NATIONAL EXERGY ACCOUNTING OF NATURAL RESOURCES

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Summary

The use of energy and material resources in society can be expressed in terms of exergy by the use of exergy flow diagrams. These diagrams offer a unique view of society. Using these techniques, the current misuse of resources in industrial societies becomes more apparent and with this also the urgent need to improve their use.

The future of life on our planet is a matter of increasing concern, as we are being confronted with several warnings about the growing fragility of the earth's life support systems. Expanding our understanding, of life support systems and sustainable development, doubtlessly two of the most important issues humankind is presently facing, is essential.

These issues are challenging to the human community at large, demanding that it critically re-assess its objectives and agenda from the perspective of sustainability. This need for re-evaluation is even important for the scientific sector. Present technology is based primarily on the knowledge offered by natural sciences and social management on that offered by our social sciences. This calls for tremendous efforts from the scientific community at large, which is gradually adapting to the new situation. In some areas of science this calls for a change of paradigm.

This chapter will point out to some important concepts in the description of the use of physical resources in society and ecological restrictions. These concepts and conditions offer an increased knowledge and understanding of the present situation and provide the basis for the new paradigm required.

A vision of and an action plan for sustainable development were proposed in "Agenda 21," the declaration of the Earth Summit held in Rio de Janeiro in 1992. The online Encyclopedia of Life Support Systems (EOLSS) (see http://www.eolss.net/) is a living source of essential knowledge concerning the earth's life support systems and guidelines for humanity to live and thrive in symbiosis with nature.

1. The Energy Supply System

1.1. Energy System of Sweden in Terms of Energy

We will begin by looking at some important new concepts and apply them to the total energy conversion system of a society (see Figure 1) to gain an understanding of its implications. This describes the *energy flow* through Swedish society in 1971. The quality of the energy results from contributions of the different kinds of energy. Arrows turned downwards imply losses. Hydropower is to be found in the top part of the diagram and fuel oil in the bottom part. The widths of the arrows representing the flows are in proportion to the energy content in the respective energy forms.

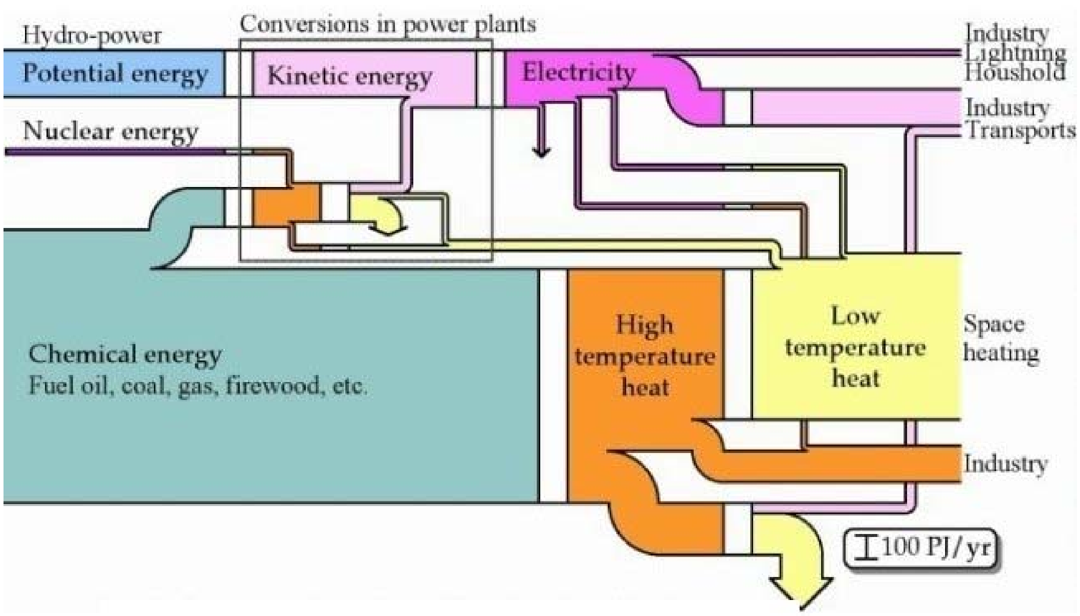

Figure 1: Energy conversion system in 1971 of Swedish society (in energy units)

Hydropower is used to generate electrical energy. The potential energy in the water reservoir is transformed into kinetic energy, which is further transformed into electrical energy via a turbine and an electric generator. Nuclear energy and chemical energy are also used to produce electrical energy. Energy transformation takes place in thermal power plants and in combined power and heating plants (also known as cogeneration plants). In the combined power and heat plant, heat is also extracted at a low temperature through a so-called back-pressure process. Thus, all production of electrical energy takes place within the sector performing “conversions in power plants”. The electrical energy is then directly used, partly in industry, e.g. in electric steel furnaces and in electrolysis, partly as lighting and for electric domestic appliances. As we see from Figure 1, most of the electrical energy is used within the industry to run machinery, i.e. the electrical energy is reconverted into mechanical energy. An increasingly greater part of the electrical energy is used in electric heating, partly as low temperature heat for space heating, partly as high temperature heat in industry.

The conversion of chemical energy into high temperature heat completely dominates in Figure 1. Fuel oil, coal, gas, waste, and firewood are burned in order to produce heat. Most of the high temperature heat is then converted, via a heat exchanger, into low temperature heat that is used for space heating. District heating and electric heating further contribute to this space heating. Part of the high temperature heat is used in industry, especially within the processing industry (iron and steel works, and the pulp and paper industry). Within the steel industry, large quantities of coal are used, and within the pulp industry, large quantities of timber waste are used. The rest of the high temperature heat is used for transportation. Almost 100% of the chemical energy from petrol and oil in a car engine is converted into high temperature heat. About 20% of this heat is then further converted into mechanical energy in the car engine. Nearly half of this energy is then lost through friction in the transmission. This section is, however, not shown in Figure 1. The efficiency of the conversion is represented through the efficiency of the car engine and is found at the lowest conversion level in Figure 1.

The losses in the diagram are minor. Within the sector performing "conversions in power plants", we find energy losses through waste heat from nuclear plants and oil using thermal power plants. There are further losses of electrical energy through transmission and distribution losses; about 10% of the transported energy is lost in this way. On the whole, about 20% or about 1 700 PJ of a total annual conversion of about 460 TWh is lost.

We also see that in each conversion process we have a one-to-one relation between the amount of energy which comes in and that which comes out of the conversion process. This is due to the fact that energy can neither be created nor destroyed.

1.2. Energy System of Sweden in Terms of Exergy

We can see an exergy diagram of the energy system above in Figure 2. The width of the arrow of flow is proportional to the exergy content in each respective energy form. The units of the flows are, however, the same both for the energy and the exergy flow diagrams, i.e. PJ per year. The difference now is that the width of the arrows of flows decreases radically for certain conversion processes, due to decreasing energy quality and, therefore, also decreasing exergy content. In the conversion of chemical exergy into high temperature heat, more than half of the exergy is lost. This is due to the fact that in heat the exergy content is much lower than its energy content.

Furthermore, there are heavy exergy losses in the conversion of high-temperature heat into low-temperature heat, and also in the conversion of electricity into high or low temperature heat. Since the exergy content of the high temperature heat is not utilized in the conversion of high temperature heat into low temperature heat, heavy losses of exergy occur here too.

Consequently, a heat exchanger cannot utilize the exergy loss when temperature is reduced. The temperature decline in an ordinary oil furnace is, thus, not utilized when a flame at a temperature of about 2000 ^{o}C is used to heat water to a temperature of perhaps 80 ^{o}C, which is then used to heat a room to about 20 ^{o}C. Electrical heat means that more than 95% of the exergy is lost in the conversion of electrical energy into low temperature heat. An efficient heat pump ("an inside-out refrigerator") should be able to improve that efficiency from about 5% to at least 30%.

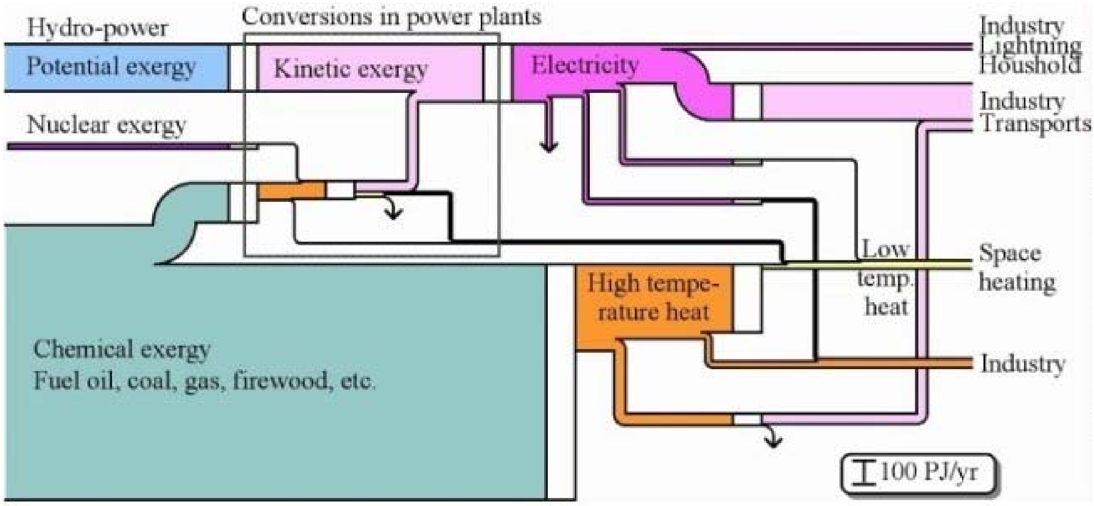

Figure 2: Energy conversion system in 1971 of Swedish society (in exergy units)

It appears that the heaviest losses of exergy occur in domestic heating. As we can see on the right hand side of Figure 2, the exergy requirements in heating are quite small and can be decreased even further through improvements in insulation and in utilizing ventilation heat.

To improve exergy use in heating even further, we can either use a good exergy converter such as a heat pump or natural exergy flow in a solar heating system.

The losses revealed in the exergy flow diagram are substantial. On the whole, more than 70% of the supplied exergy is lost. In the exergy diagram, inflows and outflows do not balance each other. Exergy is always consumed in real processes, as stated above. By using exergy diagrams to describe the energy system, possible improvements can be visualized.

However, the energy system is only a part of the total resource conversion system of a society. Material resources must also be added to get a complete picture of a society's resource use.

2. Exergy Use in Swedish Society

The main conversions of energy and materials in Swedish society in 1994 are shown in Figure 3, based on data from official statistics. The flows of resources go from left to right in the diagram, i.e. from the resource base to the consumption sector. Thus, the diagram represents the resource supply sector.

The widths of the arrows of flows are defined by their exergy content and the unit of the flows in J per year. Since the flows vary a great deal during the year, it is preferred to use the unit J per year instead of W per year.

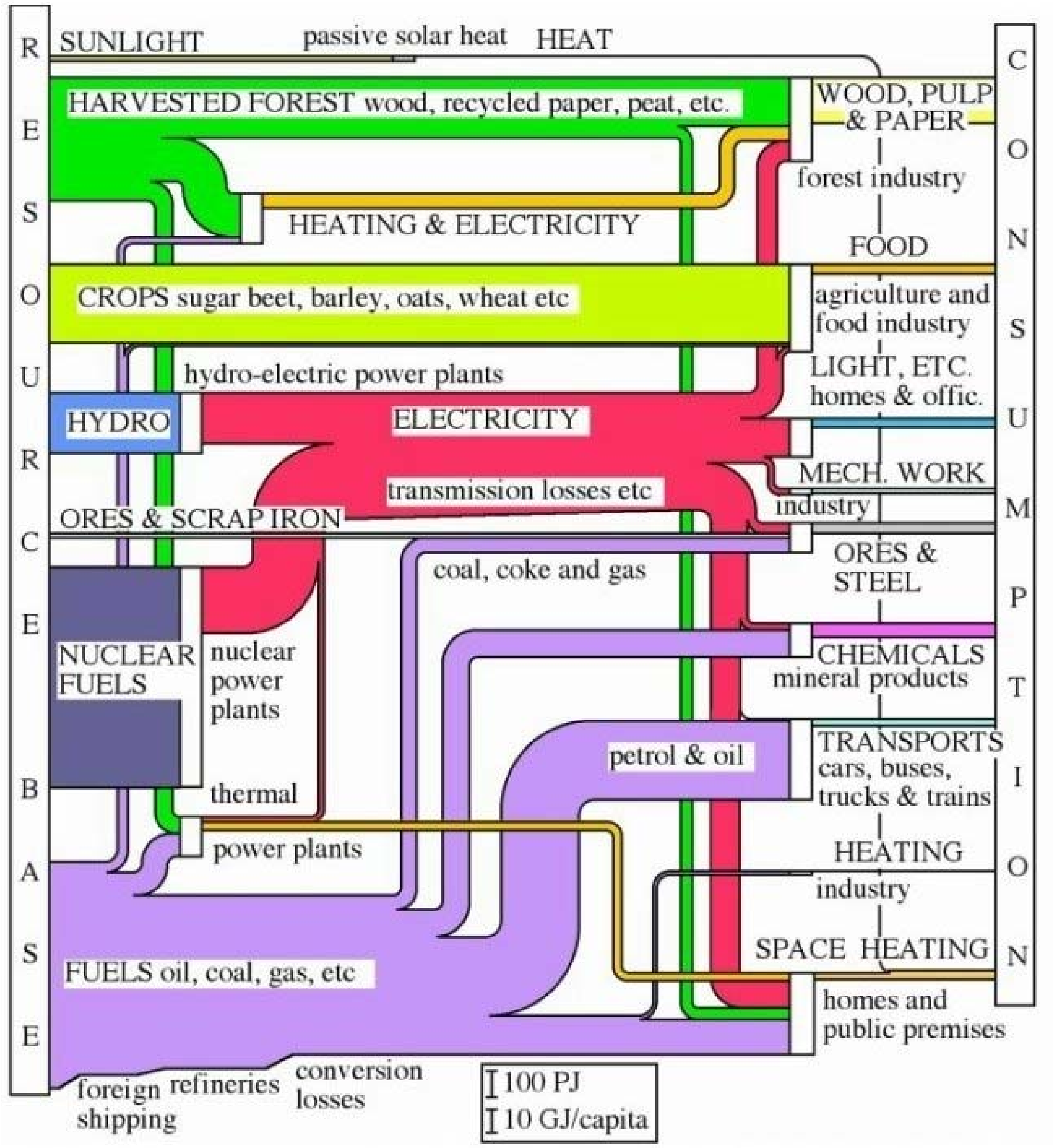

Figure 3: The exergy conversion system in Swedish society in 1994. Total input is about 2720 PJ or 310 GJ per capita, and total output is about 380 PJ or 43 GJ per capita.

The accuracy of the flows varies a great deal between the different areas. For the electricity system, the accuracy is quite high, whereas for sectors related to agriculture and forestry, we have, for obvious reasons, a different situation. In order not to make the diagram too complicated, only exergy flows exceeding 5 PJ per year are included. The inflows are ordered according to their origins. Sunlight is, thus, a renewable natural flow. Apart from the use of a small quantity of wind power, far less than 5 PJ per year, this is the only direct use of a renewable natural flow. Harvested forests, agricultural crops, and hydropower are renewable exergy flows derived from stocks, which, of course, are formed on the renewable natural flow of sunlight. Iron ore, nuclear fuels, and fossil fuels are non-renewable exergy flows from deposits, which are exhaustible and also carry with them toxic substances. The unfilled boxes represent exergy conversions, which in most cases represent a huge number of internal conversions and processes. The resources actually demanded by society appear as outflows on the right side of the diagram. The total inflow of resources during 1994 amounts to about 2720 PJ or 310 GJ per capita, and the net output becomes 380 PJ or 40 GJ per capita. Thus, the overall efficiency of the supply sector can be estimated at less than 15%, which must be regarded as poor. As we shall see, some sectors are far less efficient and, in some cases, are extremely inefficient.

We will now take a closer look into each sector starting from the top of Figure 3.

2.1. Solar Heating

In Sweden, about 20 PJ of direct solar energy is converted into heat using solar conversion systems. The total inflow of sunlight over the area of Sweden amounts to about 1,300,000 PJ per year. The converted flow of solar heat is about 1 PJ, which supplies about 5% of heat usage for space heating, which can be seen at the very bottom, on the right in the diagram, during the heating season. The exergy content in this flow must be examined in detail. A south window lets in about 7 MJ per m^2 per day during the solar-heating season in Stockholm. With adequate regulation by shutters, a south-facing window can be equivalent to a small heat radiator. The average solar inflow in Sweden is about 1000 kWh per m^2 per year or 3.6 MJ per m^2 per year in energy units. With an exergy factor of 0.93, the exergy inflow becomes 930 kWh m^{-2} per year or 3.3 MJ m^{-2} per year. If we compare this with the average heating needs for a house we have a relation between the inflow of sunlight on the house and the average heating needs of a household of about 5:1 in energy units and 93:1 in exergy units. Thus, we have access to 5 times more energy or 93 times more exergy than is physically needed to keep the house comfortable. This is an example of the lack of use of available renewable resources in our society. The surfaces of our houses, i.e. the roof and walls facing the sun, must be better utilized by the energy system in the future.

2.2 Forestry and Industry Based on Forests

In forestry, the stocks of timber and the raw materials derived from forests are generally quantified in m^3 wood without bark. Wood is used here as a general term for many different kinds of timber. The exergy of wood is about 18 MJ per kilogram dry solid. The natural water content of wood is about 25%. With an average density value equal to 450 kg of dry solid per m^3, we get an exergy of 8 GJ per m^3.

The exergy content of wood is given by the total change of chemical and "structural" exergy. The chemical exergy is the exergy stored in the material in the form of binding exergy between the atoms in a molecule. The structural exergy is the exergy or information stored in the structure of a material. This part is of great value for certain materials such as proteins or cellulose fibers. The structural exergy is well utilized when wood is used as building material or as raw material for the production of paper. By burning useful wood, this part is utilized very badly. We optimize the utility of exergy better if we only burn structurally useless wood or paper. The structural exergy is, however, often a very small part of the total exergy content of a material but nevertheless very useful.

In 1992/93, forest crops were used according to Table 1. Swedish timber cutting was 53.0 Mm^3 or 424 PJ. The annual growth of forests is estimated to be about 60 Mm^3 or 480 PJ.

In pulp production, there is a great loss of exergy due to the conversion of chemical exergy into heat during the processing of pulp. About 170 PJ of the forest crops (lignin), peat and waste together with 33 PJ of fossil fuels, gave less than 60 PJ of heat and electricity (see Figure 3). Within the wood and pulp industry, 77 PJ of electricity was also consumed. The exergy content of the outputs consisting of wood, pulp, and paper was about 174 PJ (70+104) (see Table 1).

S. No.	Description	Amount (Mm^3)	Exergy equivalent (PJ)
1	Saw-logs	25.0	200
2	Pulpwood	21.5	172
3	Fuel wood	3.8	30
4	Other wood	0.9	7
5	*Total net felling* (2+3+4)	*51.2*	*409*
6	Cut whole trees, left in the forest	1.8	15
7	**Gross Felling** (5+6)	**53.0**	**424**
8	Chips for pulp production	19.9	159
9	White deals	4.7	38
10	Red deals	4.1	33
11	*Total production of deals* (9+10)	*8.8*	*71*
	Other products	**(Mton)**	**(PJ)** 17 PJ/Mton
12	Bleached pulp	2.4	41
13	Paper	2.3	39
14	Unbleached paper	1.1	19
15	Other paper	0.3	5
16	*Pulp and paper* (12+13+14+15)	*6.1*	*104*
17	**Total production** (11+16)	**-**	**175**

Table 1: Calculated annual gross felling, sorted by felling-seasons and use of forest products

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Biographical Sketch

Göran Wall is an independent researcher specializing in exergy, sustainable development, and quality in education and management. He obtained his Ph.D. in 1986 and was appointed Associate Professor (Docent) in Physical Resource Theory at Chalmers University of Technology, Göteborg, Sweden, in 1995. In 1996 he retired from the university to become a full time consultant, and since 1995 engaged in UNESCO's Encyclopedia of Life Support Systems. Among his publications are more than forty papers in journals and international conference proceedings; for further information see home page: http://www.exergy.se