Energy, Exergy, and Extended Exergy Analysis of the Norwegian Society 2000

Ivar S. Ertesvåg*

Department of Energy and Process Engineering
Norwegian University of Science and Technology
NO-7491 Trondheim, Norway

(Received 27 June 2003, final version 21 April 2004) – Accepted for publication in Energy.

Abstract The extraction, conversion, and use of energy carriers and materials in the Norwegian society in 2000 were investigated by Sciubba's method of extended exergy accounting (EEA). In this method, extended exergy (EE) values are assigned to labor and capital fluxes in addition to thermomechanical and chemical exergy values. The interchange of resources and products was quantified in terms of energy and exergy between seven sectors of the society and between the sectors and other countries. The extraction of resources from the environment and the discharge and deposit of waste were also included in the analysis. In the extraction sector, the exergy and extended exergy conversion efficiencies both were 95%, and in the conversion sector both were approximately 76%. These two sectors are, respectively, dominated by oil and gas extraction and hydropower conversion. The third sector – agriculture, forestry, the fisheries, and food industry – had a lower exergy output to input ratio, 45%, whereas the extended exergy conversion efficiency was 62%. A fourth sector, manufacturing industry, was dominated by paper, metal, and also chemical industry, and the efficiencies were 50% and 69%, respectively. In the transportation and service sectors, the labor and capital fluxes dominated the EEA, giving EE efficiencies of 63% and 75%, respectively, whereas the exergy efficiencies were 19% and 26%, respectively. In the seventh sector, the domestic sector (i.e. households), there was a close to zero energy and exergy output in this approach, since no products or resources were transferred to the other sectors except waste for recirculation. However, the EE output of this sector was greater than the input, since labor is supplied from this sector to the other sectors.

1. Introduction

Energy analyses are conducted regularly by the official statistical agencies of all developed countries and included in the official statistical reports. These analyses quantify the extraction, import, and export of energy carriers, conversion to other energy carriers, and the detailed distribution among different types of users. Similarly, statistical analyses are made of other quantifiable aspects of a society. Most of these activities tend to be summarized and compared in terms of monetary values.

Some scientists and laymen feel a growing discomfort in the situation where money is the common metric of all activities and processes. For instance, pollution is often evaluated by the cost of cleaning, which is zero if not cleaned. Or, if it is harmful to humans, the pollution is evaluated in terms of related medical expenses. The use of fossil fuels is evaluated by its

* FAX: +47 73 59 35 80, e-mail: Ivar.S.Ertesvag@ntnu.no

spot price and not in relation to future usefulness or in view of the irreversibility associated with the use.

In searching for possible alternatives for a common metric, some scientists have pointed to exergy. Then, the activities in a society, or in other sociotechnical systems like industrial sites, factories, or thermal processes, will have to be represented by exergy values.

The role of exergy in thermodynamic analyses of technological systems has increased in recent decades. Society exergy analyses have been presented for a few countries. This application of the exergy method was introduced by Reistad [9], who analyzed the US situation in 1970. Wall [23,24] extended this approach and used Sweden as the system of analysis. A number of such society exergy analyses are reviewed and compared by Ertesvåg [1]. The exergy use in the Norwegian society was analyzed by Ertesvåg and Mielnik [3] for the year 1995. This analysis has been repeated for the year 2000 by Ertesvåg and Leintrø [2].

The method of Extended Exergy Accounting (EEA) was introduced by Sciubba [10] (cf. [11,12]) and applied to the Italian society 1996 by Milia and Sciubba [7]. In short, the EEA also assigns exergetic values (i.e. extended exergy, EE) to labor and to monetary flows within the system. Furthermore, the society EEA includes crossflows of exergy associated with products and services transferred between the different sectors in the society. This aspect is only addressed to a lesser extent in the approaches mentioned above.

This study is primarily a case study where the EEA is employed for a country. It may also contribute to the development of the method and to the discussion of some implications of using it. The EEA of Norway is compared to the corresponding energy and exergy analyses of the society with the same subsystems (sectors).

2. Methodology

In the EEA of a country, the system (society) is subdivided into the following sectors, cf. Fig. 1:

- Ex: Extraction, which includes mining and quarrying, oil and natural gas, refining and processing.
- Co: Conversion, which comprises heat and power plants.
- Ag: Agriculture, forestry, and the fisheries, and related industry.
- In: Industry, manufacturing industry except food industry and oil refineries.
- Tr: Transportation services.
- Te: Tertiary sector, services other than transportation.
- Do: Domestic sector, households.

The surroundings of the system are

- E: Environment, the Earth crust, the atmosphere, the oceans, etc.
- A: Abroad, other countries or societies.

It will be shown that the exports to other countries from Norway is very large compared with domestic use. Therefore, sector A (abroad) was introduced in the present analysis. Furthermore, the data for the Ex-sector was aggregated in such a way that this sector could be readily split into one subsector for domestic use and one purely for export. Such a split may be convenient for comparisons with other societies.

All fluxes between these sectors, and between the surroundings and a sector within the system, are accounted for. Each flux is characterized as one of the following:

R: Resources, primary (fossil fuels, solar, wind, minerals, metals, geothermal, hydraulic) and secondary (products from petroleum refining, mineral- and metal working), and electric energy.

N: Natural resources (agricultural products, wood, natural fibers, livestock, fish, game).

P: Products (products and services generated by In, Tr, and Te-sectors).

T: Trash fluxes (organic and inorganic waste materials) deposited in the environment.

D: Discharge (combustion gases, thermal discharge including radiated heat), heat and mass spread in the environment.

W: Human work, labor.

C: Capital.

In the EEA, all these fluxes are assigned an exergy value.

In an energy analysis, the energetic value of a flux is accounted for relative to some reference. Similarly, the exergetic value of the flux is accounted for in an exergy analysis.
The annual energy balances or energy accounting published by the national statistical agencies usually include only R- and some, but not all, N-fluxes. The society exergy analyses [24,1] also regard the output P-fluxes. In principle, also T- and D-fluxes can be included in both energy and exergy analyses. The exergetic value is the thermomechanical and chemical exergy described in the thermodynamics literature, e.g. Kotas [5].

When comparing the present analysis and that of [7] with society exergy analyses following the approaches of Reistad and Wall (cf. [1]), some differences have to be noted.

First, the subdivision into sectors is different in Sciubba's EEA approach followed here. Second, the conversions in the sectors are treated somewhat differently. In Wall's approach [23], useful output is accounted for whenever produced. For instance transportation, lighting, and space heating within the households contribute to the exergy output or utilization of that sector. Hence, emphasis is put on the conversion rather than on the use and transfer of the product. In the EEA, however, only services and products that are transferred to another sector are accounted for as output or useful products. Therefore, the analysis of the exergy conversion gives different results in the two approaches.

The exergetic value of labor (W-flux) is obtained [10] as

$$E_W = n \cdot \frac{E_{in}}{n_{tot}}, \qquad (1)$$

where n is the flux of work hours into a sector, n_{tot} is the total amount of work hours, and E_{in} is the exergy influx to the society.

The exergetic value of a monetary flux (C-flux) is obtained [10] as

$$E_C = C \cdot \frac{E_{in}}{C_{ref}}, \qquad (2)$$

where C is the monetary flux in a relevant currency and C_{ref} is a reference amount of money. For the latter [9] proposes to adopt the broad money, M2, published by the National Bank for each country.

The present analysis was based on data for Norway for the year 2000. The fluxes were accounted as summaries for that year, usually in PJ (petajoule). The main sources were the official statistical accounts by Statistics Norway (energy, economics, waste, export, import, manufacturing, etc.). This was supplemented by data from the industry and industry associations.

3. Extraction sector, energy carriers

This sector includes coal mining, oil and gas extraction, oil refining, natural-gas processing (to retail natural gas, LNG, LPG, etc.), and transportation and services directly related to this business. The import and export of such products are also included in the sector, since this is conducted within the same infrastructure as the extracted primary energy carriers and their products. Details are shown in Table 1, where the import includes the reduced storage. As will be seen, the export was 20 times the domestic consumption. Therefore, in order to compare this analysis with other societies, it may be useful to separate the consumption and losses related to export from those related to domestic energy use.

The domestic extraction of ores and minerals is also included in this sector and is treated in the next section together with other fluxes of raw materials.

The consumption of energy carriers within this sector, Tables 2–3, included the use of (by energy figures) 6.3 PJ petroleum products for oil and gas extraction, 0.2 PJ for coal mining, and 1.6 PJ for other mining activities. In addition, transportation in mining and quarrying used 0.2 PJ, and supply ships and oil transport from the fields used 8.8 PJ of petroleum products. This gave a total of 17.1 PJ energy in petroleum products used for extraction. The net loss and consumption of oil and petroleum products in oil refineries was 27.5 PJ. Oil refineries also produced 7.4 PJ petrol coke, which was included in the output. The natural gas (165.2 PJ) was used for oil and gas extraction. The electricity was used in oil and gas extraction (1.5 PJ), mining (1.6 PJ), and oil refineries (1.8 PJ). The consumption associated with export was that of the entire (actually 97%) oil and gas extraction, 67% of the refinery use when petrol coke production was subtracted, and 25% of the consumption in ore and mineral mining.

In the energy analysis, the discharge to the environment is equal to the energy value of the used energy carriers. That is, all energy not bound to the output energy carriers is regarded as discharged into the environment as flue gas energy, heat, and friction work. The exergetic value of this discharge is taken as a certain percentage (16% in this analysis) of the energetic value. The remaining exergy is lost by irreversibilities.

The output from the Ex-sector is shown in Table 4. It should be noted here that more than 5800 PJ corresponds to exported crude oil. Thus, the consumption in refineries related to less than one-tenth of this. It can also be noted that the import of refined products was about one-third of the domestic consumption.

4. Raw materials

The raw materials for metal industry are ores and minerals, and concentrates and oxides thereof. They are supplied from inland extraction (Ex-sector) and imported from abroad (A). Furthermore, scrap is collected and re-circulated by enterprises within the service sector (Te-sector) and imported from abroad. The data on ores, minerals, and recirculated metals are in part obtained by personal communication with the industry, cf. [2,3], and in part obtained from the foreign trade statistics [20,21].

Extraction of ores and minerals
Among the extracted ores and minerals, iron ore, ilmenite (titanic iron ore), and olivine are the main contributors to the exergy analysis. All these materials have a zero or negligible energy value.

The amount of iron ore was 0.63 Mton (million tonnes, 10^9 kg). With an exergy content of 0.50 PJ/Mton (66% iron by mass in Norwegian ore), this gave 0.3 PJ exergy. This was used in the ferrous-alloy and steel industry. From ilmenite, 0.70 Mton ilmenite concentrate and titan oxide was produced, which gave 0.4 PJ. The export was 0.37 Mton or 0.2 PJ. The remaining was mainly used in the chemical industry (paints, etc.). Olivine was produced in an amount of 3.48 Mton, which gave 3.1 PJ exergy. This was mainly exported. The production of quartzite and quartz was 1.10 Mton or 0.03 PJ exergy (containing 0.03 PJ/Mton). This was used in the ferrous-silicon industry. The production of other stone, gravel, and minerals was more than 40 Mton, however less than 0.5 PJ exergy.

The extraction of ores and minerals, excluding iron ore and quartz (see below), was 3.8 PJ exergy. Of this, approximately 0.4 PJ was used in the industry sector, approximately 0.4 PJ was used for construction and civil engineering (i.e. the Te-sector), and 3.0 PJ was exported.

Recirculation, import, and export of oxides and scrap metals
The aluminum industry imported 0.086 Mton recirculated aluminum with 2.84 PJ exergy (32.9 PJ/Mton) and 2.12 Mton aluminum oxide with 4.24 PJ exergy (2.0 PJ/Mton) for a total of 7.08 PJ exergy.

The ferrous-alloy and steel industry imported manganese ore and concentrate (assumed 76% MnO_2): 0.603 Mton (exergy 0.2 PJ/Mton); chrome ore (70% $FeCr_2O_4$): 0.370 Mton (0.4 PJ/Mton), quartzite and quartz: 0.59 Mton (0.03 PJ/Mton), and 0.19 Mton iron ore and concentrates. From the extraction (0.63 Mton, see above), 0.063 Mton was exported, and thus the net supply to the domestic industry was 0.76 Mton. The exergy content (assumed 66% Fe) is 0.50 PJ/Mton, and the exergy in ores and quartz for ferrous alloys and steel was then 0.38 PJ extracted, 0.35 PJ imported, 0.03 PJ exported, and the net supply to the non-offshore industry 0.69 PJ.

In this analysis, it was assumed that scrap metal is collected by enterprises in the Te-sector from industry waste, and recirculated into valuable raw materials. Unfortunately, no detailed statistics for recirculation was readily available. However, the industry used 0.772 Mton (exergy content 6.8 PJ/Mton) scrap iron and steel, of which the import was 0.37 Mton. Another 0.14 Mton was exported (here assumed to be from the Te-sector). Thus the exergy input was 5.2 PJ to steel industry, 2.5 PJ was imported from abroad, 2.7 PJ was recirculated for domestic use, and 1.0 PJ was recirculated for export.

The total of zinc concentrate and zinc oxide imports amounted to 0.253 Mton, that is, 0.12 PJ exergy (assumed 0.46 PJ/Mton). Magnesium was mainly extracted from seawater, which is a part of the environment and has zero exergy value. However, the magnesium industry in addition used 0.008 Mton recirculated magnesium, with 0.21 PJ exergy (25.8 PJ/Mton). Furthermore, 0.085 Mton nickel concentrate (7.39 PJ/Mton) and 0.036 Mton copper concentrate (4.86 PJ/Mton) were imported, giving 0.80 PJ exergy. The use of soda (natrium carbonate, Na_2CO_3; 0.5 PJ/Mton) was 0.026 Mton or 0.013 PJ exergy. Thus, the total input of raw materials to the non-ferrous metal production (except aluminum) was 1.14 PJ exergy, of which 0.9 PJ was imported ores and concentrates and 0.2 PJ domestic recirculated metal.

In summary, the mineral and metallic raw-material flows are 4.2 PJ from environment to Ex-sector, and from Ex-sector 3.0 PJ to abroad, 0.4 PJ to In-sector, and 0.4 PJ to Te-sector. The In-sector imports 10.9 PJ, while the Te-sector transfers 2.9 PJ to In-sector and 1.0 PJ abroad.

Raw materials for the wood, pulp and paper industry
Data for the extraction, import, export, and use of wood were found in the Forestry Statistics [17] and the Energy Statistics [16]. For the exergy content of paper and industrial wood, data from Wall [23] were used: 17 PJ/Mton for paper, 8.0 PJ/Mm^3 for solid wood. Waste paper is collected by enterprises in the Te-sector and recirculated to the In-sector, and also exported to industry abroad. These fluxes were 4.4 PJ and 4.2 PJ exergy, respectively. Another 1.2 PJ exergy was imported by the industry, which, accordingly, used 5.6 PJ from recirculated paper. In addition, the industry imported 27.3 PJ exergy in timber for raw materials and 2.6 PJ exergy in pulp.

From the domestic harvest (Ag-sector), the industry got 33.3 PJ exergy in timber for raw materials. Thus, the total exergy in raw materials for the wood, pulp and paper industry was 68.8 PJ.

In summary, the raw-material fluxes for wood, pulp and paper industry were 36.4 PJ exergy extracted from environment to Ag-sector, of which 33.3 PJ was transferred to the In-sector and 3.1 PJ exported abroad. The In-sector imported 31.1 PJ and received 4.4 PJ from the Te-sector, which also exported 4.2 PJ. The energy content in these flows are found by assuming the exergy of wood was 1.23 times the net calorific value (efficient heating value), which corresponds to 50% humidity (cf. [5]).

Finally, as seen in the waste-treatment analysis below, some plastics and textiles are recirculated. This amount, 0.6 PJ exergy, was assumed to be input to the chemical or “other” industry from the Te-sector.

5. Waste

Waste can be defined as scrapped or redundant movables or materials. This is the definition used in the Norwegian Pollution Act and in the Waste Accounts [22]. Most materials are sooner or later included in this category. However, materials that are redundant in the primary production of a factory (and thus “waste”) may still be used for other purposes and sold as raw material or used as fuel. Therefore, the waste statistics may include, for example, wood that is classified as fuelwood in the energy statistics.

The fluxes of recycled raw materials have been analyzed above. Waste materials used for energy purposes are included in the energy-carrier analysis. These fluxes are also included in the waste statistics. This section will consider issues such as how to quantify the waste flow that was deposited in landfills, discharged into the environment, or burned without energy recovery. In the method used in this analysis, these are denoted as trash (T) and discharge (D) fluxes, respectively. The latter also includes the exergy discharged with combustion flue gases, and thermal discharge.

The main contributors to the exergy figures of waste to trash, discharge, and energy purposes are paper, plastics, metals, and textiles. These are shown in Table 5. Here, the quantities classified under "other or unspecified treatment" (main contribution from metals) in the source, were assumed to be deposited (i.e. T flux).

The material-recovery figures also deviate from that of the raw-material analysis above, which gave 8.6 PJ exergy in paper and 3.9 PJ in metals. This is due to uncertainties in underlying data of both analyses. Moreover, the differences may be attributed to the definition of "waste" and thus to the definition of "recovery".

In addition to the types of waste shown in Table 5, some wet-organic waste is deposited or discharged. Since the water content is very high, the net calorific value is quite low and was neglected. However, this material may contain some exergy (assumed 2 PJ/Mton). This estimate gave 0.7 PJ exergy from households (Do), 0.1 PJ from industry (In), and 0.1 PJ from services (Te). These figures add to the trash (T fluxes) above. Furthermore, the discharge (D flux) of organic matter to the sea from fishing (Ag-sector) was estimated to 0.7 PJ exergy.

6. Conversion sector

In Norway, 99% of the produced electricity comes from hydropower. In addition, this sector comprises some minor thermal powerplants and some district heating plants. Furthermore, some thermal conversion in metal-works is included in the energy statistics, and accordingly, included in this analysis as well.

Hydropower plants utilized 602.4 PJ of waterfall energy. This was the main input to this sector. Furthermore, some other energy carriers were used as shown in Table 6. It was assumed that the waste used for energy purposes was collected by the service sector (Te). It should be noted that the estimated energy recovery from waste (7.1 PJ) was larger than that found in the national energy balance (5.4 PJ energy) [16]. One reason for this may be inaccuracies in the waste-for-energy estimate. However, the main reason is that the figure in the energy balance was the energy transferred to the secondary energy carrier (water, steam) in thermal plants. The fraction of the fuel energy content lost by flue-gas and diffuse furnace losses was not included in that figure. The energy efficiency used in the statistics [22] was 73%. Thus, the 7.1 PJ of waste was represented by 5.2 PJ in the Energy Statistics [16]. Consequently, the remaining 0.2 PJ of the figure in the national energy balance was fuelwood.

Coal, petroleum products (except 0.2 PJ used for transportation within the sector), natural gas, wood, and waste were used in thermal plants, and coke was used in ironworks for energy conversion. These plants produced 1.1 PJ exergy (5.4 PJ energy) district heating and 2.7 PJ electricity. Waterfall energy was lost (15%) in the conversion to electric energy. Electricity was lost in the grid (35.7 PJ) and used in hydropower plants for operation (4.1 PJ) and for pumping (3.2 PJ). A fraction of these losses was associated with export according to the fraction (14.8%) of the delivered electric energy. The remaining conversion sector used 1.7 PJ of electricity. The losses are summarized in Table 7 and the output in Table 8.

7. Agriculture and the fisheries

This sector comprises agriculture, forestry, fish farming, fishing, hunting, and the food-processing industry. The main input to the sector is natural resources harvested from the environment or imported, and energy carriers.

Table 9 shows the use of energy carriers in the Ag-sector. These figures included 1.4 PJ exergy (energy: 1.3 PJ) in petroleum products for transportation within the fisheries and agriculture. In forestry, only 0.6 TJ (terajoule) of petroleum products was used, which is negligible compared to the figures given for the remaining sector.

Other input
Imported food, fodder, raw materials, etc., contributed 49.2 PJ exergy. The harvest from agriculture and the fisheries gave 88.6 PJ exergy in hay, grain, vegetables, fruit, fish, and game [2]. Domestic animals and farmed fish were not included in this figure. Forestry produced 69.0 PJ exergy in wood. This was the amount exported, sold to industry (In) and households (Do), and used within the sector.

Output
Food consumption in Norway was estimated to 12 MJ exergy per capita per day [3]. With an average population of 4.491 million during the year 2000, this amounted to 19.7 PJ of net consumption for that year. When 5% loss was assumed in the household (Do) sector, the flux from the service (Te) sector was 20.7 PJ. Furthermore, when a 10% loss was estimated in the Te-sector (groceries, restaurants, etc.), the output from the Ag-sector to the Te-sector became 23.0 PJ. In addition, exported food, fodder, food raw materials, etc., contained 24.1 PJ exergy.

Produced industrial wood gave 27.1 PJ exergy (24.4 PJ energy) for energy purposes and 33.3 PJ exergy for raw-material purposes to Norwegian industry. In addition, exported timber (with no processing) contained 3.1 PJ exergy. These quantities were included in the raw-materials and energy-carriers analyses above.

The commercially produced fuelwood contained 5.4 PJ exergy (energy: 4.9 PJ), which was supplied to households (Do-sector). In addition, a considerable amount of non-commercial fuelwood was extracted directly by households, as seen in the analysis of that sector below.

8. Industry

The manufacturing industry sector (In) was subdivided into wood, pulp, and paper industry, aluminum industry, other metal-producing industry, chemical industry, and other industry. The latter group consisted primarily of mechanical industry, shipbuilding, and textiles, that is, industry that was not included in the other groups. The food industry was included in the agriculture and fisheries sector (Ag). The use of energy carriers is shown as energy and exergy figures in Tables 10-11. Transportation by the manufacturing industry was estimated separately as shown in the tables.

This gave 167.1 PJ exergy (energy: 160.4 PJ) from the Ex-sector, 168.9 PJ (energy: 169.2 PJ) from the Co-sector, and 27.1 PJ (energy: 24.4 PJ) from the Ag-sector, whereas the remaining 0.2 PJ (energy, exergy) fuelwood was imported directly by industry. Included in these figures for energy carriers are considerable amounts of petroleum products, natural gas, coal, and coke that are used as raw materials and reducing agents.

The input of other raw materials, that is, timber, ores, minerals, oxides, and recirculated materials, was analyzed above. Some minor output flows were also described in the waste and raw-material analyses above.

The production of paper and cardboard was 39.1 PJ exergy, of which 34.9 PJ was exported. Wood for building materials was produced in an amount of 18.1 PJ exergy, including export of 10.8 PJ. Some of the produced pulp and cellulose, 9.3 PJ exergy, and also some wood chips, 1.5 PJ exergy, was exported as intermediate products. Thus, the products represented a total of 68.0 PJ exergy, of which the export was 56.5 PJ.

The production of metals is shown in Table 12. The energy content (enthalpy of devaluation or heating value) was 70.0 PJ. For the chemical industry, the production was estimated [3] to be 60% (of total input 118.0 PJ): 70.8 PJ exergy in products. Both chemicals and metals were mainly for export.

In the remaining partial sector, “Other industry”, the utilization of the 41.6 PJ exergy used was found from an estimate similar to that made by Ertesvåg and Mielnik [3] for 1995. The result was an output of 9.4 PJ, or 22.6% of the input.

Summarized, these output product fluxes amounted to 215.3 PJ exergy while the energy content was estimated to 205 PJ. There were no complete statistics available describing all details of domestic use, export, and import of metals, chemicals, and other industry products. For wood, pulp, and paper, and some other products, we have sufficiently accurate figures [17,20,21]. It seems reasonable to estimate that 10% of the products are used domestically. Accordingly, the export from industry represented 193.8 PJ exergy, and the domestic use represented 21.5 PJ exergy, including the 11.5 PJ of wood and paper.

An exact breakdown of this domestic output into input to the other sectors cannot be obtained from the available statistics. However, based on data in the National Accounts Statistics [13], a rough but reasonable estimate was made: 70% to the service sector (Te), 15% to the Ex-sector, 4% to the Co-sector, 7% to the Ag-sector, and 4% to the Tr-sector. These figures reflect that, compared to many other countries, the extraction sector is very large (30% of the nation's consumption of fixed capital). Furthermore, the fisheries sector (within Ag) is relatively large.

9. Transportation

This sector (Tr) is the commercial transportation services (passenger, goods). Services directly related to transportation are also included.

The input of energy carriers consisted mainly of petroleum products: 95.2 PJ exergy (energy: 89.8 PJ; hereof gasoline/ kerosene: 29.0 PJ, diesel/heavy oil: 60.7 PJ). In addition, some electricity, 6.6 PJ, was used, for a total of 101.8 PJ exergy (energy: 96.4 PJ).

Transportation within the other sectors was not included, most notably households (60.7 PJ exergy, 57.3 PJ energy) and wholesale and other services (26.2 PJ exergy, 24.7 PJ energy). This is different from the analysis by Ertesvåg and Mielnik [3], where all transportation was included in the transportation sector. The distinction is also found in the official Energy Statistics [16]: The energy balance sheet includes all transportation under this term, whereas the energy accounts only includes commercial transportation services. The latter sector boundaries are also used in the National Accounts Statistics [13,14], which is the main source of labor and capital-flow data in this analysis.

An attempt to split this into inputs to the other sectors was made as follows: Data on energy usage per passenger kilometer and per tonne kilometer was found in [4], and data on the relative importance of the various means of transportation was adapted from [15]. Although these sources do not completely distinguish between private and hired transportation services, an estimate can be attempted. Inland goods transportation was 27.0 PJ exergy (25.5 PJ energy), including 1.6 PJ (1.5 PJ energy) road and rail transportation of imported and exported goods, 14.4 PJ (13.6 PJ energy) by ship between Norwegian ports, and 11.0 PJ exergy (10.4 PJ energy) by other carriers, mainly by road and rail. Some of this should be reckoned under wholesale etc. The remaining transportation services are passenger transport, Table 13.

It was estimated that 75% of the goods transport services were conducted for industry customers, and the remaining 25% for the wholesale and other services. Furthermore, based on the national survey of travel habits [6], it was estimated that 50% of the air transport and 85% of passenger transport was conducted for households. The remaining passenger transport services were distributed among the other sectors according to their share of the total amount of labor work-hours. The result is shown in Table 20. Notice that 0.4 PJ transportation for the Tr-sector itself was not regarded as an output from the sector. The output is performed work against friction, etc., and therefore the energy and exergy values are equal.

10. Tertiary sector, services

This sector (Te) includes trade, commerce, hotels, entertainment, finance, real estate, construction, local and central government, municipal engineering, hospitals, schools of all grades, and nursing. However, transportation services is a separate sector (Tr, see above). Furthermore, services directly related to transportation (specified in the Energy accounts [16]) are withdrawn from the Te-sector.

Use of exergy from energy carriers
The Te-sector used 26.2 PJ exergy (energy: 24.7 PJ) from petroleum products for transportation within the sector, and 13.7 PJ (energy: 12.9 PJ) from petroleum products and natural gas for other purposes. Electricity contributed 79.6 PJ and district heating 0.6 PJ exergy (energy: 3.7 PJ). Fuelwood and waste gave 0.2 PJ (energy: 0.2 PJ). In summary, the total exergy of energy carriers was 120.3 PJ (energy: 121.1 PJ), which included 94.1 PJ (energy: 96.4 PJ) for purposes other than transportation.

The exergy output from the use of these energy carriers was estimated [3] to be 13% for the transportation and 10% of the remaining, that is, 12.8 PJ. This included 2.2 PJ in space heating and 5.0 PJ in lighting and equipment. This utilization was mainly related to use within the sector. The output is only the share of this that is directly to the benefit of other sectors. That is heating, lighting, etc. for groups such as customers in shops, patients in hospitals, students in schools, clients visiting offices. This share is hard to define and to measure. However, it is only a fraction of the total utilization in the sector. Here, the output to the household sector, i.e. the public, was set to 1.0 PJ exergy and 10.0 PJ energy, and the output to other sectors was neglected.

Other input and output
Stone, gravel, etc. extracted from the environment by the Ex-sector is supplied to the service sector. The amount was estimated to 0.4 PJ exergy.

Food products from agriculture, the fisheries and food industry (cf. the Ag-sector) gave 23.0 PJ (N-flux) exergy. A 10% loss was estimated, and thus the output to the household sector (Do) became 20.7 PJ exergy.

Transportation (Tr) contributed 4.5 PJ exergy input to the Te-sector, see above.

Waste is collected by this sector for material and energy recovery, as described in the waste analysis above. This input was 11.8 PJ from the In-sector, and 6.8 PJ from the Do-sector, in addition to 5.0 PJ from within the Te-sector. The output was 7.1 PJ to the Co-sector for energy recovery, and 11.3 PJ to the In-sector (paper, metals, plastics), and 5.2 PJ (paper, iron) for export abroad (A).

This sector receives a considerable fraction (assumed 70% or 15 PJ) of the domestically used products from industry. Some of this amount is used within the sector, whereas some is for resale to the public, and should be added to the output of the Te-sector. Here, this resale to the Do-sector was assumed to 5 PJ.

11. Households, the domestic sector

The main part of this sector (Do) is the private households. In the National Accounts Statistics [14], ideal organizations are also included. That is, non-commercial organizations that to a large extent rely on non-paid work, donations, membership fees, and government support.

The use of exergy from energy carriers was 121.0 PJ from electricity, 0.2 PJ (energy: 0.9 PJ) from district heating, 11.1 PJ (energy: 10.5 PJ) in petroleum products and coal for purposes other than transportation, and 60.7 PJ exergy (energy: 57.3 PJ) in petroleum products for transportation. This was the resource (R) fluxes from the Co- and Ex-sectors. Furthermore, the use of fuelwood was 26.8 PJ exergy (energy: 24.1 PJ), of which 5.4 PJ (energy: 4.9 PJ) was commercially sold fuelwood from the Ag-sector, whereas the remaining 21.4 PJ (energy: 19.2 PJ) was extracted from the environment by the households. Summarized, the total use of energy carriers represented 219.8 PJ exergy (energy: 213.8 PJ).

It was assumed that the 37.9 PJ of exergy (energy: 34.6 PJ) from fuels was used for space heating, in addition to the district heating and 41% of the electricity. Using an analysis similar to that for 1995 [3], the output was estimated [2] to 19.2 PJ exergy or 12.1% of the exergy in energy carriers.

Food consumption, mainly obtained through the Te-sector, was assumed to represent an input of 20.7 PJ, see the Ag-sector.

12. Monetary and labor fluxes

The capital flux into each of the sectors other than the Do-sector was taken as the sum of production, the gross investment, and, if positive, the net product subsidies. These quantities are the value of the products delivered from the sector, the investment paid into the enterprises by the owners, and the net governmental support. The capital flow out of the sectors was taken as the production input (cost of goods and services consumed in production), compensation of employees (including salaries, insurance of employees, employer's tax), net product taxes (if positive), return to the owners, and the gross investment (payment for fixed capital, i.e. purchase of machinery, and structures). The difference between inflow and outflow then equaled the sum of the consumption of fixed capital and the net investment. The former compensates for the degradation of the fixed capital, i.e. for the renewal of machinery, which in EEA is irreversibility or loss of extended exergy (EE). The latter part increases the fixed capital, which is the increase of EE stored within the system.

In economics, owners and employees are normally regarded as part of the system that benefits from the gross product (production minus production input). In the present analysis, owners and employees were regarded to be outside the sector, and the return and salaries were taken out of the sector.

The quantities described above were found in the annual National Accounts Statistics [13] in million Norwegian kroner (MNOK), and shown in Table 14, while the derived quantities are shown in Table 15. The net investment is the gross investment minus the consumption of fixed capital, whereas the return to the owners is the operational surplus minus net investment. The statistics contain figures for groups that, with one exception, can be readily placed into the sectors in the present analysis. The exception is the group of oil refineries, chemical, and mineral industry (excluding production of chemical raw materials), which should be divided into the Ex and In sectors here. Based on the economics figures from the Industry Statistics [18,19], it was estimated that refineries constituted 60% of the capital flows of this group.

The quantities listed above also have small contributions to the capital in- and outflows of the household sector (Do). The main inflow is the income from salaries, pensions, interest, dividend, insurance, and support as found in the Institutional National Accounts [14]. The outflow comprises taxes, payment for insurance and pension funds, and consumption of goods and services. The difference is the net savings, which constitutes an increase in the stored EE of the sector. It is seen that the capital outflux nearly balances the influx for all the sectors covered by this study. This can be regarded as a general feature. For enterprises, the return to the owners will be increased if there is a high net influx and thus make up the balance. For households, the expenditures tend to rise with increased income.

The exergetic fluxes related to a capital is obtained by multiplying the monetary flux by the exergy influx to the system and dividing by the reference amount of money, Eq. 2. For this reference, the "broad money" (M2) [8] was chosen [10]. Specifically, the median for the 12 monthly values of M2 was used, NOK 713 220 million in 2000.

The average exchange rates given by the National Bank for 2000 were NOK 8.81 per USD and NOK 8.11 per EUR [8]. Some key quantities can be mentioned for comparison: The gross national product (GNP) was NOK 1 465 096 million. The export of oil and natural gas had a value of NOK 340 000 million in 2000, while the total export and total import were NOK 686 473 million and NOK 439 963 million, respectively [13]. Some of this net surplus was capital inflow to society but a substantial fraction was invested in funds abroad for later use.

Labor is considered an output from the household sector (Do) and input to all other sectors. Labor in million work hours (Mh) can be found in the annual National Accounts [13]. The total flux of labor was 3091.2 Mh into the other sectors of this analysis. The figures for each group are included in the tables for each sector. As for the capital fluxes, the labor flux into the group of oil refineries, chemical, and mineral industry, should be divided into the Ex and In sectors here. Based on figures for compensation to the employees in the Industry Statistics [18], it was estimated that the refineries received 8% of the labor of this group.

In the service sector (Te), labor associated with services is a major output. Moreover, the main flux is to the households (i.e., the public). Similar to the discussion of energy and exergy fluxes associated with services, also the definition and measuring of labor flux from the service sector can also be discussed. Because of a lack of more precise data, this study has taken 30% of the labor input to be output from the Te-sector to the Do-sector. This corresponds to 75% of the labor input to the subsectors social and health care, personal services, education, and hotels and restaurants.

The fraction of the total number of work-hours was multiplied with the total influx of exergy to the entire system to obtain the labor EE flux into a sector, Eq. 1. This gives a balance that produces zero net influx to the system. The total influx of exergy to the system was the sum of extracted and imported resources (R and N fluxes), minus the export of these resources. This gave a domestic input of 1625.5 PJ exergy (Table 23), which was the E_{in} in Eqs. 1-2.

13. Results and Discussion

The results of the sector analyses are shown in Table 16 to Table 23. The conversion efficiencies for energy and exergy are taken as the outflux of products (P-flux) and resources (R- and N-fluxes) divided by the corresponding input to the sector. For EE, the conversion efficiency is the outflux of extended exergy (EE) associated with products, resources, labor, and capital (P, R, N, W, and C fluxes) divided by the corresponding influx. If the net formation of fixed capital was positive, this is also included in the "useful" output.

The extended-exergy conversion efficiency was notably larger than the exergy conversion efficiency for all sectors but the Ex- and Co-sectors, where it was close to the value of the exergy conversion. A primary reason for this was that the outflow of capital was from 87% to 97% of the capital inflow. Moreover, for the sectors other than Ex and Co, this throughflow of capital contributed a major part of the EE inflow and outflow, ranging from 67% to 97% of the inflows and from 50% to 99% of the outflows.

In the Ex- and Co-sectors, capital and labor contributed 15% to 20% of the EE in- and outflow. These sectors are dominated by large inflows of energy resources, which lead to large contributions of thermomechanical or chemical exergy to the EE flows.

Not surprisingly, the EE balance of the Te sector was dominated by capital and labor, contributing 97% of both inflow and outflow.

The Do-sector had energy and exergy conversion efficiencies close to zero, since the households produce very little for other sectors. The small but non-zero value was only due to waste re-circulated for energy and material recovery. However, the households had an EE conversion efficiency greater than unity. This will be discussed below.

The EE values of labor and capital in this analysis were 525.8 MJ/h and 2.38 MJ/NOK, respectively. The latter corresponds to 20.09 MJ/USD or, given as the reciprocal cost factor, 0.050 USD/MJ. The labor value is nearly twice the figure 235.5 MJ/h found for Italy of 1998 [11]. The difference can be explained by the large role of the energy-converting industry in Norway. On the other hand, the EE value of capital is remarkably close to that of Italy, which in 1998 was 18.18 MJ/USD (or 0.055 USD/MJ) [11].

For the reference monetary flow, Sciubba [10] adopted, "somewhat arbitrary" (cf. the discussion in [11,12]), the global monetary circulation, M2. Other measures for the monetary flow exist, and the topic ought to be further investigated.

It is interesting to discuss the impact of the choice of reference monetary flow. The capital and labor flows into a sector mainly come from other sectors. The physical exergy flows are to a large extent extracted from the environment or imported from abroad, and then distributed among the sectors. No sector, except Ex, had a physical exergy inflow of the same magnitude as the total net exergy input. Similarly, the sum of labor EE inflow to the sectors was equal to the total net exergy input of the society, since this was chosen as the reference exergy input, Eq. 1. Hence, the labor EE acts to redistribute the effects of the physical exergy flows. However, with M2 as the reference for monetary fluxes, the corresponding EE fluxes may be much larger than the total net exergy input. In the presented analysis, the sum of EE inflows to all sectors was 3.5 times larger than the total net exergy input. This figure would increase if the number of sectors was increased. Accordingly, the monetary fluxes may dominate the EE balance for the sectors, and do not have a redistributing effect like that of the labor fluxes. Furthermore, as noted above, the capital influx and outflux of a sector tend to be nearly in balance. Therefore, when the capital flows into and out of a sector are large compared to the reference capital flow, they tend to even the EE balance of the sector.

In the households sector (Do), labor is produced with no corresponding EE influx. As discussed above, the influx of physical exergy to the sector is only a fraction of the total net exergy input to the society, E_{in}, whereas the sum of labor EE output is equal to this quantity. The outflux of physical exergy is close to zero, and the influx of labor EE is much lower than the outflux. It can be shown that under normal conditions for an industrialized country, the outflux of EE is larger than the influx for the Do-sector. Only with a reference monetary flux that is much less than the capital loss in the Do-sector, can the conversion efficiency be less than unity.

Some comments should also be added with relation to the 2nd law of thermodynamics. Under normal circumstances, the capital influx to a sector is larger than the outflow. The difference is the formation of funds or fixed capital and the compensation for degradation of fixed capital. Furthermore, for the sectors other than Do, the outflux of labor must be less than the influx. Thus, it is readily seen that the EEA is in accordance with the 2nd law in these cases. However, as shown above, the households sector (Do) is different. A net production of EE seems at, first sight, to contradict the 2nd law. When considered more closely, this is not the case. As pointed out by Sciubba [10], humans exert a substantial amount of influence on processes that they direct. The EE production within the Do-sector can be regarded as a result of man's creativeness. A parallel to this notion is found in information theory, where man-made coding reduces entropy and increases (if defined) the corresponding exergy.

14. Concluding remarks

The energy and exergy analysis of the Norwegian society following Sciubba's approach showed a high conversion ratio in the extraction sector, 95%, mainly due to a large export of crude oil and natural gas. Also the conversion sector had a high conversion ratio, 76%, primarily due to the dominating role of hydropower. The agriculture, forestry, and fisheries sector had a lower output to input ratio, 45%, owing to low conversion efficiency in domestic animals and farmed fish, and to low-temperature heating in the food-processing industry. The manufacturing-industry sector, dominated by paper, metal, and chemical industry had an exergy conversion efficiency of 50%.

The transportation sector had a lower conversion efficiency, 19%. Water and air transport had a considerable influence on raising this figure, whereas it was lowered by land transportation. It should be noted that this sector comprised transportation services only and that own transportation within the other sectors was not included. The tertiary or service sector showed an exergy conversion of 26%. A substantial contribution to this figure was resale of food products and industry products to households, and also collection and recirculation of waste for materials recovery and energy recovery.

The domestic sector, i.e. households, had a close-to-zero energy and exergy output in this approach, since no products or resources are transferred to the other sectors except waste for recirculation.

The energy-conversion analysis gave results close to those of the exergy analysis. The main reason is the way of accounting flows between subsystems in this method. The analysis is dominated by resources and products for which the exergy and energy values do not differ substantially. The main difference is that the energy is discharged to the environment, while the exergy is lost by irreversibilities.

The results from extended exergy accounting (EEA), where exergy values are assigned to labor and capital flow, showed considerably different results for all sectors except for extraction and conversion. Most notably, the household sector, because of its supply of labor to all other sectors, gave an output that was 34% larger than the input. It can be shown that a higher-than-unity EE conversion efficiency in the Do-sector is the normal situation for an industrialized country.

The service and transportation sectors showed extended-exergy conversion efficiencies of 75% and 63%, respectively, which was much larger than the exergy and energy conversion efficiencies. This was due to large relative contributions from the capital flow into and out of these sectors. The same tendency, though to a lesser extent, was seen in the industry and agriculture sectors with 69% and 62%, respectively. On the other hand, the capital flow had a relatively low contribution to the conversion sector. Here, the extended-exergy efficiency was 77%, slightly higher than the exergy efficiency.

The extraction sector had a very large throughflow of capital. However, the extended-exergy accounting of the sector was dominated by resources and the extended-exergy efficiency was 95%, close to the exergy efficiency.

Acknowledgements

I would like to thank Professor Enrico Sciubba, University of Roma "La Sapienza", for useful discussions on and further explanations of the method used in this study.

References

[1] Ertesvåg IS. Society exergy analysis: a comparison of different societies. Energy 2001;26:253-70.

[2] Ertesvåg IS, Leintrø, E. Energy utilization 2000 – Exergy analysis of the Norwegian society, report no. TR A5828. Trondheim, Norway: Sintef Energy Research, 2003 (in Norwegian).

[3] Ertesvåg IS, Mielnik M. Exergy analysis of the Norwegian society. Energy 2000;25:957-73.

[4] Holtskog S. Direct energy use and emissions to air from transport in Norway, report no. 2001/16. Oslo, Norway: Statistics Norway, 2001 (in Norwegian). See also: http://www.ssb.no/emner/01/04/10/rapp_200116/rapp_200116.pdf

[5] Kotas TJ. The exergy analysis of thermal plant analysis. 2nd ed. Malabar, FL: Krieger, 1995.

[6] Lian JI. Mobility and use of transport modes in Norway, report no. 604/2002. Oslo, Norway: Institute of Transport Economics, 2002 (in Norwegian).

[7] Milia D, Sciubba E. Exergy-Based Lumped Simulation of Complex Systems: an Interactive Analysis Tool. In: Proc. 2nd Intl. W.shop on Advanced Energy Studies. P.Venere, Italy: 2000. p. 513-23.

[8] Norway National Bank. National bank statistics. Oslo, Norway: 2001 See also: http://www.norges-bank.no/front/statistikk/en/pengemengden/ and http://www.norges-bank.no/english/statistics/exchange/

[9] Reistad GM. Available energy conversion and utilization in the United States. ASME J Eng Power 1975;97:429-34.

[10] Sciubba E. Beyond thermoeconomics? The concept of Extended Exergy Accounting and its application to the analysis and design of thermal systems. Exergy Int J 2000;1(2):68-84.

[11] Sciubba E. Cost analysis of energy conversion systems via a novel resource-based quantifier. Energy 2003;28:457-77.

[12] Sciubba E. Extended exergy accounting applied to energy recovery from waste: The concept of total recycling. Energy 2003;28:1315-34.

[13] Statistics Norway. Annual national accounts 1970-2001. Oslo, Norway: 2002. See also: http://www.ssb.no/english/subjects/09/01/nr_en/tables.html

[14] Statistics Norway. Annual national accounts 1978-2001 Institutional sectors. Oslo, Norway: 2002. See also: http://www.ssb.no/english/subjects/09/01/nri_en/tables.html

[15] Statistics Norway. Domestic transport performances 2000. Oslo, Norway: 2001. See also: http://www.ssb.no/english/subjects/10/12/transpinn_en/arkiv/art-2001-07-05-01-en.html

[16] Statistics Norway. Energy statistics 2000, Official Statistics of Norway, report no. C703. Oslo, Norway: 2002. See also: http://www.ssb.no/emner/10/08/10/nos_energi/nos_c703/nos_c703.pdf
[17] Statistics Norway. Forestry statistics 2000, Official Statistics of Norway, report no. C709. Oslo, Norway: 2002. See also: http://www.ssb.no/emner/10/04/20/nos_skogstat/arkiv/nos_c709/nos_c709.pdf
[18] Statistics Norway. Manufacturing statistics 2000 - industrial figures, Official Statistics of Norway, report no. D284. Oslo, Norway: 2002. See also: http://www.ssb.no/emner/10/07/nos_industri/nos_d284/nos_d284.pdf
[19] Statistics Norway. Manufacturing statistics - Commodity figures 2000. Oslo, Norway: 2002. See also: http://www.ssb.no/english/subjects/10/07/vti_en/arkiv/art-2001-09-27-01-en.html
[20] Statistics Norway. Statistical yearbook of Norway 2001. Oslo, Norway: 2001. See also: http://www.ssb.no/english/yearbook/2001/
[21] Statistics Norway. Statistics of external trade 2000. Oslo, Norway: 2002. See also: http://www.ssb.no/muh/mu2000/
[22] Statistics Norway. Waste accounts 1993-2000, Official statistics of Norway, report no. D256. Oslo, Norway: 2003 (in Norwegian). See also: http://www.ssb.no/emner/01/05/40/nos_d256/nos_d256.pdf
[23] Wall G. Exergy – a useful concept. PhD thesis. Göteborg, Sweden: Chalmers University of Technology, 1986.
[24] Wall G. Exergy conversion in the Swedish society. Resour Energy 1987;9(1):55-73.

Table 1: Input of energy carriers to the extraction sector. Flux type: Resources (R).

	Total (PJ)		Inland extraction (PJ)		Imported (PJ)	
	Energy	Exergy	Energy	Exergy	Energy	Exergy
Coal	45.2	47.9	17.8	18.9	27.4	29
Coke	28.1	29.5			28.1	29.5
Oil/petr. products	6950.3	7367.4	6804.3	7212.6	146	154.8
Natural gas	2181.1	2268.3	2181.1	2268.3		
Electricity	4.9	4.9				
Sum input	9209.6	9718.0	9003.2	9499.8	201.5	213.3

Table 2: Use of energy carriers within the extraction sector, energy figures.

Energy carrier	Total use (PJ)	Extraction (PJ)	Refining (PJ)	For inland use (PJ)	Related to export (PJ)
Oil/Petr. products	44.6	17.1	27.5	14.7	29.9
Natural gas	165.2	165.2		0.0	165.2
Electricity	4.9	3.1	1.8	1.0	3.9
Sum	214.7	185.4	29.3	15.7	199.0

Table 3: Use of energy carriers within the extraction sector, exergy figures.

Energy carrier	Total use (PJ)	Extraction (PJ)	Refining (PJ)	For inland use (PJ)	Related to export (PJ)
Oil/Petr. products	47.2	18.1	29.2	15.6	31.7
Natural gas	171.8	171.8		0.0	171.8
Electricity	4.9	3.1	1.8	1.0	3.9
Sum	223.9	193.0	31.0	16.6	207.4

Table 4: Output of energy carriers from the extraction sector. Flux type: Resources (R).

	Total (PJ)		Inland supply (PJ)		Exported (PJ)	
	Energy	Exergy	Energy	Exergy	Energy	Exergy
Coal	44.0	46.6	27.9	29.6	16.1	17.1
Coke	33.5	35.2	32.6	34.2	0.9	0.9
Oil/petr. products	6726.6	7130.2	302.7	320.9	6423.9	6809.3
Natural gas	1987.8	2067.3	27.6	28.7	1960.2	2038.6
Sum output	8791.9	9279.3	390.8	413.4	8401.1	8865.9

Table 5: Exergy figures of waste deposited (Trash), burned without energy recovery (Discharge), materials recovered, and burned for energy recovery. (PJ)

	Paper	Metals	Plastics	Wood	Textiles	Total
Assumed exergy content (PJ/Mton)	17.0	7.0	20.0	10.0	15.0	
Deposited (Trash, T-flux)						
by Industry (In)	0.4	4.9	0.5	0.5	0.1	6.3
by Services (Te)	8.1	0.4	2.5	1.0	0.1	12.1
by Households (Do)	1.9	0.8	5.6	0.2	0.9	9.5
Sum	10.4	6.2	8.6	1.7	1.1	27.9
Burned (Discharge, D-flux)						
by Industry (In)	0.0		0.0	0.1	0.0	0.1
by Services (Te)	0.3		0.1	0.0	0.1	0.5
by Households (Do)	0.5		0.1	0.0	0.0	0.6
Sum	0.9		0.1	0.1	0.1	1.2
Material recovery (P-flux)						
by Industry (In)	1.6	4.2	0.3	1.5	0.0	7.7
by Services (Te)	2.8	0.4	0.0	0.7	0.1	4.0
by Households (Do)	4.3	0.3	0.1	0.0	0.1	4.8
Sum	8.8	4.9	0.4	2.3	0.2	16.5
Energy-purposes (P-flux)						
by Industry (In)	0.2		0.1	3.7	0.0	4.0
by Services (Te)	0.6		0.5	0.0	0.0	1.1
by Households (Do)	1.2		0.5	0.1	0.2	2.0
sum	1.9		1.1	3.8	0.3	7.1

Table 6: Input of energy carriers to the conversion sector

Energy carrier	Flux type	Energy (PJ)	Exergy (PJ)
Coal	R	0.9	0.9
Coke	R	0.9	0.9
Petroleum products	R	1.1	1.1
Natural gas	R	0.1	0.1
Sum input from Ex-sector	R	3.0	3.0
Waterfall energy (from E)	R	602.4	602.4
Fuelwood (from Ag-sector)	N	0.2	0.2
Waste (from Te-sector)	P	7.1	7.1
Sum domestic input		612.7	612.7
Electricity (imported)	R	5.3	5.3
Sum input		618.0	618.0

Table 7: Losses and use of energy carriers within the conversion sector (energy figures).

	Total energy (PJ)	Related to inland use (PJ)	Related to export (PJ)
Waterfall energy lost in conversion	90.4	77.0	13.4
Electricity grid loss or use in Co-sector	44.7	38.3	6.4
Other losses (flue gases etc.)	8.8	8.8	
Sum	143.9	124.1	19.8

Table 8: Output from the conversion sector. Flux type: Resources (R).

	Total (PJ)		For inland use (PJ)		Export (PJ)	
	Energy	Exergy	Energy	Exergy	Energy	Exergy
Electricity	468.7	468.7	394.8	394.8	73.9	73.9
District heat	5.4	1.1	5.4	1.1		
Sum	474.1	469.8	400.2	395.9	73.9	73.9

Table 9: Use of energy carriers in the fisheries and agriculture, and in the food-processing industry. Flux type, input: Resouces (R), Natural resources (N; fuelwood); output: Discharge (D).

	Fisheries and agriculture		Food industry		Sum	
	Energy (PJ)	Exergy (PJ)	Energy (PJ)	Exergy (PJ)	Energy (PJ)	Exergy (PJ)
Petroleum products	25.7	27.3	6.0	6.4	31.7	33.6
Natural gas			0.28	0.29	0.28	0.29
Sum input from Ex-sector	25.7	27.3	6.3	6.7	32.0	33.9
Electricity	7.0	7.0	10.3	10.3	17.3	17.3
Steam			0.33	0.12	0.33	0.12
District heating			0.10	0.01	0.10	0.01
Sum input from Co-sector	7.0	7.0	10.7	10.4	17.7	17.4
Fuelwood	0.1	0.1	0.0	0.0	0.1	0.1
Sum	32.8	34.4	17.0	17.1	49.8	51.4

Table 10: Use of energy carriers in industry, energy figures (PJ).

	Wood, paper, pulp	Aluminum	Other metals	Chemical	Other industry	Trans-portation	Total
Petr.prod.	4.7	2.9	2.1	50.6	10.9	3.8	75.0
Nat.gas			0.5	26.1	0.2		26.8
Coke		6.5	14.4	5.3	5.5		31.7
Coal			13.1	6.3	7.5		26.9
Electricity	29.0	62.3	34.6	26.8	16.1		168.8
Distr.heat				0.3	0.1		0.4
Wood	24.6						24.6
Total	58.3	71.7	64.7	115.4	40.3	3.8	354.2

Table 11: Use of energy carriers in industry, exergy figures (PJ).

	Wood, paper, pulp	Aluminum	Other metals	Chemical	Other industry	Trans-portation	Total
Petr.prod.	4.9	3.0	2.3	51.7	11.6	4.0	77.5
Nat.gas			0.5	27.1	0.2		27.8
Coke		6.8	15.1	5.6	5.8		33.3
Coal			13.9	6.7	7.9		28.5
Electricity	29.0	62.3	34.6	26.8	16.1		168.8
Distr.heat				0.1	0.0		0.1
Wood	27.3						27.3
Total	61.2	72.1	66.4	118.0	41.6	4.0	363.3

Table 12: Exergy in products of the metal industry. Flux type: Product (P).

Metal	Production (Mton)	Exergy content (PJ/Mton)	Exergy (PJ)
Zink	0.138	5.4	0.75
Nickel	0.059	4.3	0.25
Copper	0.025	2.1	0.05
Cobalt	0.003	4.4	0.01
Magnesium	0.040	25.8	1.03
Silicon *)	0.155	28.6	4.43
Ferrosilicon	0.45	22.8	10.30
FeSiMn	0.249	12.5	3.11
Ferromanganese	0.18	10.3	1.85
Ferrochrome	0.15	11.5	1.73
Steel	0.65	6.8	4.40
Total (ex. aluminum)			27.91
Aluminum	1.19	32.9	39.15
Total			67.1

*) Silicon is not a metal but produced by the same industry

Table 13: Transportation services, estimated input and output.

	Input		Output
	Energy (PJ)	Exergy (PJ)	Exergy (PJ)
goods by water	8.9	9.4	2.4
goods by rail/road	11.6	12.2	1.6
goods, total	20.5	21.6	3.9
passengers by air	27.8	29.5	7.4
passengers by water	12.6	13.4	3.4
passengers by rail/road	36.1	38	4.9
passengers, total	76.5	80.9	15.7
total	97.0	102.5	19.6

Table 14 Economics figures from the National Accounts Statistics (million NOK)

Sector	Production	Production input	Consumption fixed capital	Compensat. of employees	Operational surplus	Gross investment
Ex	433850	82630	58921	23098	262749	60466
Co	38974	11121	7749	6148	11010	4336
Ag	157246	110785	12180	22695	21217	13286
In	334569	226212	13267	76053	19435	12933
Tr	131972	86660	11361	35334	1716	15719
Te	1255382	570195	92522	463552	130730	157056

Table 15 Derived figures from the National Accounts Statistics (million NOK)

Sector	Net investment	Return to owners	Net taxes	Cin	Cout
Ex	1544	261205	6450	494315	433850
Co	-3413	14423	2946	43310	38974
Ag	1106	20111	-9631	180163	166877
In	-333	19768	-396	347899	334966
Tr	4358	-2642	-3099	150790	135071
Te	64534	66196	-1617	1414055	1256999

Table 16 Analysis of the extraction sector (Ex).

Fluxes		Energy (PJ)	Exergy (PJ)	Ext.Ex (PJ)		
Input						
Rtot,ex		9209.6	9722.2	9722.2		
	Ra,ex	201.5	213.3	213.3		energy carriers
	Re,ex	9003.2	9499.8	9499.8		energy carriers
	Re,ex	0.0	4.2	4.2		minerals, ores
	Rco,ex	4.9	4.9	4.9		energy carriers
Ptot,ex		3.3	3.3	3.3		
	Pin,ex	3.2	3.2	3.2		
	Ptr,ex	0.1	0.1	0.1		transport
Wdo,ex				24.8		labor
Cinput,ex				1126.6	494315	MNOK capital inflow
sum input		9212.9	9725.5	10876.9		
Output						
Rex		8791.9	9283.1	9283.1		output as seen from Ex
	Rex,a	8401.1	8865.9	8865.9		energy carriers
	Rex,a		3.0	3.0		minerals, ores
	Rex,co	3.0	3.0	3.0		energy carriers
	Rex,ag	32.0	33.9	33.9		energy carriers
	Rex,in		0.4	0.4		minerals, ores
	Rex,in	160.4	167.1	167.1		energy carriers
	Rex,tr	89.8	95.2	95.2		energy carriers
	Rex,te	37.6	39.9	39.9		energy carriers
	Rex,te		0.4	0.4		stone, gravel, etc.
	Rex,do	67.8	71.8	71.8		energy carriers
	Rex,inland	390.6	411.7	411.7		
	Rex,unacc.	0.2	2.5	2.5		not accounted for
Coutput				988.8	433850	MNOK capital outflow
Cform				3.5	1544	MNOK fixed capital formation
Tex	Tex,e	0.0	0.0	0.0		deposited waste
Dex		421.7	67.5	67.5		total discharge
	Dex,e	214.7	34.4	34.4	0.16	disharged gases and heat from energy carriers
	Dex,e	0.0	0.0	0.0		discharged or burned waste
	Dex,e	206.3	33.0	33.0	0.16	other discharge
exloss			375.6	534.7		
	exloss		189.5	189.5		from energy carriers
	exloss		185.5	344.6		other exergy losses
Conversion efficiency		0.954	0.955	0.945		

Table 17 Analysis of the conversion sector (Co).

Fluxes		Energy (PJ)	Exergy (PJ)	Ext.Ex (PJ)		
Input						
Rtot,co		610.7	610.7	610.7		
	Ra,co	5.3	5.3	5.3		energy carriers
	Re,co	602.4	602.4	602.4		energy carriers
	Rex,co	3.0	3.0	3.0		energy carriers
Ntot,co	Nag,co	0.2	0.2	0.2		energy carriers
Ptot,co		8.0	8.0	8.0		
	Pin,co	0.9	0.9	0.9		industry products
	Ptr,co	0.0	0.0	0.0		transport
	Pte,co	7.1	7.1	7.1		waste for energy
Wdo,co				12.7		labour
Cinput,co				98.7	43310	MNOK capital inflow
sum input		618.9	618.9	730.3		
Output						
Rco		474.1	469.8	469.8		
	Rco,a	73.9	73.9	73.9		energy carriers
	Rco,ex	4.9	4.9	4.9		
	Rco,ag	17.7	17.4	17.4		
	Rco,in	169.2	168.9	168.9		
	Rco,tr	6.6	6.6	6.6		
	Rco,te	83.3	80.2	80.2		
	Rco,do	121.9	121.2	121.2		
	Rco,inland	403.6	399.2	399.2		
	Rco,unacc.	-3.4	-3.3	-3.3		not accounted for
Coutput				88.8	38974	MNOK capital outflow
Cform				-7.8	-3413	MNOK fixed capital formation
Tco	Tco,e	0.0	0.0	0.0		deposited waste
Dco	Dco,e	144.8	14.5	14.5	0.10	consumed energy carriers
exloss			134.6	165.0		
	exloss		129.4	129.4		consumed/lost energy carriers
	exloss		5.2	35.5		other exergy losses
Conversion efficiency		0.766	0.759	0.765		

Table 18 Analysis of the agriculture, forestry, the fisheries, and food sector (Ag).

Fluxes		Energy (PJ)	Exergy (PJ)	Ext.Ex (PJ)		
Input						
Rtot,ag		49.7	51.3	51.3		
	Rex,ag	32.0	33.9	33.9		energy
	Rco,ag	17.7	17.4	17.4		energy
Ntot,ag		194.0	206.9	206.9		
	Na,ag	49.2	49.2	49.2		food etc.
	Ne,ag	0.1	0.1	0.1		fuelwood, own use
	Ne,ag	88.6	88.6	88.6		harvest
	Ne,ag	56.1	69.0	69.0		wood
Ptot,ag		1.9	1.9	1.9		
	Pin,ag	1.5	1.5	1.5		industry products
	Ptr,ag	0.4	0.4	0.4		transport
Wdo,ag				136.9		labor
Cinput,ag				410.6	180163	MNOK capital inflow
sum input		245.6	260.1	807.6		
Output						
Nag,outsum		106.2	116.2	116.2		
	Nag,a	24.1	24.1	24.1		food etc
	Nag,a	2.5	3.1	3.1		wood
	Nag,co	0.2	0.2	0.2		fuelwood
	Nag,in	24.4	27.1	27.1		energy
	Nag,in	27.1	33.3	33.3		wood
	Nag,te	23.0	23.0	23.0		food etc
	Nag,do	4.9	5.4	5.4		fuelwood
	Nag,inland	79.6	89.0	89.0		
Coutput				380.3	166877	MNOK capital outflow
Cform				2.5	1106	MNOK fixed capital formation
Tag	Tag,e	0.0	0.0	0.0		deposited waste
Dag		137.4	17.6	17.6		
	Dag,e	0.0	0.7	0.7		discharged wet organic waste
	Dag,e	49.8	8.0	8.0	0.16	consumed energy carriers
	Dag,e	89.6	9.0	9.0	0.10	other discharge
exloss			126.3	291.0		
	exloss		43.4	43.4		from energy carriers
	exloss		82.8	247.5		other exergy losses
Conversion efficiency		0.432	0.447	0.615		

Table 19 Analysis of the industry sector (In).

Fluxes		Energy (PJ)	Exergy (PJ)	Ext.Ex (PJ)		
Input						
Rtot,in		329.6	347.3	347.3		
	Ra,in	0.0	10.9	10.9		ores, oxides
	Rex,in	160.4	167.1	167.1		energy carriers
	Rex,in	0.0	0.4	0.4		ores etc.
	Rco,in	169.2	168.9	168.9		energy carriers
Ntot,in		77.0	91.7	91.7		
	Na,in	0.2	0.2	0.2		Fuelwood
	Na,in	25.3	31.1	31.1		Wood
	Nag,in	24.4	27.1	27.1		Energy
	Nag,in	27.1	33.3	33.3		Wood
Ptot,in		11.1	11.1	11.1		
	Ptr,in	3.5	3.5	3.5		Transport
	Pte,in	7.7	7.7	7.7		recycle material
Wdo,in				195.7		Labor
Cinput,in				792.9	347899	MNOK capital inflow
sum input		417.8	450.2	1438.8		
Output						
Pin		205.0	227.0	227.0		
	Pin,a	183.5	193.8	193.8		metal, paper, wood prod.
	Pin,sectors	21.5	21.5	21.5		prod. to other sectors (inland)
	Pin,ex	3.2	3.2	3.2		0.15
	Pin,co	0.9	0.9	0.9		0.04
	Pin,ag	1.5	1.5	1.5		0.07
	Pin,tr	0.9	0.9	0.9		0.04
	Pin,te	15.1	15.1	15.1		0.70
	Pin,te	7.7	7.7	7.7		material recovery from waste
	Pin,te	4.0	4.0	4.0		waste for energy
	Pin,inland	33.2	33.2	33.2		
Coutput				763.4	334966	MNOK capital outflow
Cform				-0.8	-333	MNOK fixed capital formation
Tin	Tin,e	6.4	6.4	6.4		waste, disposed
Din		206.4	33.1	33.1		
	Din,e	0.1	0.1	0.1		waste, burned
	Din,e	206.3	33.0	33.0	0.16	used energy carriers
exloss			183.7	409.6		
Conversion efficiency		0.491	0.504	0.688		

Table 20 Analysis of the transportation sector (Tr).

Fluxes		Energy (PJ)	Exergy (PJ)	Ext.Ex (PJ)		
Input						
Rtot,tr		96.4	101.8	101.8		
	Rex,tr	89.8	95.2	95.2		energy carriers
	Rco,tr	6.6	6.6	6.6		energy carriers
Ptot,tr	Pin,tr	0.9	0.9	0.9		industry products
Wdo,tr				90.7		labor
Cinput,tr				343.7	150790	MNOK capital inflow
sum input		97.3	102.7	537.0		
Output						
Ptr		19.2	19.2	19.2		
	Ptr,ex	0.1	0.1	0.1		passenger tr.
	Ptr,co	0.0	0.0	0.0		passenger tr.
	Ptr,ag	0.4	0.4	0.4		passenger tr.
	Ptr,in	0.5	0.5	0.5		passenger tr.
	Ptr,in	3.0	3.0	3.0		goods tr.
	Ptr,te	3.5	3.5	3.5		passenger tr.
	Ptr,te	1.0	1.0	1.0		goods tr.
	Ptr,do	10.7	10.7	10.7		passenger tr.
Coutput				307.8	135071	MNOK capital outflow
Cform				9.9	4358	MNOK fixed capital formation
Ttr	Ttr,e	0.0	0.0	0.0		deposited waste
Dtr	Dtr,e	78.1	12.5	12.5	0.16	used energy carriers
exloss			71.0	187.5		
Conversion efficiency		0.197	0.187	0.628		

Table 21 Analysis of the tertiary (service) sector (Te).

Fluxes		Energy (PJ)	Exergy (PJ)	Ext.Ex (PJ)		
Input						
Rtot,te		120.9	120.5	120.5		
	Rex,te	37.6	39.9	39.9		fuels
	Rex,te		0.4	0.4		stone, gravel, etc.
	Rco,te	79.6	79.6	79.6		electricity
	Rco,te	3.7	0.6	0.6		district heating
Ntot,te		23.2	23.2	23.2		
	Nag,te	0.2	0.2	0.2		fuelwood
	Nag,te	23.0	23.0	23.0		food
Ptot,te		38.1	38.1	38.1		
	Pin,te	15.1	15.1	15.1		industry products
	Pin,te	11.7	11.7	11.7		waste for recovery
	Pdo,te	6.8	6.8	6.8		waste for recovery
	Ptr,te	4.5	4.5	4.5		transport
Wdo,te				1164.7		labor
Cinput,te				3222.8	1414055	MNOK capital inflow
sum input		182.2	182.8	4569.2		
Output						
Pte		55.7	46.7	46.7		
	Pte,a	5.2	5.2	5.2		recirculated material
	Pte,in	7.7	7.7	7.7		recirculated material
	Pte,co	7.1	7.1	7.1		waste for energy
	Pte,do	20.7	20.7	20.7		food
	Pte,do	5.0	5.0	5.0		resale of industry products
	Pte,do	10.0	1.0	1.0		energy by services
Wte	Wte,do			349.4		services
Coutput				2864.8	1256999	MNOK capital outflow
Cform				147.1	64534	MNOK fixed capital formation
Tte	Tte,e	12.2	12.2	12.2		deposited waste
Dte		91.3	15.0	15.0		
	Dte,e	0.5	0.5	0.5		burned waste
	Dte,e	113.8	18.2	18.2	0.16	used energy carriers
exloss			104.2	1130.3		
Conversion efficiency		0.306	0.257	0.746		

Table 22 Analysis of the household sector (Do).

Fluxes		Energy (PJ)	Exergy (PJ)	Ext.Ex (PJ)		
Input						
Rtot,do		189.7	193.0	193.0		
	Rex,do	10.5	11.1	11.1		energy carriers
	Rex,do	57.3	60.7	60.7		energy carrier, transport
	Rco,do	121.0	121.0	121.0		energy carrier
	Rco,do	0.9	0.2	0.2		energy carrier
Ntot,do		24.1	26.8	26.8		
	Ne,do	19.2	21.4	21.4		fuelwood
	Nag,do	4.9	5.4	5.4		fuelwood
Ptot,do		46.4	37.4	37.4		
	Ptr,do	10.7	10.7	10.7		transport
	Pte,do	20.7	20.7	20.7		food
	Pte,do	5.0	5.0	5.0		resale of industry products
	Pte,do	10.0	1.0	1.0		energy by services
Winput	Wte,do			349.4		services
Cinput,do				2438.3	1069873	MNOK capital inflow
sum input		260.2	257.2	3045.0		
Output						
Pdo		6.8	6.8	6.8		
	Pdo,te	4.8	4.8	4.8		material recovery
	Pdo,te	2.0	2.0	2.0		waste for energy
Wdo				1625.5	3091.2	Mh work
	Wdo,ex			24.8	47.2	Mh work
	Wdo,co			12.7	24.2	Mh work
	Wdo,ag			136.9	260.4	Mh work
	Wdo,in			195.7	372.1	Mh work
	Wdo,tr			90.7	172.4	Mh work
	Wdo,te			1164.7	2214.9	Mh work
Coutput				2368.6	1039261	MNOK capital outflow
Cform				69.8	30612	MNOK savings
Tdo	Tdo,e	10.2	10.2	10.2		deposited waste
Ddo		243.2	39.4	39.4		
	Ddo,e	0.6	0.6	0.6		burned waste
	Ddo,e	242.6	38.8	38.8	0.16	used energy carriers
exloss			200.8	-1075.3		
Conversion efficiency		0.026	0.026	1.337		

Table 23 Summary of the exchange with environment (E) and abroad (A).

Fluxes		Energy (PJ)	Exergy (PJ)	
Input				
Rtot,sys		9812.4	10335.9	
	Re,ex	9003.2	9504.0	energy carriers
	Re,co	602.4	602.4	energy carriers
	Ra,ex	201.5	213.3	energy carriers
	Ra,co	5.3	5.3	ores, minerals
	Ra,in		10.9	ores, oxides
Ntot,sys		213.4	259.6	
	Ne,ag	144.8	157.7	harvest, wood
	Ne,do	19.2	21.4	Fuelwood
	Na,ag	49.2	49.2	food etc.
	Na,in	25.5	31.3	wood, fuelwood
extracted	e,sys	9769.6	10285.5	
imported	a,sys	256.2	310.0	
Gross input of resources		10051.1	10595.5	
Exported resources				
	Rex,a	8401.1	8868.9	energy carriers
	Rco,a	73.9	73.9	energy carriers
	Nag,a	26.6	27.2	food etc.
sum	sys,a	8501.6	8970.0	
Net input of resources		1549.5	1625.5	
Other output				
Psys,a		188.7	199.0	exported products
	Pin,a	183.5	193.8	metal, wood, etc.
	Pte,a	5.2	5.2	recirc. Materials
Tsys		28.8	28.8	Trash
Dsys		1117.8	166.5	Discharge
exloss			1176.2	Irreversibility

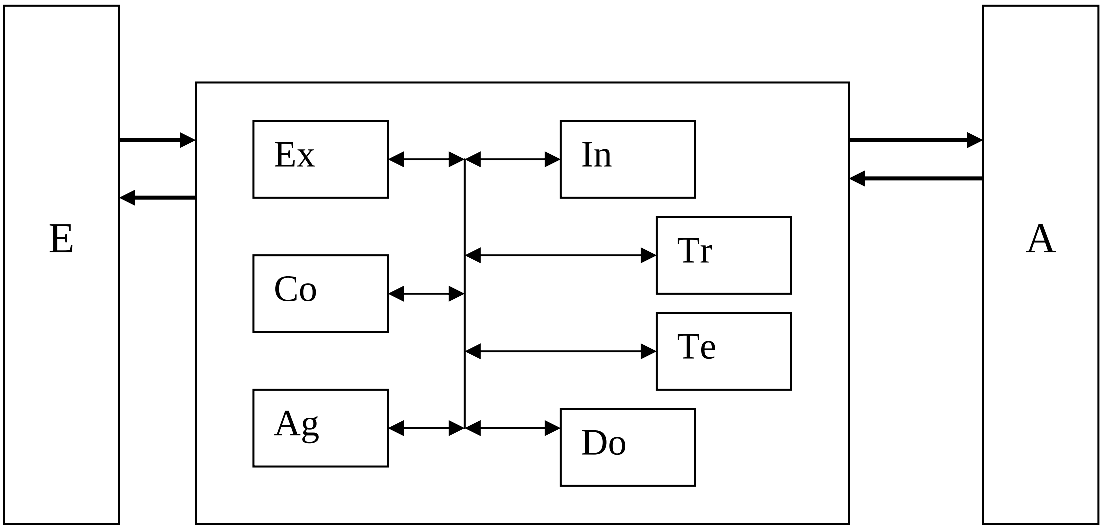

Figure 1 System with subsystems and surroundings for analysis employing Extended Exergy Accounting.

Ivar S. Ertesvåg: “Energy, Exergy, and Extended Exergy……”