Accepted for publication in
"Energy"

Exergy Analysis of the Norwegian Society

Ivar S. Ertesvåg * and Michal Mielnik

(Received 5 January 2000)

Department of Applied Mechanics, Thermodynamics and Fluid Dynamics,
Norwegian University of Science and Technology
N-7491 Trondheim, Norway

* Author for correspondence. E-mail: ivar.s.ertesvag@mtf.ntnu.no
Fax.No.: +47 73 59 35 80

Abstract– The use and conversion of energy carriers and materials in the Norwegian society in 1995 were investigated by an exergy analysis. All resources that enter the society, such as waterfall energy, fossile fuels, ores and minerals, harvested crops, fishing and hunting, and wood, were included. However, exported oil and gas were excluded from the analysis. The end use was broken down into nine end-use sectors: forest industry, food sector, aluminum industry, steel and other metal industry, chemical industry, transportation, households, public service, and other industry. Each of these sectors was treated in further detail. The last three sectors were also regrouped into mechanical work, space heating, and lighting, equipment, etc. The total exergy input was 1184 PJ, which was 278 GJ per capita. The output of products and services contained 280 PJ exergy or 68 GJ per capita. This was 24% of the input. The household and public-service sectors had exergy efficiencies of approximately 10%, whereas the aluminium and forestry sectors had efficiencies of approximately 40% and 50%, respectively.

1 INTRODUCTION

All energy usage has limits, either because the energy source is limited or because the environmental impacts impose limits. This has led to an increasing awareness that energy-utilization techniques need to be more environmentally sound and efficient. The notion of energy quality follows from the second law of thermodynamics. Some forms of energy can be converted into any other form, whereas other forms cannot. Electricity can be converted into mechanical work or into heat. For practical purposes, hot-water thermal energy can most often only be used for heating. On the other hand, for space heating hot waste-water suffices, whereas an aluminum plant requires electrical energy. This study was part of an effort to increase the understanding of these aspects of energy among students, engineers, administrators, politicians, and the public.

With regard to energy supply, Norway is in a unique situation. Steep mountains at the European Rain Coast provide large amounts of hydropower. Together with fuelwood, this means that more than half the energy is supplied from renewable energy sources. Furthermore, in the 1960's and 70's, substantial reserves of oil and natural gas were found off the coast. Norway produces approximately 2% of the world's oil and provides 10% of all exported oil.

At present, the amount of oil and gas exported is nearly ten times that used domestically. Thus, this industry has to be treated separately in an analysis of the Norwegian society. In the analysis presented here, exported oil and gas, and the fuel used for exploitation and production of oil and gas, were excluded from the analysis. In addition, oil and gas transported ashore before export, and the installations for this transport and treatment, were kept outside the system boundary of the analysis.

The total production for export and domestic use of energy carriers is listed in Table 1. Table 1

2 THE EXERGY METHOD APPLIED TO A SOCIETY

2.1 The Exergy Method

The method of exergy analysis has been developed and mainly utilized for thermal and thermochemical systems over recent decades and is well known from textbooks. This method has also been developed for analyzing the energy use of an entire country. This was introduced by Reistad's analysis of the USA [1], where the exergy of energy carriers was followed through the society. The end use was divided into three sectors, that is, industry, transportation, and the residential-commercial sector. Similar analyses have been presented for Canada in 1986 [8], Brazil in 1987 [9], and Turkey in 1995 [10]. The OECD (the Organizaton for Economic Cooperation and Development, that is, Western Europe, USA, Canada, Japan, Australia, and New Zealand) and global exergy conversions in 1990 have been studied by Nakićenović et al. [11]. In a further development of the method, Wall [2, 3, 4] used the Swedish society during the years 1975, 1980, and 1920 as examples. In these analyses, the exergy of all types of energy and material flows were accounted for. In later analyses of this type, the exergy conversions of Japan in 1985 [5], Italy in 1990 [6], and Sweden in 1994 [7] have been studied.

Choosing the boundary of a country as the system boundary of an analysis is convenient because statistical data are available. The input to the system consists of all commodities and energy carriers that are imported, harvested, harnessed, extracted, etc. The output from the system is all products, raw materials, goods, food, and services that are consumed or exported. In Ref. [12], the analyses cited and the present one are compared and the method is discussed.

The analyses are based on the processes that are actually present. For example, a new refrigerator is better insulated and less heat transfer is needed. In addition, the refrigeration cycle will be more efficient. However, many older refrigerators exist, and the service provided is to remove the actual heat transferred into these. Similarly, transport service is the actual motion of the existing vehicles, although the same goods and passengers could have been transported using lighter vehicles with less friction.

The major part of the input to the system is fuels and other energy carriers. In the statistics, these are expressed in terms of energy content. The exergy content can be calculated from this.

For mechanical and electrical energy, the exergy content is equal to the energy content. The exergy of chemical fuels was found from expressions and data given by Kotas [13]. This led to the exergy factors or exergy-energy ratios shown in Table 2. These exergy factors are based on the lower heating values, which are the quantities used in energy statistics. Fuelwood contains water and the fuelwood energy is the efficient heating value, that is, the lower heating value for moist fuel. In the studies of Wall [3, 5, 6, 7], the fuel exergy was set equal to the lower heating values. As per the discussion in Ref. [14], this may be regarded as an approximation where the non-utilizable flue-gas chemical exergy is withdrawn from both sides of the balance. In Rosen's [8] study of Canada and Schaeffer and Wirtshafter's [9] study of Brazil, the chemical-exergy calculations were similar to the present study. Table 2

The chemical exergy of metals and minerals were found according to Kotas [13], while the exergy content of industrial wood was taken from the study of Wall [3]. For food and fodder, the exergy content was set equal to the nutrient energy, primarily due to lack of more appropriate models. For all raw materials and chemical fuels, thermophysical exergy was neglected.

2.2 Exergy of Space Heating

The exergy conversion in space heating requires some discussion. As will be seen, a large part of the total irreversibility occurs when high-quality energy is transferred into heat at room temperature. Basically, the exergy content of heat at temperature T is found from the Carnot ratio, $(T - T_\circ)/T$. The environmental temperature $T_\circ$ varies over time and from place to place. Wall [3] has developed a model for the outdoor air temperature that assumes that the air temperature varies harmonically (i.e. a sine function) during the year and during the day. The parameters of the models are the length of the heating season, the annual average temperature, the minimum five-day mean temperature, and the day-night amplitude – all temperatures being outdoor air temperatures.

This model was used for Sweden, which has a relatively stable inland winter climate. For locations with other types of weather, the model may give peculiar results. For Swedish towns, Wall's model (i.e. a corrected version) gave exergy to heat ratios of 5–8%. For the generally milder Norwegian coast, the model gave figures of 8–12%. During a normal winter, coastal areas in Norway experience shorter periods of relatively cold weather. This brings the minimum 3-day or 5-day mean temperature down, without increasing the overall deviation from the annual mean temperature correspondingly. For locations in Norway, a typical average temperature duration curve may be closer to a tangent function than a sine function. Furthermore, this model is based on outdoor temperature, whereas the environment also includes heat sources such as the sea and ground. For most locations in Norway, heat is readily available at 0–2 °C all year long. A third objection to the model is that the exergy conversion of a specific year is modeled by temperature data averaged over many years.

In this study, we choose to estimate a representative exergy to heat ratio for all space heating. That is, heating through district-heating systems was not treated separately. More than half the population of Norway lives near the sea. For most areas, heat from the surroundings is available at about 0 °C, either from seawater or from the ground. Furthermore, for substantial parts of the heating season, the air temperature is between 0–10 °C. Thus, we assumed that a exergy to heat ratio of 6% is representative for space heating. This factor corresponds to an indoor air temperature of 21 °C and a representative environmental temperature of 3 °C.

3 EXERGY AND MATERIAL FLOWS INTO THE NORWEGIAN SOCIETY

3.1 Introduction

The Norwegian energy system is mainly based on two energy carriers: hydroelectricity and petroleum products. Each of these contributes more than 40% of the energy used. Wood also makes a substantial contribution. The flows of exergy through the society is visualized in Figure 1. Figure 1

Norway has no nuclear power plants – and, actually, no significant thermal power plant at all. Wind, wave and geothermal energy make negligible contributions. In addition, active solar heating is negligible. Passive solar energy such as light through windows and heat through walls, etc., was not included either. This energy is very difficult to quantify, and the distinction in relation to natural climate is unclear.

In 1995, the year that was analyzed here, the net export of electricity was 24 PJ. As with the energy of exported oil and gas, this electric energy and the associated waterfall energy were not included in the analysis. In subsequent years, the net import has increased.

More details of the analysis are given in a report by the authors [16]. It may be noted that the present analysis has a more detailed breakdown of energy end use than similar studies referred to above. The analysis was based on a variety of statistics. Two important sources were the annual Statistical Yearbook [17, 18] and the Energy Statistics [19, 20]. These sources include all energy-carrier flows, broken down to the end-use sectors detailed in Sec. 3. Other official statistics include the major industry production accounted for in the analysis. Additional details were obtained through personal communication with Statistics Norway (i.e., the central institution for producing official statistics) and with the industry and industry associations. Furthermore, colleagues at the various departments in the Sintef Group (The Foundation for Industrial and Technological Research) and at the University have provided helpful information.

3.2 Oil, Coal, Coke, and Natural Gas

As noted above, the export-oriented oil industry was kept outside the system boundary of this analysis. The fuel used by this industry is easily identified in the statistics.

The domestic supply of oil, coal, coke, and natural gas is listed in Table 3. Most oil, coal, and natural gas is used directly as fuel. Some of it is used for raw material and a very small fraction is used in small powerplants and in district heating. Coke, as well as some petrol coke produced from oil, is mainly used by the metal industry. Table 3

The consumption and losses in the energy sector, 31.2 PJ exergy (29.4 PJ energy), was calculated from the energy statistics. This includes refining of raw oil for domestic use. In addition, 9 PJ of electricity was used by this sector. Fuel for fuel transportation and distribution was not included in these figures, but reckoned under the transportation sector. Based on the statistics for truck transport and coastal transport, an estimate of 1–2 PJ seemed reasonable. This was approximately 1% of the input to the transportation sector.

3.3 Hydropower and Electricity

Virtually all electricity produced in Norway is hydroelectricity. Waterfall energy is treated as primary energy, whereas electricity is a secondary energy carrier, see Table 3. The known quantity is the production in the power plants. The waterfall energy is found by estimating a 15% loss due to pipe friction, mechanical losses, leakage, etc. This percentage is used in the energy statistics of all OECD countries. In addition to this, distribution losses and consumption in the power plants is specified in the energy statistics to 26.2 PJ.

Exergy in freshwater released to the sea, i.e. power potential due to the salinity difference, was not included. Actually, this is the chemical exergy of freshwater.

3.4 Wood, Recirculated Paper, and Fuelwood

Wood enters the analysis in two streams: fuelwood and industrial wood. The latter comprises wood for building materials, woodware, pulp and paper production, and for industrial heating. The distinction is convenient for two reasons. In the statistics, industrial wood is accounted for as the volume of solid wood, cf. Sec. 4.2, whereas fuelwood is accounted for as an energy quantity. Secondly, there is a difference in quality. Fuelwood is usually air dried, and contains less moisture. Furthermore, fuelwood is mainly non-commercial, and is used for household heating. The quantity was estimated by Statistics Norway using sample surveys.

Fuelwood exergy was found from expressions given by Kotas [13]. The lower heating value of dry wood is 19.1 MJ/kg. With a moisture content of 20% by mass, the effective heating value is 14.8 MJ/kg, and the chemical exergy becomes 16.5 MJ/kg. Thus, the ratio of exergy to effective heating value becomes 1.11. For dry material, this ratio is 1.08. It should be noted that the exergy is reduced as the moisture content increases, but the effective heating value is reduced to a greater extent. This explains the increased ratio with moisture.

3.5 Food and Fodder

Raw materials to the food sector are crops for human consumption and animal fodder, harvested seafood, and hunted wild animals. In addition, imported food and fodder is input to the system. Note that products from livestock and fish farming are not inputs.

3.6 Ores and Metals

Ores, recirculated scrap metal, metal oxides, etc., enter the analyzes of the metal industries. This includes inland mining and imports, see Secs. 4.3 and 4.4.

4 EXERGY CONVERSIONS IN THE NORWEGIAN SOCIETY

4.1 Agriculture, Fish and Food Industry

Imports and exports [17] of food and fodder are shown in Table 4, and the domestic production [18, 21, 22] is shown in Table 5. The exergy content was set equal to the nutrient energy content, which was found from the USDA Nutrient Database [23].

Table 4
Table 5

Food industry, agriculture, and fisheries consumed 15.2 PJ from electricity and 31.6 exergy (29.8 PJ energy) from petroleum products. That is, 46.8 PJ exergy from energy carriers. With a domestic harvest of 103.6 PJ and 18.8 PJ imported, the total exergy input was 169.2 PJ.

The average nutrient intake has been estimated by the National Council on Nutrition to 11.7 MJ/day for males and 8.4 MJ/day for females [24]. With approximately 2.15 million males and 2.2 million females, this amounted to 15.9 PJ food exergy consumption. With the export of 12.6 PJ, the total output from the food sector was 28.5 PJ, which was 16.8% of the input.

It can be seen that a substantial contribution is from grass, which has to be "processed" in animals. It should also be noted that domestic animals and farmed fish are not inputs, but are regarded as processes within the system. Table 4 shows that in terms of exergy, the fish export approximately balances the grain import. When economy is considered, the fish export has a considerably higher value. This situation has more or less prevailed for at least 8 centuries and enabled the coastal population to consume more nutrient energy than their own production. Therefore, fishing has been and still is an important part of the Norwegian economy.

4.2 Wood, Pulp and Paper Industry

The forest and wood industry used 7.8 PJ exergy (7.3 PJ energy) from petroleum products, and 28.3 PJ electricity [19]. Forestry produced 9.34 Mm^3 solid wood [25, 26]. With Wall's figure of 8 PJ/Mm^3 [3], this gave 74.7 PJ exergy. Net import gave an additional 0.45 Mm^3 and 3.6 PJ exergy in timber, and 3.24 Mm^3 chips and residues giving 25.9 PJ exergy. Recirculated paper contributed 0.246 Mton. With an exergy content of 17 PJ/Mton, this amounted to 4.2 PJ exergy. Of the wood, approximately 3.8 PJ was used as fuelwood in other sectors. Altogether, the forest and wood industry used 104.6 PJ exergy from wood and recirculated paper. The total exergy input was equal to 140.7 PJ.

The production of paper and cardboard amounted to 2.26 Mton, and there was 0.684 Mton of cellulose and mechanical pulp [26]. With an exergy content of 17 PJ/Mton, this gave 38.9 PJ and 11.6 PJ exergy. Plank and other wood products [27] were estimated to give an additional 22.0 PJ exergy. This resulted in a total exergy output of 72.1 PJ from the forest and wood industry, which was 51.2% of the input.

4.3 Aluminum Industry

Aluminum is a major industry in Norway, and was treated separately in this study. It used 55.3 PJ electricity and 10.6 PJ exergy (10.3 PJ energy) from coal, coke, and petroleum products [19]. The raw material was imported pure Al_2O_3 and small amounts of bauxite. The exergy content is 2.0 PJ/Mton. The usage [18, 28] was 1.58 Mton, which gave 3.2 PJ exergy. In addition, 0.066 Mton recirculated aluminum [28] gave 2.2 PJ exergy. Thus, the input to this sector was 71.3 PJ exergy.

The exergy content of aluminum is 32.1 MJ/kg. The production [18] of aluminum was 0.85 Mton, giving 28.0 PJ exergy, which was 39.3% of the input.

The refining of aluminum oxide (Al_2O_3) takes place abroad, and the energy required for this was not included in this study. The efficiency had most likely been lower if this process had been included.

4.4 Steel and Metal Industry

The metal industry, not including the aluminum industry, had a variety of products [18, 29] that are listed in Table 6. The major contributions were from the ferro-alloy and steel industries. Table 6

These industries used 13.0 PJ exergy (12.3 PJ energy) from coal, 13.3 PJ exergy (12.7 PJ energy) from coke, 2.1 PJ from petroleum products and gas (2.0 PJ energy), and 32.7 PJ electricity [19, 20], for a total of 61.1 PJ exergy (59.7 PJ energy) from energy carriers.

The ferro-alloy industries used quartz (99% Si_2), manganese ore, and chrome ore giving 0.3 PJ exergy. Mining gave 2.2 Mton iron ore. With approximately 66% iron on the basis of mass, the exergy content of the ore is approximately 0.50 PJ/Mton. Approximately 0.9 Mton was exported, and 1.3 Mton with 0.7 PJ exergy was used in the inland steel and ferro-alloy industries. In addition, 0.58 Mton scrap iron with an exergy content of 6.8 PJ/Mton gave 3.9 PJ exergy. The total exergy of the raw materials [18, 29, 31] was 4.9 PJ. The raw materials for the remainder of the metal industry gave only negligible exergy input. Magnesium, for example, is extracted from plain seawater, which is part of the environment and thus per definition has zero exergy.

The output of the sector is shown in Table 6. Ferrosilicon is mainly a mixture containing approximately half $FeSi_2$ and half pure silicon. The exergy of $FeSi_2$ is not given in the referred literature, and was calculated to 1905.3 kJ/mole. Ferrosilicomanganese (FeSiMn) mainly consists of a mixture of 20% Si (on a mass basis), 10% Fe, and 70% Mn in different phases.

The total input was 66.0 PJ exergy, and the total output was 22.2 PJ exergy. Thus, the exergy efficiency was 33.9%.

4.5 Chemical Industry

The chemical industry uses energy carriers for energy purposes, and for raw material as well. It used 14.7 PJ exergy (13.9 PJ energy) from coal, 7.2 PJ exergy (6.9 PJ energy) from coke, 45.7 PJ (43.1 PJ energy) from petroleum products, 10.9 PJ (10.5 PJ energy) from gas, and 28.2 PJ electricity [19, 20]. This gave 106.7 PJ exergy (102.5 PJ energy) from energy carriers. The contribution from other raw materials was neglected.

The chemical industry produces a wide variety of products, mainly cement, fertilizers, and petrochemical products. In this study, we have not detailed the output. We estimated the exergy efficiency to be 0.60. As many chemical products technically can be regarded as fuels, this factor seemed to be reasonable, although uncertain. Using this factor the exergy output was 64.0 PJ.

4.6 Transportation

The transportation sector is the major user of petroleum products. In 1995, a total of 189.5 PJ exergy (178.9 PJ energy) was used by this sector [19]. Of this, 187.1 PJ exergy (176.5 PJ energy) were from petroleum products. The remaining 2.4 PJ was from electricity used by trains and electric streetcars.

The exergy usage was divided into three subgroups: road and rail, 135.4 PJ exergy; coastal transport, 28.9 PJ; and air transport, 25.1 PJ. The efficiencies were estimated to be 13% for road and rail transport, and 25% for water and air transport. These estimates do not differ significantly from those made by Rosen [8] and by Nakićenović et al. [11]. Efficiencies of transportation is discussed in Ref. [12]. The weighted average efficiency was 16%, and the exergy output from this sector became 31.1 PJ.

Due to the differences in fuel specifications and distribution system, the subdivision of transportation-energy usage into road, air, sea, and rail is rather simple and accurate. A far more difficult and uncertain task is to discern e.g. transport end use for public service, households, industry – or for energy transport. Therefore, in the statistics, and thus in this study, all transport is gathered in one end-user sector.

4.7 Households

In Norway, the largest user of electricity is the household sector. In 1995 it consumed 125.2 PJ electrical energy. Furthermore, it used 27.3 PJ exergy (24.6 PJ energy) from fuelwood and waste, and 13.7 PJ exergy (12.9 PJ energy) from petroleum products [19, 32]. As noted in the preceding section, transportation for households was not included in these figures.

This sector comprises a large number of participants. There is considerable variation within this sector, however, the general trends regarding energy are similar. One of the problems in dealing with energy and exergy usage by sectors such as households and public services is that the information required is not available. In this study, the breakdown into the various end uses reported in Table 7 was based on detailed market data and models from the Market Research Division of Sintef Energy Research [33]. Table 7

All wood, waste, and petroleum products were used for space heating purposes, as well as 41% of the electricity. As discussed in Sec. 2.2, we estimated a 6% exergy efficiency for space heating. We estimated that 24% of the electricity was used for warm-water heating at 60–70 °C, with an exergy efficiency of 17%. Furthermore, we estimated that lighting consumed 11% of the electricity, cooling 8%, other electric equipment 7%, cooking 4%, washing 3%, and drying 2%. The assumed exergy efficiencies are shown in Table 7. The total exergy output from the household sector was then 19.9 PJ, or 12% of the input.

4.8 Public Services, Commerce, etc.

There are many similarities between this sector and the household sector. In both sectors, the related transportation was excluded, and in both sectors significant portions of the energy are used for heating. Actually, lighting and equipment also make a large contribution to heating.

The public sector consumed 71.3 PJ exergy from electricity, and 15.1 PJ exergy (14.3 PJ energy) from petroleum products [19, 32], for a total of 86.4 PJ exergy (85.6 PJ energy). The breakdown into different purposes (cf. households above) and the efficiencies are shown in Table 8. Table 8

4.9 Other Industry

This final sector consists of the industry that is not included in the preceding sectors. This is primarily mechanical industry, shipbuilding, textile industry, etc., where the majority of the energy is used for mechanical work and heating. In 1995, this industry consumed 17.8 PJ exergy (16.8 PJ energy) from petroleum products and coke, and 17.2 PJ electricity [19, 20], in total 35.0 PJ exergy (34.0 PJ energy).

Using the same basis as for the household and public services sectors, we estimated that 65% of the electricity was used for mechanical work, 20% for lighting, 5% for water heating, and 10% for space heating. Furthermore, we assumed that 60% of the fuel was used for space heating, and 40% for process heating. The estimated efficiencies are shown in Table 9. The total exergy output summarized to 8.7 PJ, or 24.8% of the input. Table 9

4.10 Space Heating

In Sections 4.7, 4.8, and 4.9, it was shown that the total exergy for the sectors households, public services, and other industry can be divided up into percentages expended on various uses. On this basis, the total exergy input for space heating for these sectors may be estimated to 136.0 PJ exergy (131.1 PJ energy). Given an exergy efficiency of 6%, the output was 8.2 PJ exergy.

4.11 Lighting, Electrical Equipment, etc.

As the preceding sector, this is only a rearrangement of the estimates for the sectors described in Sections 4.7, 4.8, and 4.9. For lighting, electric equipment, warm water, process heat, etc., the total input was 140.3 PJ exergy (139.9 PJ energy). The exergy output was 23.4 PJ, giving an efficiency of 16.7%.

4.12 Mechanical Work

The exergy for mechanical work was taken from the "other industry" sector above and amounted to 11.2 electric exergy (energy). With an assumed average exergy efficiency of 50%, the output was 5.6 PJ exergy.

4.13 Exergy Conversion of the Norwegian Society

The partial analyses of the nine end-use sectors are summarized in Table 10. Three sectors Table 10
are rearranged in Table 11. The weighted exergy efficiency of all the end-use sectors was 27%. Table 11
The total result, with the domestic energy sector and the nine end-user sectors, is shown in Table 12. The total exergy output from the end-user sectors was 24% of the total input. The Table 12
exergy input per inhabitant was 278 GJ/cap and the exergy output was 68 GJ/cap.

This can be compared to 16% output of 301 GJ/cap input to Sweden in 1994 [7], 17% output of 145 GJ/cap input to Italy in 1990 [6], and 19% output of 148 GJ/cap input to Japan in 1985 [5]. The underlying differences between these and some other societies are studied in Ref. [12].

5 DISCUSSION OF THE PRESENT ANALYSIS

Generally, an assessment of possible errors in the underlying statistical material is very complex and is outside the scope of this work. However, it may be clarifying to investigate how large errors must be to exert a certain influence on the results.

The most important statistical figures were taken from official Norwegian statistics and industry statistics. This includes all energy and raw materials, harvest, and industrial products. That is, the left side, and the industrial/commercial part of the right side of the flowsheet shown in Figure 1. The Official Statistics are based on a variety of more specific sources. The quality of the statistics is evaluated in the various publications, but the accuracy is not analyzed in detail by Statistics Norway. In some cases, the different statistical figures did not always agree. This can be seen in the Energy sources balance sheet [19], where the statistical differences were reckoned to 37 PJ, which was 3.8% of the domestic energy supply. In addition to statistical errors, this also seems to include, e.g., losses due to evaporation of petrol and fuel oil during transportation and storage. An error of this magnitude can change the total exergy efficiency by ±1%.

Some material flows are hard to measure and account for exactly. For instance, wood is quantified in volume of solid material, and this is difficult to measure. The alternative, accounting by mass, is less accurate since the moisture content will change during transportation and storage. The exergy of minerals and metals is based on a reference. This reference may be difficult to define correctly, particularly for ores and, therefore, these figures may be uncertain. However, in the present analysis, a large part of the input to the metal industry is imported pure oxides. The exergy difference between oxide and metal is more accurate than the absolute value. Moreover, the input of minerals, oxides, and ores amounts to 10,3 PJ or 1% of the total input. Therefore, errors in these figures will not have a significant influence on the total result.

In the study, we neglected chemical exergy of freshwater released to the sea. This is the power potential due to the salinity difference. A rough estimate for harnessed waterfalls indicated that 5-10% could be added to the waterfall energy input. On the other hand, if, as in Wall's studies (see above), the fuel exergy was set equal to the energy figures, the total exergy input would have been 2.1% lower, and the total exergy efficiency 0.5% higher.

For some figures used in the end-use sector analyses, accurate values were not available. Since this is a complicated system, we may have overlooked some details. In particular, cross flows between sectors are hard to trace properly. This may result in one sector beeing a bit more efficient, at the cost of another. However, the efficiency of the total system is not affected by unaccounted crossflows.

Exergy in imported manufactured products has been excluded, e.g. cars and machinery. A rough estimate on the number, mass, and materials of cars and heavy machinery indicated that this import may represent approximately 1 PJ exergy.

Three sectors are, for different reasons, difficult to quantify. The chemical industry is so diverse that a reasonably complete overview would be an overwhelming task, even though statistical material was available. Moreover, a detailed exergy analysis requires data on the content of the products. Such data may very well be product secrets. In this study, we have assumed that the chemical products contains 60% of the exergy input to the chemical industry. If we had chosen this figure ±10%, the total exergy output would have changed ±4%, and the total efficiency would be affected by ±1%.

The efficiency of transportation sector is uncertain. The important question in this case is how much of the performed work is "useful". A study like this has to be based on the equipment that is actually used, and in the way it is actually used. One alternative may be to use idealized or best-performance vehicles as a reference for comparison. However, this may lead to a line of discussion that ultimately ends up by concluding that, ideally, most transportation is not necessary.

Space heating was discussed in section 2.2. We choose to use 6% as a representative exergy efficiency. This factor corresponds to an indoor air temperature of 21 °C and a representative environmental temperature of 3 °C. This was based on the year-around sea and ground temperature and the fall and spring air temperatures. An error of less than ±2% seemed reasonable. This would affect the total exergy output by ±1%, and the total efficiency by ±0.3%.

6 CONCLUDING REMARKS

For 1995, the year of the analysis, the total exergy input was 1184 PJ. From this, 280 PJ exergy was contained in products and services. This output was 24% of the input. Oil and gas for export, and the fuel required for this export, was not included in the analysis.

Sectors of the society that are noted as having low exergy efficiencies are space heating, lighting and electric equipment, transportation, and the food sector. Each of these sectors used a considerable share of the total input, and had an irreversibility or loss of exergy above 80%. About three-quarters of the total end-use irreversibility occurred here. The first and second of these sectors can be regrouped into households and public services, both with approximately 10% exergy conservation.

The industrial sectors, mainly forestry, metal, and chemical industry had exergy efficiency of 30–60%. Due to the substantial contribution from hydropower, the energy sector had relatively low losses.

Acknowledgements – We wish to thank all the people who helped us in securing the necessary statistical data and models, whithout which this study would have been impossible. In particular: B. Grinden at Sintef Energy Research, Trondheim; H. Tveit, E. Ringdalen, and H. Karoliussen at Sintef Material Technoloy, Trondheim; E. Andersen at Elkem Rana, Rana; Maria Mielnik at Matforsk Norwegian Food Research Institute, Ås; G. Wall, Mölndal, Sweden; T. Tandle and numerous other members of the staff at Statistics Norway, Oslo.
This work was funded by Sintef Energy Research, Trondheim, and we are grateful for the enthusiasm and support shown by the head of the Department of Applied Thermodynamics and Fluid Dynamics, Professor Bjørn F. Magnussen.

References

1. Reistad G. M. Available energy conversion and utilization in the United States. *ASME J. Eng. Power* 1975; 97: 429-434.

2. Wall G. "Exergy - a useful concept within resource accounting", Report No. 77-42, Institute of Theoretical Physics, Chalmers University of Technology and University of Göteborg, Göteborg, Sweden (1977).

3. Wall G. "Exergy - a useful concept," Dr.thesis, Chalmers University of Technology, Göteborg, Sweden (1986).

4. Wall G. Exergy conversion in the Swedish society. *Resour. Energy* 1987; 9(1): 55-73.

5. Wall G. Exergy conversion in the Japanese society. *Energy* 1990; 15(5): 435-444.

6. Wall G., Sciubba E., and Naso V. Exergy use in the Italian society. *Energy* 1994; 19(12):1267-1274.

7. Wall G. Exergy use in the Swedish society 1994. In: Int. Conf. on Thermodynamic Analysis and Improvement of Energy Systems (TAIES'97), June 10-13, Beijing, China (1997).

8. Rosen M. A. Evaluation of energy utilization efficiency in Canada using energy and exergy analyses. *Energy* 1992; 17(4): 339-350.

9. Schaeffer R. and Wirtshafter R. M. An exergy analysis for the Brazilian economy: From energy production to final energy use. *Energy* 1992; 17(4): 841-855.

10. Ílerí A. and Gürer T. Energy and exergy utilisation in Turkey during 1995 *Energy* 1998; 23(12): 1099-1106.

11. Nakićenović N., Gilli P. V., and Kurz R. Regional and global exergy and energy efficiencies *Energy* 1996; 21(3), 223-237.

12. Ertesvåg I. S. "Society exergy analysis: A comparison of different societies", submitted for publication.

13. Kotas T. J. *The exergy method of power plant analysis*, 2nd ed. Malabar, Florida: Krieger, 1995.

14. Bedringås K. W., Ertesvåg I. S., Byggstøyl S., and Magnussen B. F. Exergy analysis of solid-oxide fuel-cell (SOFC) systems, *Energy* 1997; 22(4): 403-412.

15. Wall G. Corrected expression for space-heating exergy to heat ratio. Personal communication (1999).

16. Ertesvåg I. S. and Mielnik M. "Energiutnytting i Noreg – Eksergianalyse av det norske samfunnet" ("Energy utilization in Norway – Exergy analysis of the Norwegian Society"; in Norwegian). Report No. TR A4991, Sintef Energy Research, Trondheim, 1999.

17. *Statistical Yearbook 1996*. Oslo: Statistics Norway, 1996.
    In part available at `http://www.ssb.no/`

18. *Statistical Yearbook 1997*, Oslo: Statistics Norway, 1997.
In part available at `http://www.ssb.no/`

19. *Official Statistics of Norway: Energy Statistics 1995*. Oslo: Statistics Norway, 1997. Also in: *Ukens statistikk No.38*, (1997). Available at `http://www.ssb.no/`.

20. Further details and breakdown of the data in Ref. [19]. Statistics Norway, Oslo. Personal communiation (1998).

21. *Official Statistics of Norway: Fishery Statistics 1993-1994*. Oslo: Statistics Norway, 1997.

22. *Official Statistics of Norway: Hunting Statistics 1995*. Oslo: Statistics Norway, 1996.

23. USDA Nutritient Database, Beltsville Human Nutrition Research Center, USA. `http://www.nal.usda.gov/fnic/cgi-bin/nut_search.pl`

24. "NORKOST 1993-94 Landsomfattende kostholdsundersøkelse blant menn og kvinner i alderen 16-79 år" (Nationwide diet survey among men and women at ages 16-79 years) Norum K. R. and Bjørneboe G.-E. A. (eds.), National Council on Nutrition, Oslo (1997).

25. *Official Statistics of Norway: Forestry Statistics 1995*. Oslo: Statistics Norway, 1997.

26. "Key Figures 1996", Norwegian Pulp and Paper Association, Oslo (1996).

27. *Official Statistics of Norway: Manufacturing Statistics 1995*. Oslo: Statistics Norway, 1997. Also in: *Ukens statistikk No.51-52*, (1996). Available at `http://www.ssb.no/`

28. Data from Statistics Norway, Skanaluminium, and Hydro Aluminium. Personal communication (1998).

29. Data from Statistics Norway, Elkem Rana, Sintef Material Technology, and Hydro Magnesium. Personal communication (1998,1999).

30. *Official Statistics of Norway: External Trade 1995*. Oslo: Statistics Norway, 1996.

31. *Statistisk månedshefte No.11*, Statistics Norway, Oslo (1997). Available at `http://www.ssb.no/`

32. *Official Statistics of Norway: Electricity Statistics 1995*. Oslo: Statistics Norway, 1996.

33. Grinden B. Department for Power Generation and Market, Sintef Energy Research, Trondheim. Personal communication (1998).

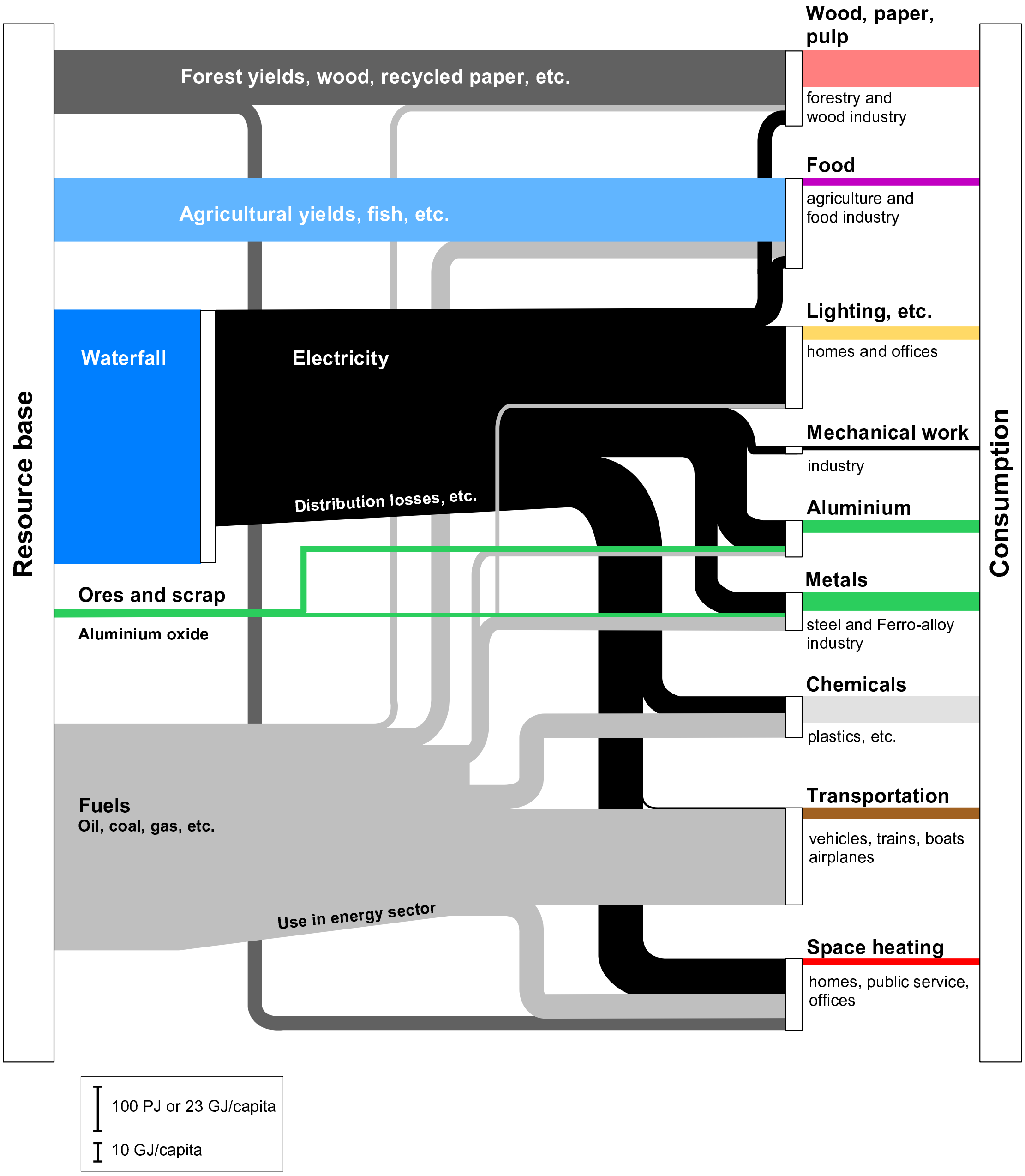

Figure 1: Exergy flows in the Norwegian society 1995, excluding oil and gas for export.

Tables

Table 1: Total production of primary energy carriers and commodities in Norway 1995

Energy carrier	Energy (PJ)	Exergy (PJ)
Coal, coke	8.2	8.7
Crude oil, petroleum products	5968.3	6327.4
Natural gas	1302.6	1354.7
Waterfall energy	518.8	518.8
Fuelwood	24.6	27.3
Wood (industrial)		75.1
Food, fodder		103.9
Ore, scrap		6.8
Sum		8421.7

Table 2: Exergy factors for energy carriers: Exergy divided by energy. For fuels the energy is the lower heating value, and for fuelwood the efficient heating value.

Energy carrier	Exergy factor
Waterfall energy	1
Electrical energy	1
Oil, petroleum products	1.06
Natural gas	1.04
Coal	1.06
Coke	1.05
Fuelwood (20% humidity)	1.11

Table 3: Domestic supply of energy carriers in Norway 1995

Energy carrier	Energy (PJ)	Exergy (PJ)	Fraction of input (%)	Loss/usage in energy sector (PJ)	Exergy to user sectors (PJ)
Coal	28.6	30.3	2.6		30.3
Coke	24.7	25.9	2.2		25.9
Petroleum products	372.8	372.8	31.5	31.2	341.6
Natural gas	0.6	0.6	0.1		0.6
Waterfall	489.4	489.4	41.3	73.4	
Electricity				35.2	380.8
Fuelwood	24.6	27.3	2.3		27.3
Wood for industry		104.6	8.8		104.6
Food, fodder		122.7	10.4		122.7
Ore, scrap		10.3	0.9		10.3
Sum		1183.8	100.1	139.8	1044.1

Table 4: Exergy in imported and exported food

	Mass (10^6 kg)		Exergy	Exergy (TJ)	
	Import	Export	(MJ/kg)	Import	Export
Meat	11	3	4.5	49.5	13.5
Dairy produce	7	33	4.9	34.3	161.7
Fish	237	1349	5.75	1362.8	7756.8
Grain	536	14	14.9	7986.4	208.6
Vegetables, fruit	410	9	1.9	779.0	17.1
Sugar, honey	247	4	15.2	3754.4	60.8
Coffee, tea, spices, etc.	64	9	10.7	684.8	5.4
Animal fodder (ex. grain)	242	262	16.1	3896.2	4218.2
Various	28	17	9.0	252.0	153.0
			Total:	18.8 PJ	12.6 PJ
			Net Import:	6.2 PJ	

Table 5: Exergy in harvested crops, fish and game

	Mass (Mton)	Exergy (PJ/Mton)	Exergy (PJ)
Wheat	0.312	13.9	4.337
Oats	0.354	16.3	5.770
Barely	0.547	14.8	8.096
Oil seeds	0.017	37.0	0.629
Potatoes	0.400	3.3	1.320
Fruit, vegetables	0.178	1.9	0.338
Hay	3.274	16.1	52.711
Green fodder	0.973	16.1	15.665
Cod	0.707	3.5	2.475
Herring, brisling	0.730	7.4	5.402
Mackerel, capelin, etc.	0.970	6.3	6.111
Other (shellfish, etc.)	0.114	3.9	0.444
Seaweed, sea tangle	0.185	1.6	0.296
Game	0.0065	4.5	0.029
		Total:	103.6

Table 6: Metal production

Metal	Production (Mton)	Exergy (PJ/Mton)	Exergy (PJ)
Zinc	0.12	5.4	0.65
Nickel	0.05	4.3	0.22
Copper	0.03	2.1	0.06
Magnesium	0.03	25.8	0.77
Silicone	0.09	28.6	2.57
Ferrosilicon	0.385	22.8	8.78
FeSiMn	0.2	12.5	2.50
Ferromanganese	0.16	10.3	1.65
Ferrochrome	0.14	11.5	1.61
Steel	0.5	6.8	3.40
Total (ex. Aluminum)	1.71		22.2
Aluminum	0.85	32.9	28.0

Table 7: Household exergy consumption and conversion

Purpose	Electricity (PJ)	Total input (PJ)	Fraction of total (%)	Efficiency	Output (PJ)
Space heating	51.3	92.3	55.5	0.06	5.5
Water heating	30.0	30.0	18.1	0.17	
Lighting	13.8	13.8	8.3	0.10	
Cooling	10.0	10.0	6.0	0.30	
Other equipment	8.8	8.8	5.3	0.30	
Cooking	5.0	5.0	3.0	0.20	
Washing	3.8	3.8	2.3	0.20	
Drying	2.5	2.5	1.5	0.20	14.4
Total	125.2	166.2	100.0	0.12	19.9

Table 8: Public service exergy consumption and conversion

Purpose	Electricity (PJ)	Total input (PJ)	Fraction of total (%)	Efficiency	Output (PJ)
Space heating	16.2	31.3	36.2	0.06	1.9
Lighting, equipment	43.0	43.0	49.8	0.10	
Water heating	11.0	11.0	12.7	0.17	
Motors	1.1	1.1	1.3	0.50	6.7
Total	71.3	86.4	100.0	0.10	8.6

Table 9: Other industry exergy consumption and conversion

Purpose	Electricity (PJ)	Total input (PJ)	Fraction of total (%)	Efficiency ratio	Output (PJ)
Mechanical work	11.2	11.2	32.0	0.50	5.6
Space heating	1.7	12.4	35.4	0.06	0.7
Lighting, equipment	3.4	3.4	9.7	0.10	
Water heating	0.9	0.9	2.6	0.17	
Process heating	0.0	7.1	20.3	0.26	2.3
Total	17.2	35.0	100.0	0.25	8.7

Table 10: Results from the different end-user sector analyses

User sector	Exergy input (PJ)			Fraction of	Exergy	Efficiency
	Commodities	Energy carriers	Sum	input (%)	output (PJ)	(%)
Forest industry	104.6	36.1	140.7	13.6	71.2	51.2
Food industry	122.4	46.8	169.2	16.4	28.5	16.8
Aluminum	5.4	65.9	71.3	6.9	28.0	39.3
Steel/metal	4.9	61.1	66.0	6.4	22.2	33.6
Chemical industry		106.6	106.6	10.3	64.0	60.0
Transportation		189.5	189.5	18.4	31.1	16.0
Lighting, equipment, etc.		140.4	140.4	13.6	23.4	16.7
Mechanical work		11.2	11.2	1.1	5.6	50.0
Space heating		136.0	136.0	13.2	8.2	6.0
Total	237.3	793.6	1030.9	99.9	282.3	27.4

Table 11: Alternative grouping of the results for the sectors "Lighting, equipment, etc.", "Mechanical work", and "Space heating" in Table 10

User	Exergy input (PJ)			Fraction of	Exergy	Efficiency
sector	Commodities	Energy carriers	Sum	input (%)	output (PJ)	(%)
Other industry		35.0	35.0	3.4	8.7	24.8
Households		166.2	166.2	16.1	19.9	12.0
Public service		86.4	86.4	8.4	8.6	10.0

Table 12: Main result, exergy conversion in Norway 1995

	Exergy (PJ)	Fraction of total input (%)
Total input	1184	100.0
Lost/used in energy sector	140	11.8
Input to end-user sectors	1031	87.1
Loss in end-user sectors	751	63.4
Output from end-user sectors	282	23.8