notion of 'socioeconomic energy metabolism' that includes the 'non-technical' energy flows usually not assessed in conventional energy statistics is essential if we want to understand the changes in the socioeconomic energy system associated with industrial modernization. The current concepts of both energy accounting and CEBs are focused on the industrial energy system, in which only technical energy conversions are of interest. Any analysis of changes in socioeconomic energy use from pre-industrial to modern times that is based upon such an oversimplified notion of energy use (e.g. Fouquet and Pearson, 1998) must, therefore, fail to capture essential processes and will lead to distorted results.

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