Society Exergy Analysis: A Comparison of Different Societies

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Abstract– Data from exergy analyses for a number of different countries found in the literature were compared and the differences were discussed. In studies of Sweden, Ghana, Japan, Italy, and Norway, the exergy in material flows had been considered, in addition to the flows of energy carriers. In other studies, the use of energy carriers was analyzed for the USA, Finland, Canada, Brazil, Turkey, OECD, and the World. The exergy of material flows in these societies was estimated. The total annual exergy input per capita to the societies ranged over one order of magnitude. The total exergy efficiency varied from approximately 0.1 to 0.3, whereas the end-use exergy efficiency in general was slightly higher. It was found that different investigators had made somewhat different assumptions on exergy efficiencies in specific sectors, and these assumptions are discussed. However, the structure of the energy system appeared to be more important for the total exergy efficiency than the assumptions on the sectors. In particular, the residential-commercial sector represents major irreversibilities in many societies. In countries where electricity from thermal power plants has a significant contribution to the end use, this also caused large irreversibilities. Finally, the method of society exergy analysis was discussed. It was pointed out that, because of structural dissimilarities, different countries should be compared with care. However, the development within each society can be evaluated using exergy analyses. Furthermore, such analyses can be used as a means to increase the awareness of the notion of energy quality and degradation.

1 INTRODUCTION

Effective use of energy has been the focus of public debate for the last three decades. The public and politicians have demanded, and engineers and industry have delivered, cars with lower fuel consumption, refrigerators that use less electricity, houses with better insulation, and power plants with higher efficiencies. However, less attention has been given to the structure of our energy usage, i.e., what we use energy for and what form of energy we use. The car may use less gasoline, but if we drive more, we still use more gasoline. One house may need less heat, but changes in the family structure lead to more houses. The power plants are more efficient, but we use more electricity. Such issues are related to personal decisions made by individuals, and cannot be resolved by engineers. However, as scientists we can use thermodynamics to illuminate these questions.

For a thermodynamicist, the issues above deal with the first law of thermodynamics. The term "energy" refers to the heating value of the energy carrier, be it fuel, electricity, geothermal or solar heat. A combination of the first and second law of thermodynamics leads to the concept of exergy (also called availability). This is the maximum mechanical work that theoretically can be obtained from a quantity of energy. It can be regarded as a measure of the energy quality. Thus, energy does not have one but two values: the heating value and the work value. For most politicians, this is far beyond the limit of "complicated matters". Therefore, there is a strong need for developing tools that can visualize the notion of energy quality and exergy utilization. An exergy analysis of the society is one such tool.

2 THE EXERGY METHOD APPLIED TO A SOCIETY

2.1 The exergy method

The laws of thermodynamics were established and formulated for thermal systems around 1850 [1]. At the turn of the 19th century, they were extended to chemical systems [2]. For material flows, such as ore, earth minerals, wood, paper, etc., the theory is still under development. The method of exergy analysis is well known from textbooks (e.g. Ref. [3]) and scientific papers, and will not be repeated here. The method has been applied to a wide variety of thermal and thermochemical systems.

A particular thermodynamical system is the society, e.g. of a country or a region. From yearbooks and other statistical publications, we are familiar with energy balances for such systems. Exergy balances for the same systems are not that usual. Actually, only a few such analyses are available. The first one appears to be Reistad's analysis of the USA 1970, published in 1975 [4].

The exergy analyses of countries can be grouped into two types. The first type of analysis follows Reistad's approach. Here, flows of energy carriers for energy use are considered. The end-use is divided into three sectors, that is, industry, transportation, and the residential-commercial sector. The latter comprises homes, offices, public services, health care, hotels, commerce, etc. The energy sector, with oil refining and electricity generation and distribution, is treated separately, or can readily be separated from the industry sector. Flows of energy carriers for non-energy use are not included in these analyses. This approach is followed in the analyses of Canada [5], Brazil [6], and Turkey [7]. Also the analyses [8] of the OECD countries and the World, and the analysis of Finland [9], are of this type.

The second approach originates from Wall's analyses of Sweden [10, 11, 12]. Here, all types of energy and material flows are accounted for. In addition to energy carriers for energy use, these flows encompass wood for construction materials and for the pulp and paper industry, harvested food and fodder, oil and gas for the petrochemical industry, and ores and minerals, and the products from these raw materials. The necessary models for exergy accounting of materials have mainly become available after Reistad's paper in 1975. Furthermore, in this approach, the end use is detailed in a variety of sectors. This requires more detailed statistics and models of energy use. The analyses of Sweden [11, 12, 13], Ghana (adapted from Ref. [14]), Japan [15], Italy [16], and Norway [17, 18] follow Wall's approach.

2.2 Procedure

In this study, results from the different analyses are compared. The analyzed societies are, of course, different, and it may be difficult to directly relate one to another. For instance, Japan has a population density 25 times higher than that of Norway. Thus, the transportation sectors of the two societies must be quite different. Similarly, the cold climate of Norway and Sweden requires significant heating, whereas space heating was neglected in the analysis of Brazil. Furthermore, assumptions on exergy efficiencies appear to differ among the investigators. This raises the question of whether the structure of the energy system is more important than the exergy efficiencies of the specific sectors.

Some of the details tabulated below are readily obtained from the referred analyses. However, in order to make the studies more comparable, some recalculations had to be done. These are based on the information given in the papers. Furthermore, in some cases the necessary details are not clearly reported, and some estimates had to be made. The studies of Sweden 1920, Ghana, and Finland are mainly reported as overview diagrams. The data for the non-OECD World are derived from the OECD and World analyses, and is not a separate analysis.

The analyses usually consider net import of energy and raw materials as input, and exported products as output. There are some deviations from this. For instance, a small net import or export of oil may imply a larger change in quality by refining. Thus the associated loss of exergy should be accounted for by including the total import and export in the input and output. Similarly, a minor net import of food may cover a process that actually utilizes exergy. However, these deviations have only minor influence on the figures tabulated below.

3 COMPARISON OF THE ANALYSES

3.1 Total use of exergy

The total annual per capita input of exergy in the societies analyzed is shown in Table 1. The input to end use and the total output are also shown, together with the end-use and total exergy efficiencies. It should be noted that the output figures may include significant amounts of export, e.g. food, metals, or paper. Due to the fact that two different approaches have been used, one with and one without the exergy of raw materials, this and subsequent tables are divided in two. Table 1

The first observation from Table 1 is that the total exergy efficiency seems to be independent of the per capita exergy usage. The input per capita ranges over one order of magnitude. Secondly, we see that nearly all analyses give end-use exergy efficiencies ranging approximately from 20 to 30%. However, it should be remarked that most of the studies are made for industrialized countries. It is also noted that for Norway, exported oil and gas, and the exergy required for this production, was not included in the analysis. This is an important distinction since the production of oil and gas was 20 times the domestic consumption.

The figures in Table 1 are taken from the original publications, and are not corrected for differences in the accounting of exergy. In the studies by Wall (i.e. for Sweden, Italy, and Japan), the exergy of fossil fuels and fuelwood is reckoned equal to the lower heating value. In the other studies, the chemical exergy of the fuel is used. For fossil fuels, this value is about 4–6% higher than the lower heating value, and about 10–15% higher for dry fuelwood. If these values were used in the studies of Sweden, Italy, and Japan, the annual input would be increased by 5–7 GJ/capita. The effect on the total exergy conversion would be small.

As mentioned, food and raw materials were not included in the analyses of Turkey, Brazil, Canada, and the USA. For the OECD and World analyses, non-energy uses of fuels were included, but not other raw materials. However, for comparison, this non-energy use and the corresponding refinery losses were subtracted in the present study. In the World analysis, about 1 GJ/capita of international marine bunkers was included in the end use and added to the transportation sector. No international transportation was included in the other analyses.

In the Brazil analysis, the non-energy uses of fuels were estimated to give a 6% greater primary input. This would add about 2.5 GJ/capita to the figure in Table 1. Coal and coke for metallurgical use seem to be included, whereas ores and industrial wood are not. From the World and OECD analysis, the non-energy uses of fuels was estimated to 13.0 GJ/capita for the OECD, 3.1 GJ/capita for the World, and 1.2 GJ/capita for the non-OECD World. For Turkey and the USA, the non-energy use of energy carriers is probably relatively small, whereas Canada has a substantial pulp and paper industry. Data on paper and pulp production was found in the annual-review issues of Ref. [19], and showed that produced paper and exported pulp (exergy content 17 GJ/ton) corresponded to 0.3 GJ/capita for Turkey 1995, 0.7 GJ/capita for Brazil 1987, 15.4 GJ/capita for Canada 1986, 31.4 GJ/capita for Finland 1985, 4.1 GJ/capita for the USA 1970, and 3.5, 0.8, and 0.2 GJ/capita for the OECD, World, and non-OECD World, respectively, in 1990. These output figures can be added to those in Table 1. The corresponding input of wood may be roughly estimated to twice the output figures and can be added to the total input and to the end-use input in the Table 1. In comparison, the wood-input figures were 31 GJ/capita for Norway in 1995 and 55 GJ/capita for Sweden in 1980.

The materials input to the steel and other metal industries are not included in the analyses for the USA, Finland, Canada, Brazil, Turkey, the OECD, and the World. This input is primarily ores and oxides, which have very low exergy contents. Thus, the main input to these industries is energy carriers, which are included. The output of pure metals is covered by the assumed exergy efficiencies of the industry sector. Actually, the estimated exergy efficiency for steel and metal industry in Canada is 52%. This is substantially higher than any of the calculated metal-industry exergy efficiencies for other societies.

When food is considered for Turkey and Brazil, a rough estimate may be that the annual output is about 4 GJ per capita. The input may then be 10–20 GJ/capita, which is a substantial contribution to the total input. For the USA and Canada, where higher food-input estimates are reasonable, the input may be at about 30–50 GJ/capita for domestic consumption.

3.2 End-use sectors and energy sector

The end use of energy or exergy can be divided into three main sectors: industry, transportation, and the residential-commercial sector. The latter sector comprises a great variety of energy users such as homes, offices, hospitals, and municipal engineering. In those analyses where the food sector is investigated, this makes a fourth end-use sector. In Table 2 the input to these sectors is shown as a fraction of the total input given in Table 1. The total input to the end-use sectors is also shown in the table.

Table 2

The energy sector comprises refining of fuels and production and distribution of electricity. The electricity sector, including production and distribution of electricity, can be separated from the rest of the energy sector. This sector delivers electricity to end use and to e.g. refining of oil. Table 2 also shows the input to the energy sector and the electricity sector. In the analyses of Norway, Sweden, Italy, and Japan, a large part of the exergy input is outside the energy sector. This is the raw-materials to the metallurgical industry, the wood industry, and the harvested yield of plants, fish, and game to the food sector. As previously mentioned, the other analyses do not include these flows. Thus, all input goes through the energy sector.

The irreversibilities of the sectors described above are shown in Tables 3 and 4. This is the lost exergy, and in Table 3 it is reported as a fraction of the the total exergy input given in Table 1. In Table 4, the annual irreversibility per capita is shown. Note that the last column (total society) is the sum of total energy sector and total end use, which is equal to the difference of total input and output in Table 1. (Accumulated round-off errors may cause inaccuracies.) The corresponding exergy efficiencies are shown in Table 5. Since electricity distribution is included in the electricity sector, the sector efficiencies are lower than the average power-plant efficiencies. In Table 4, we see a remarkably low irreversibility in the food sector of Japan. This can partly be attributed to a lower consumption of animal products. However, as the food import was 3.5 GJ/cap or 30% of the food input, a considerable irreversibility took place abroad.

Table 3
Table 4
Table 5

The energy sectors of the different societies show a great variation. This is seen in Table 6 which shows a breakdown of the total input of different exergy carriers. From Tables 2 and 3, we can see that the importance of the electricity sector differs. The breakdown of input to electricity production is shown in Table 7. The majority of the World electricity is produced in fossil-fueled power plants. For some societies, other sources are more important. Most notably is Norway, which has no thermal power plants at all. The average power-plant efficiencies are also shown in the table.

Table 6
Table 7

The fraction of the total input that goes to electricity was shown in Table 2. Table 8 shows the electricity share of the exergy input to end-use sectors. Also here, great variation appears. Sweden and Norway have a particularly high electrification, 40–50%, compared to about 15% for the other analyzed societies. As Sweden also has a large contribution from nuclear power, the irreversibility of the electricity sector is relatively large (Table 3). Norway, on the other hand, only uses hydroelectricity and, therefore, has quite small losses. However, Sweden also has a relatively large contribution from hydroelectricity, as is seen in Table 8.

Table 8

A more electrified society has a potential for more efficient end-use. When fuel is used in internal-combustion engines, only 15–50% of the exergy is utilized. In comparison, the efficiency of electric motors is often above 90%. Here, it should be noted that with electricity from thermal power plants, the losses are moved from end-use to the energy sector. When mechanical work is desired, exergy from electricity can be used more efficiently than fuel exergy. This is also true for heating with heat pumps. By direct heating, however, fuels and electricity are equally inefficient. This may explain why the end-use efficiencies (Table 3) do not correspond to the degree of electrification.

In the analyses of Norway, Sweden, Italy, and Japan, the end use of exergy is studied in further detail. The relative distribution of the exergy input to end use is shown in Table 9. Table 9 The figures are fractions of the total input to end use shown in Table 1. The sectors of the analyses are not completely equal, which can be seen from the table. For some analyses, the report allows an alternative breakdown of the sectors. This is shown in parentheses in the table.

The corresponding figures for end-use sectoral exergy efficiencies are shown in Table 10 Table 10 and the relative distribution of the exergy output in Table 11. The latter are fractions of the Table 11 total output shown in Table 1.

3.3 Sector exergy efficiencies

The average sector exergy efficiencies (Tables 5 and 10) are obtained in two ways. For some sectors, both the input and the output is known. This is the case, for instance, for the metal and paper industries. For other sectors, the input is known, whereas the exergy efficiency and output is based on certain assumptions. Such assumptions can always be debated. From Table 5 we see that the conversion ratio for transportation varies from 0.10 to 0.23. To some extent, the transportation systems are different. However, the variation is mainly due to different assumptions on efficiencies by the investigators. This is discussed in Sec. 4.2. On the other hand, the different assumptions agree in magnitude.

One might expect that densely populated countries such as Italy (192 capita/km^2) and Japan (320 capita/km^2) have more efficient transportation systems than sparsely populated countries such as Norway (11 capita/km^2) and Canada (3 capita/km^2). The efficiencies in Tables 5 and 10 relate to the actual transportation that is performed, and, therefore, do not account for the various means of transportation. However, from Tables 1 and 2, we see that the annual exergy input to the transportation sector was 25 GJ/capita in Italy and 21 GJ/capita in Japan. For Norway it was 44 GJ/capita, and for Canada 61 GJ/capita. To some extent, these figures reflect the differences in transportation distances and use of collective transportation. However, they are also caused by differences in habits and possibilities of the individual. This is underlined by the USA figures, which show a population density of 22 capita/km^2 and an annual exergy use of 83 GJ/capita for transportation.

In addition to transportation, space heating is an important end-use sector for many societies. Also here, the assumed efficiencies differ significantly. In this case, the useful service is heat delivered at room temperature, say 21 °C. When a representative temperature for the surroundings is decided, the Carnot expression can be used to calculate the exergy fraction of the heat. However, as Nakićenović et al. [8] point out, some investigators used a higher supply temperature. For instance, in the Canada study, the supply temperature was 55 °C, and the exergy content was 17% of the heat. In the other studies, the exergy to heat ratio was estimated to 6% for Norway, 5% for Sweden, and 3% for Italy, Japan, and Turkey. In the Brazil study, space heating was neglected.

When specific industries are considered, Table 10 shows differences e.g. in the metal industries. In this case, differences in the structure can account for the variation in exergy. For Norway, a major part of the metal industry is aluminum. The Swedish metal industry is based on domestically mined iron ore. This is quite different from the Italian steel industry, which apparently uses about 80% recirculated scrap iron. As previously mentioned, the Canada analysis was based on energy input and estimated efficiencies. The exergy efficiency for the iron and steel industry of Canada was estimated to 52%. This is higher than any of the calculated efficiencies of the other analyses.

For other activities or services the estimates may also differ among the different studies. However, the main differences between the analyzed societies result from the structure of the energy use of the society. For example, even if Canada is analyzed with Swedish assumptions on efficiencies, the total and end-use exergy efficiencies will turn out higher than those of Sweden.

All the referred studies agree that the industry has a higher exergy efficiency than the transportation and residential-commercial sectors. In particular, large losses are associated with space heating and lighting. Thus, a society with a relatively large use of energy for industry has a higher exergy efficiency compared to a society where the residential-commercial sector is more dominant. Accordingly, if the society develops in a direction towards more use of heating and lighting, the exergy utilization becomes poorer.

It should be noted that sectors have different characteristics. Space heating, lighting, and transportation have to take place were people live. Food has to be harvested were this is possible, whereas industry can be moved to another country. All products have a life cycle (or life course). The irreversibilities associated with the product may take place in several countries, and not necessarily in the society of the final use.

4 DISCUSSION

4.1 Energy and non-energy use

The petrochemical industry, the pulp and paper industry, and other forestry industries, are the most important users of energy carriers for non-energy use. In the pulp and paper industry, wood is both a raw material and a fuel. Bark, wood, and scrap paper are fuels that may be substituted by the fossil fuels included in the analysis. Moreover, some harvested agricultural products, or their derivatives, are used for fuels. Thus, there is no clear distinction between food and fuel either. This is particularly apparent in the Brazil study. From the tables above, we see that raw materials is a substantial part of the input to some societies. For Finland, the wood and food input was about one-third of the input for energy-use.

Bark normally has a high moisture content and a correspondingly low net heating value. Therefore, a bark-fired boiler is more complicated and expensive than a boiler fired with oil or gas. Thermodynamically, oil- or gas-fired boilers and power plants are more efficient than bark- or wood-fired boilers. With a low environmental awareness, the cheaper way may be to deposit the bark as waste and use oil or natural gas for fuel. Thus, if bark is regarded as non-energy, an analysis of this situation gives a higher utilization than an analysis where bark is regarded as an energy carrier.

Furthermore, wood and paper have a large energy and exergy content. The input of heat and mechanical energy results in a structural change that is necessary to make the product, paper, from the raw material, wood. Therefore, an exergy-in-heat analysis does not provide the complete picture. Paper is a product of wood and energy, and both inputs should be considered in the analysis.

4.2 On the reference for exergy efficiency

As noted in Sec. 3.3 above, investigators make somewhat different assumptions on the exergy efficiencies, e.g. of transportation and space heating.

There may be different opinions about what is useful work done by a vehicle. For the motor, a reversible engine is the reference. However, if frictionless transmission and motion is the reference, horizontal driving needs no work at all. The useful work then is zero, and so also the efficiency. Moreover, there would be no possibility to improve the performance, since the efficiency would be zero in any case. An alternative may be to establish a "best-practice" means of transportation for reference. In this case, however, one also has to decide whether transportation has to occur within a certain time interval – and in the final end, whether the transportation is necessary. Apparently, all the referred studies have based their assumptions on the equipment that was actually used, and in the way it was used. Work performed to overcome friction of motion and transmission, and work for acceleration, is then regarded as useful work.

The efficiency of space heating can be discussed in a similar manner. Rosen [5], for instance, assumed a representative heat supply temperature of about 55 °C and an exergy efficiency of 17%. As a temperature difference is needed, and the heat-exchange area is limited, it seems reasonable to refer to a representative heating-media temperature. However, this depends on chosen heating technology, and also on the usage of the room. For instance, in many new buildings, the floor is used as the heat exchanger and the heating media may be supplied at 35 °C. Technically, but probably not economically, also ceiling and walls could be used as heating surfaces, with an even lower supply temperature. In this way, the ideal heat-pump process could be approached. Contrary to that of the transportation, the ideal heating process has a finite exergy efficiency which can be used for reference. This reference is used in the other studies referred to.

4.3 On the motivation for an exergy analysis of a specific society

An important motivation for the analysis we did of Norway was to create an awareness of what scientists call exergy and irreversibility. We think that the public, the political authorities, and the industry need our knowledge – and we have to tell them that they do. To reach this audience, we have to touch on everyday life, and with an analysis of the society it seems that we did.

The Norwegian study was reported in a technical report [17] and the main results presented in a popularized magazine article [20]. The message was threefold: Energy has a quantifiable measure of quality (i.e. exergy); the quality is not conserved even though the energy is; and space heating in homes and offices is the least efficient sector. Direct heating with hydroelectricity has been regarded as clean and efficient, and is very common in Norway. A utilization (i.e. exergy efficiency) of 6% presents an entirely different picture. The response ranged from enthusiasm from environmentalists, curiosity from journalists and electricity providers, and to disbelief and near-aggressivity from individuals in the electric-heating business.

The flowsheet showing the exergy flow through the society (in Refs. [17, 18, 20]) proved to be a very useful visual tool in explaining the notion of energy quality. It should now be noted that exergy analyses of other societies have been available for years. However, this does not generate nearly the same interest as seeing an analysis of our own society.

4.4 What can be learned from such studies

Thermodynamicists know that the exergy content of heat for space heating is low or, expressed the opposite way, that the exergy requirement is low. They know that heat pumps are far more efficient than direct electrical heating. They also know that products such as metals, food, and chemical products contain substantial amounts of energy and exergy. In this sense, a study like those reviewed here does not reveal anything surprising. Moreover, the analysis is based on theoretical considerations. In reality, a reversible society is impossible.

What has been shown here and in similar analyses, is that there is in fact a substantial potential for improving energy utilization. That is, a realistic level of exergy usage has to be found above the theoretical minimum given by the exergy efficiency, but still less than the 100% that is actually spent. This is also valid for the individual end-use sectors. Such an analysis identifies and quantifies the losses or irreversibilities in the system. With this knowledge, appropriate measures can be taken to reduce the significant losses.

A second lesson is that the major part of the losses are at the end use. When we face a deficit in domestic electric energy production, a ready answer is more power plants. The referred studies show that the irreversibilities or losses associated with electricity end use are significant. Therefore, end-use improvements are a more obvious remedy to meet the deficit.

The third thing to learn from the analyses is that certain sectors conserve a large part of the exergy, whereas other sectors merely consume their exergy. For instance, the aluminum industry in Norway has about 40% exergy conversion efficiency. Theoretically it could produce two and a half times as much with the same exergy input. This is, however, the absolute limit. Even with a hypothetical future new technology, it cannot increase the output by more than 50-100% from the same input. Compared to this, the space heating sector can increase the utilization 3–4 times with available technology, and 5–6 times with technology available in the near future. It seems that this lesson is surprising news for many politicians, administrators, and even researchers and engineers in electric power technology. An exergy analysis of the society can provide information and insight that are helpful in making the right priorities.

It should be noted that the analysis is based on the actual activities, processes, and services provided in the society. As a thermodynamic analysis, it does not make any judgment of the necessity or acceptability of the actual activities, artifacts, and services. However, this study should contribute to the knowledge that has to be the basis for the ethical and political considerations regarding our way of living and of developing our society.

5 CONCLUDING REMARKS

An important motivation for such studies may be to create an awareness of the notion of energy quality and degradation of energy. An exergy analysis of our own society can be helpful in communicating this message.

Figures for different societies are tabulated together for comparison. It is seen that some societies are more “efficient” than others, that is, in the strict thermodynamic sense of the word. However, it can not be deduced that one society is “better” than another, or more “efficient” in the wider, everyday meaning of the word. Nevertheless, when a specific society develops in a direction towards reduced efficiency (e.g. more electric heating, less materials produced by industry), the word is correct in both senses.

The review of society exergy analyses showed that, although the total exergy input per capita ranged over an order of magnitude, the total end-use exergy efficiency ranged from 0.13 to 0.30 for all analyses. Assumptions on specific efficiencies showed some variation. However, the main differences resulted from the structure of the society. In particular, societies with a large contribution from thermal power plants had relatively low total efficiencies. Other sectors with relatively high irreversibilities were transportation, space heating, and lighting. Industry generally had a higher efficiency. The total exergy efficiencies for the analyzed societies ranged from 0.09 to 0.28.

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Tables

Table 1: Total annual input and output of exergy in the analyses

Society	Total input (GJ/capita)	Input to end use (GJ/capita)	Total output (GJ/capita)	End-use efficiency	Total efficiency
Analyses following Wall's approach					
Norway 1995	278	240	68	0.27	0.24
Sweden 1994	301	217	48	0.22	0.16
Italy 1990	145	117	24	0.21	0.17
Japan 1985	148	108	29	0.26	0.19
Sweden 1980	298	246	65	0.27	0.22
Sweden 1975	300		55		0.18
Ghana 1975	38	37	11	0.29	0.28
Sweden 1920	120		30		0.25
Analyses following Reistad's approach[a]					
Turkey 1995	44	32	6	0.18	0.13
Brazil 1987	42	36	10	0.26	0.23
Canada 1986	322	262	78	0.30	0.24
Finland 1985	246	137	33	0.24	0.13
USA 1970	321	256	66	0.26	0.21
OECD 1990	192	130	23	0.17	0.12
World 1990	72	51	7	0.15	0.10
Non-OECD 1990	48	35	4	0.13	0.09

[a] Only energy use, no raw materials included. For estimates of non-energy use, see text.

Table 2: Input to various sectors as fractions of the total exergy input

	Total energy sector	Electricity sector	End use				
			Food sector	Industry	Transportation	Residential-commercial	Total end use
Norway 1995	0.80	0.41	0.14	0.35	0.16	0.21	0.87
Sweden 1994	0.74	0.44	0.12	0.30	0.12	0.19	0.72
Italy 1990	0.78	0.23	0.17	0.28	0.17	0.17	0.80
Japan 1985	0.88	0.35	0.08	0.37	0.14	0.15	0.73
Sweden 1980	0.66	0.28	0.14	0.35	0.10	0.24	0.83
Ghana 1975	0.13	0.05	0.16	0.15	0.06	0.58	0.98
Turkey 1995[a]	1	0.26		0.26	0.17	0.31	0.74
Brazil 1987[a]	1	0.18		0.42	0.23	0.21	0.87
Canada 1986[a]	1	0.34		0.38	0.19	0.24	0.81
Finland 1985[a]	1	0.61		0.25	0.15	0.16	0.56
USA 1970[a]	1	0.24		0.29	0.26	0.25	0.81
OECD 1990[a]	1	0.40		0.21	0.24	0.23	0.68
World 1990[a]	1	0.31		0.23	0.18	0.31	0.71

[a] Non-energy use and raw materials not included

Table 3: Irreversibility in various sectors as fractions of the total input

	Total energy sector	Electricity sector	End use					Total society
			Food sector	Industry	Transportation	Residential-commercial	Total end use	
Norway 1995	0.12	0.08	0.12	0.19	0.13	0.19	0.63	0.76
Sweden 1994	0.29	0.26	0.10	0.19	0.10	0.17	0.56	0.84
Italy 1990	0.19	0.12	0.15	0.16	0.16	0.17	0.64	0.83
Japan 1985	0.27	0.23	0.05	0.22	0.13	0.14	0.54	0.81
Sweden 1980	0.17	0.16	0.13	0.18	0.09	0.22	0.61	0.78
Ghana 1975	0.01	0.01	0.11	0.01	0.05	0.58	0.75	0.76
Turkey 1995[a]	0.26	0.16		0.18	0.15	0.29	0.61	0.87
Brazil 1987[a]	0.13	0.07		0.24	0.21	0.19	0.64	0.77
Canada 1986[a]	0.18	0.17		0.22	0.15	0.20	0.57	0.76
Finland 1985[a]	0.44	0.37		0.14	0.14	0.15	0.42	0.87
USA 1970[a]	0.19	0.15		0.17	0.21	0.21	0.60	0.79
OECD 1990[a]	0.32	0.25		0.14	0.20	0.22	0.56	0.88
World 1990[a]	0.29	0.19		0.17	0.15	0.29	0.61	0.90

[a] Losses associated with non-energy end use are not included

Table 4: Annual irreversibility per capita in various sectors (GJ/capita)

	Total energy sector	Electricity sector	End use					Total society
			Food sector	Industry	Transportation	Residential-commercial	Total end use	
Norway 1995	33	23	33	53	37	53	176	212
Sweden 1994	86	77	30	58	31	51	169	252
Italy 1990	27	18	21	24	23	25	93	121
Japan 1985	40	35	8	32	19	21	80	119
Sweden 1980	50	46	38	52	27	64	181	232
Ghana 1975	<1	<1	4	<1	2	22	28	29
Turkey 1995[a]	11	7		8	6	13	27	38
Brazil 1987[a]	5	3		10	9	8	27	32
Canada 1986[a]	60	56		72[b]	47	66	185	244
Finland 1985[a]	109	91		35[b]	34	36	104	213
USA 1970[a]	62	49		55[b]	67	68	189	251
OECD 1990[a]	62	47		27[b]	38	42	108	170
World 1990[a]	20	14		12	11	21	44	64

[a] Losses associated with non-energy end use are not included

[b] In addition, the irreversibilities in the pulp and paper industry were roughly estimated to 15 GJ/capita for Canada, 30 GJ/capita for Finland, and 4 GJ/capita for USA and the OECD.

Table 5: Exergy efficiencies in various sectors

	Total energy sector	Electricity sector	End use					Total society
			Food sector	Industry	Transportation	Residential-commercial	Total end use	
Norway 1995	0.85	0.80	0.17	0.46	0.16	0.11	0.27	0.24
Sweden 1994	0.61	0.40	0.12	0.36	0.13	0.13	0.22	0.16
Italy 1990	0.76	0.40	0.16	0.42	0.10	0.02	0.21	0.17
Japan 1985	0.69	0.37	0.34	0.41	0.10	0.03	0.26	0.19
Sweden 1980	0.75	0.45	0.10	0.49	0.10	0.10	0.27	0.22
Turkey 1995[a]	0.74	0.36		0.33	0.15	0.06	0.18	0.13
Brazil 1987[a]	0.87	0.63		0.43	0.10	0.12	0.26	0.23
Canada 1986[a]	0.81	0.49		0.42	0.23	0.15	0.30	0.24
Finland 1985[a]	0.56	0.40		0.43	0.10	0.08	0.24	0.13
USA 1970[a]	0.81	0.36		0.41	0.20	0.14	0.26	0.21
OECD 1990[a]	0.70	0.38		0.32	0.15	0.07	0.17	0.12
World 1990[a]	0.71	0.38		0.27	0.16	0.05	0.15	0.10

[a] Losses associated with non-energy use are not included

Table 6: Breakdown of the total exergy input: fractions from each carrier

Exergy carrier	Wood	Food	Hydro	Coal	Oil	Gas	Nuclear	Other[a]
Norway 1995	0.11	0.10	0.41	0.05	0.32	0.00	0	0.01
Sweden 1994	0.16	0.10	0.09	0.04	0.25	0.02	0.32	0.02
Italy 1990	0.04	0.16	0.02	0.07	0.47	0.20	0	0.05
Japan 1985	0.03	0.05	0.02	0.17	0.50	0.09	0.10	0.03
Sweden 1980	0.20	0.12	0.10		0.45[b]		0.11	0.02
Ghana 1975	0.64	0.21	0.05	0.00	0.08	0.00	0	0.00
Sweden 1920	0.38	0.27	0.00	0.31	0.01	0	0	0.02
Turkey 1995	0.12[c]	†	0.06	0.28	0.46	0.09	0	0.00
Brazil 1987	0.40[c]	†	0.14	0.08	0.34	0.03	0.00	0.01
Canada 1986	0.00[c]	†	0.14	0.13	0.37	0.28	0.09	0.00
Finland 1985	†	†	0.04		0.73[b]		0.21	0.01
USA 1970	0.00[c]	†	0.02	0.23	0.38	0.37	0.00	0.00
OECD 1990	0.04[c]	†	0.02	0.23	0.42	0.19	0.10	0.00
World 1990	0.14[c]	†	0.02	0.25	0.35	0.18	0.06	0.00
Non-OECD 1990	0.22[c]	†	0.02	0.26	0.29	0.18	0.02	0.00

[a] Scrap, ore, geological heat, imported electricity

[b] Including unspecified amount of coal and coke

[c] Only fuelwood and other biomass for combustion, wood for industry is not included

†Not included in the analysis

Table 7: Breakdown of the electricity production: fraction produced from each exergy carrier

Energy source	Hydro	Geo	Bio	Fossil	Nuclear	Import	Eff.
Norway 1995	1	0	0	0	0	0	0.85
Sweden 1994	0.42	0	0.00	0.07	0.51	0.00	0.42
Italy 1990	0.14	0.01	0	0.71	0	0.14	0.43
Japan 1985	0.14	0.00	0	0.62	0.24	0.00	0.37
Sweden 1980	0.61	0		0.11	0.27	0.01	0.48
Ghana 1975	1	0	0	0	0	0	
Sweden 1920	1	0	0	0	0	0	
Turkey 1995	0.41	0.001	0.003	0.59	0	0	0.45
Brazil 1987	0.85	0	0.004	0.06	0.005	0.08	0.73
Canada 1986	0.66	0	0	0.19	0.15	0.00	0.53
Finland 1985	0.22	0	0	0.33	0.38	0.07	0.40
USA 1970	0.17	0	0	0.81	0.02	0	0.36
OECD 1990	0.16	0	0.02	0.60	0.23	0.00	0.38
World 1990	0.18	0	0.01	0.65	0.16	0	0.37
Non-OECD 1990	0.21	0	0.00	0.71	0.07	0	0.37
Typical eff.	0.85	0.2	0.3	0.3–0.5	0.3	1	

Eff. = (average) efficiency of power plants

Table 8: Electricity and hydroelectricity shares of exergy input to end-use sectors

	Electricity	Hydro
Norway 1995	0.49	0.49
Sweden 1994	0.25	0.11
Italy 1990	0.11	0.02
Japan 1985	0.18	0.03
Sweden 1980	0.15	0.09
Ghana 1975	0.04	0.04
Sweden 1920	0.003	0.003
Turkey 1995	0.12	0.05
Brazil 1987	0.13	0.12
Canada 1986	0.20	0.13
Finland 1985	0.27	0.07
USA 1970	0.10	0.02
OECD 1990	0.19	0.03
World 1990	0.13	0.02
Non-OECD 1990	0.09	0.02

Table 9: Relative distribution of the exergy input to end-use sectors.

	Norway 1995	Sweden 1994	Italy 1990	Japan 1985	Sweden 1980	Sweden 1920	Turkey 1995	Ghana 1975
Forest industry	0.14	0.27	0.08	0.08	0.30	0.18	†	0.12
Food	0.16	0.16	0.11	0.11	0.17	0.32	†	0.16
Steel, metal	0.13	0.06	0.19	0.19	0.06	0.03	0.08	0.03
Chemical industry	0.10	0.07	0.20	0.20	0.02		0.13	
Transportation	0.18	0.16	0.20	0.20	0.12	0.00	0.23	0.07
Lighting, etc.	0.14	0.10			0.09	0.00		0.01
Mechanical work	0.01	0.02			0.01			
Space heating	0.13	0.16			0.24	0.34		
Other industry	(0.03)		0.03	0.03		0.13	0.14	
Households	(0.16)	(0.26)	0.20	0.20	(0.29)		0.42	0.60
Service, commerce	(0.08)							

Figures in parentheses are also included in other sectors.

†Food and forestry are not included in the Turkey analysis.

Table 10: Exergy efficiencies for end-use sectors.

	Norway 1995	Sweden 1994	Italy 1990	Japan 1985	Sweden 1980	Sweden 1920
Forest industry	0.51	0.34	0.42	0.62	0.55	0.60
Food	0.17	0.12	0.16	0.34	0.10	0.11
Steel, metal	0.37	0.34	0.48	0.29	0.28	
Chemical industry	0.60	0.40	0.43	0.49	0.80	
Transportation	0.16	0.13	0.10	0.10	0.10	
Lighting, etc.	0.17	0.24			0.27	
Mechanical work	0.50	0.50			0.50	
Space heating	0.06	0.07	(0.02)	(0.03)	0.06	
Other industry	(0.25)		0.20	0.45		0.14
Households	(0.12)	(0.13)	0.02	0.03	(0.10)	(0.03)
Service, commerce	(0.10)					
Total of end use	0.27	0.22	0.21	0.26	0.27	0.25

Table 11: Relative distribution of the exergy output from end-use sectors.

	Norway 1995	Sweden 1994	Italy 1990	Japan 1985	Sweden 1980	Sweden 1920
Forest industry	0.26	0.41	0.11	0.18	0.61	0.57
Food	0.10	0.09	0.17	0.14	0.07	0.26
Steel, metal	0.18	0.09	0.20	0.21	0.06	0.00
Chemical industry	0.23	0.12	0.36	0.32	0.06	
Transportation	0.11	0.09	0.10	0.07	0.05	0.00
Lighting, etc.	0.08	0.11			0.09	0.00
Mechanical work	0.02	0.04			0.02	
Space heating	0.03	0.05			0.05	0.07
Other industry	(0.03)		0.03	0.06		0.10
Households	(0.07)	(0.16)	0.02	0.02	(0.11)	(0.07)
Service, commerce	(0.03)					