EXERGY USE IN THE SWEDISH SOCIETY 1994

Göran Wall
Exergy Studies
Solhemsgatan 46, SE-431 44 Mölndal
Sweden
Phone/Fax: +46-31-877579, Email: gw@exergy.se, WWW: http://exergy.se

Presented at

TAIES'97

International Conference on **T**hermodynamic **A**nalysis and **I**mprovement of **E**nergy **S**ystems
Beijing, China, June 10-13, 1997

published in

Ruixian Cai, et al. Eds., "Thermodynamic Analysis and Improvement of Energy Systems," pp. 403-413, Beijing World, Chinese Society of Engineering Thermophysics and American Society of Mechanical Engineers(1997)

ISBN 7-5062-3264-Z

ABSTRACT

The exergy concept is reviewed as a tool for resource accounting. Conversions of energy and material resources in the Swedish society in 1994 are described in terms of exergy. Necessary concepts and conventions are introduced. Exergy losses in transformations of material resources and in conversions of various forms of energy into heat are described in some detail.

INTRODUCTION

Exergy, ecology and democracy are necessary tools to create and maintain a sustainable or vital society. (Wall 1993) Exergy relates to the physical world, ecology describes the living nature and democracy is the best tool for human co-operation.[1] In order to improve systems involving all these parts, i. e. a society, all of these tools must be considered, and an exergy tax has earlier been proposed as an economic force towards the development of a more sustainable society. However, the basic driving forces in a vital society must be founded on morals and love. (Wall 1996)

Nothing disappears and everything disperse, these are two fundamental laws referring to the first and second laws of thermodynamics. These laws have a strong impact on our living conditions. The resource use in the developed world implies a resource depletion and an environmental destruction never seen before in the history of mankind. Resource management is characterized by unconscious incompetents, mainly based on a number of myths and lack of morals. (Wall 1993)

At present process of change man is facing a soon extinction. The first signs are already visible; new diseases appear and the average duration of life is decreasing in many developed countries. The situation can be described by Fig. 1.

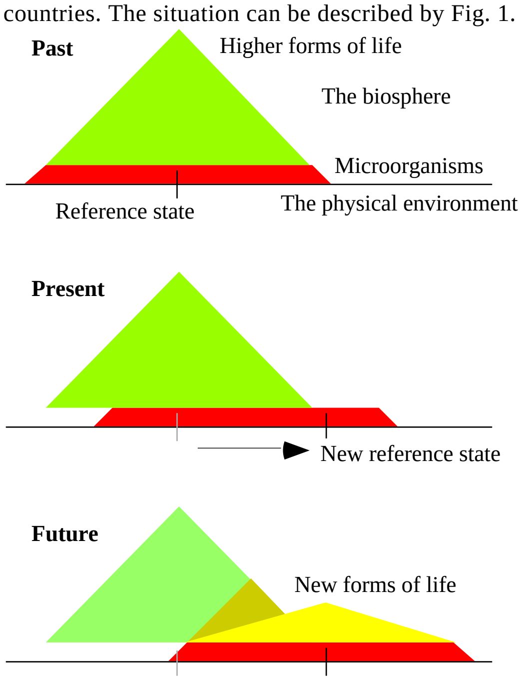


Figure 1 The physical change of the environment will imply catastrophic changes in the biosphere.

The environmental pollution changes the chemical composition of the environment, i.e. the reference state. This causes the nature to create new forms of life and organisms, as it has always done. Some microorganisms may create 25,000 new generations in a year, so new organisms quickly appear. Sometimes we see this as a sudden and mysterious numerous death among animals and plants from poisonous algae or viruses or as an increased human mortality from cancer and

[1]Nota bene, I am here referring to direct democracy, i.e. true democracy and not oligarcy.

allergy. In short, the present industrial development is nourishing new diseases that will kill all higher forms of life.

Thus, the main environmental problem with nature is not the depletion of species, it is the opposite, i.e. the development of new vital species. According to what Darwin expressed in the revolutionary book "On the Origin of Species by Means of Natural Selection" in 1859 new species of microorganisms will evolve from the change of the reference state of the environment, as indicated in Fig. 1. This is the far most dangerous threat to mankind, mainly because it is completely unpredictable and it will kill the most developed, and also most vulnerable species. Being unpredictable is also probably a reason why it is not made explicit in politics, e.g. Agenda 21 (United Nations 1992). However, according to the theory of evolution, we know that it is directly connected to the depletion and disperse of non-renewable resources and it is unavoidable.

From this insight there is an obvious need to improve the use of physical resources in the society, in order to decrease the change of the ambient reference state indicated in Fig. 1. From analyzing the physical resource use in the societies by using the concept of exergy, the inefficient and wasteful resource use will become obvious. This, in turn, will clarify possible improvements and major emissions that immediately must be taken care of. Beside, measuring physical resources in exergy, we also need to classify them with regard to their origin.

A CLASSIFICATION OF RESOURCES

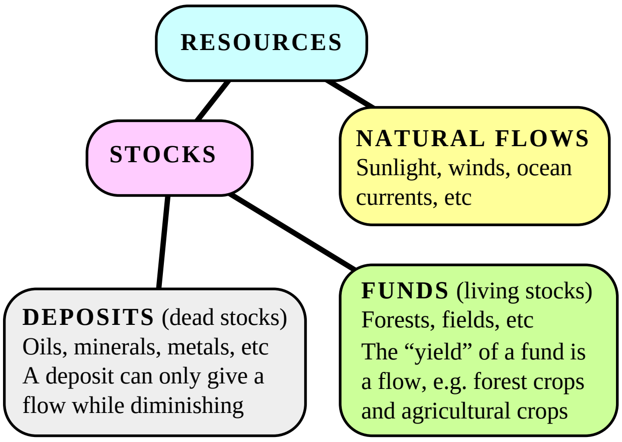


Figure 2 A classification of resources.

Natural resources, such as energy and material resources, appear partly as *flows* and partly as *stocks*, Fig. 2. We regard constantly flowing solar energy, wind energy and water flows as natural flows. A natural flow has a limited size, but usually lasts for a very long time. An ecosystem, such as a forest, forms a valuable stock. It is built up of natural flows of sunlight, water, carbon dioxide, and mineral substances. It gives rise to a flow of new biological matter and part of this flow (the yield) can be taken out of the system without decreasing the stock. Other stocks, such as oil deposits, have quite different qualities. A deposit can only yield a flow if it is gradually depleted and dispersed.

Among stocks we therefore differentiate *dead stocks* or *deposits* from *living stocks* or *funds* (Georgescu-Roegen 1971 and 1975). This is partly a time based classification because the time of reproduction is the physical concept that is of interest here. Deposits and funds are defined with regard to the difference in the time of reproduction. Natural flows and flows from funds are often called renewable flows.

We could also, by referring to Fig. 3 and 12 below, distinguish between deposits and funds by means of origin. Deposits origins from the toxic matter which is being removed by the ongoing recycling processes in the biosphere, and put into the lithosphere. Thus, it builds up exergy on the earth. Whereas, funds are deflections of the matter, which is part of the cyclic processes in the biosphere, that are powered by the sun, see further below.

EXERGY AS A GENERAL RESOURCE CONCEPT

Energy and matter cannot be created or destroyed. We can not understand what energy actually is, since everything we can observe is energy in different forms. Thus, one way to define energy is that it is everything. Another way is to define energy as motion or ability to produce motion. (Wall 1986) Energy and matter appears in many forms and different qualities and the quality can increase locally or be destroyed. However, the total quality must always decrease. This is best explained by the concept of exergy. When we use the word energy in everyday life we should, if accurate, use the word exergy instead. Exergy can be defined as work or ability to produce work. (Wall 1986) Work is <u>ordered</u> motion, in distinction to energy. In short, we can state that nothing disappears and everything disperse. The following expressions for exergy E are used in this analysis: (Wall 1977)

$$E = U - U_{\text{eq}} + p_0(V - V_{\text{eq}}) - T_0(S - S_{\text{eq}}) - \sum_i \mu_{i0}(n_i - n_{i,\text{eq}}) \quad (1)$$

where U, V, S, and n_i denote extensive parameters of the system (energy, volume, entropy, and the number of moles of different chemical materials i) and p_0, T_0, and μ_{i0} are intensive parameters of the environment (pressure, temperature, and chemical potential) and "eq" denotes equilibrium with the environment.

The exergy content of a material is

$$E = n\left[\mu - \mu_0 + RT_0 n \ln\left(\frac{c}{c_0}\right)\right] \quad (2)$$

where R is the gas constant and c is the consentration of the material.

Let us illustrate the meaning of *exergy* by some very simple examples:

1. A system in complete equilibrium with its environment does not have any exergy. There is no difference in temperature, pressure, or concentration etc. that can drive any processes. Thus, a waste flow, of any kind, with no exergy does, by definition, not influence the environment.

2. The more exergy a system carries, the more it deviates from the environment. Hot water has a higher content of exergy during the winter than it has in a hot summer day. A block of ice carries hardly any exergy in winter while it does in summer. This fact was the basis of a very prosperous trade of ice in the last century, when ice was regularly shipped from North America to West Indies, South Africa, and finally to Europe.

3. When a physical resource, i.e. energy, matter or information, loses its quality, this means that exergy is destroyed. The exergy is the part of the resource which is useful in the society and therefore has an economic value and is worth taking care of.

4. Almost all energy, converted in the thin layer on the earth's surface, where life can be found, derives from the sun. Sunlight, which is rich in exergy, reaches the earth. A lot of it is reflected, mainly the harmful ultraviolet light by the ozone layer, but the energy absorbed, partly by photosynthesis in the green plants, on the earth is converted and finally leaves the earth as heat radiation with no exergy relative to the earth. The net exergy absorbed by the earth is consequently gradually destroyed, but during this destruction it manages to drive the water/wind system and the life on earth, see Fig. 3. The green plants absorb solar exergy and convert it via photosynthesis into chemical exergy. The chemical exergy then passes through different food chains in the ecosystems. On every tropical level exergy is consumed and micro organisms live on the last level in this food chain. There exists no waste, i.e. all exergy is being taken care of and efficiently used by the living nature, see Fig. 12.

5. A concentrated deposit of mineral "contrasts" with the environment and this contrast increases with the concentration of the mineral. The mineral is thus a carrier of exergy. When the mineral is mined the exergy content of the mineral is kept constant, and if it is enriched the exergy content increases. A poor deposit of mineral contains less exergy and can accordingly be utilized only through a larger input of external exergy. Today this substitution of exergy often comes from exergy forms such as coal and oil. When a concentrated mineral is dispersed, the exergy content decreases (point 3). However, from the environmental point of view this decrease might not be harmless. In many cases it has catastrophic effects to the environment, as described above by Fig. 1.

6. An obstacle in the use of the exergy concept is that it depends on the environment. This difficulty could, however, be solved through conventions; one could define a "standard environment" with a given chemical composition at a certain temperature and pressure. A possible standard environment for global use could, for instance, be a standard atmosphere, a standard sea and a standard bed-rock. One principal problem is, however, that these systems are not in equilibrium with each other. Sometimes one should, in addition to this, use local standards depending on the season (point 2). This problem has been well treated by Szargut, who has stated commonly used reference states. (Szargut 1980 and Szargut et al. 1988).

Exergy is *the* "fuel" for dissipative systems, i.e. systems that are sustained by converting energy and materials; e.g. a living cell, an organism, an eco-system, the earth's surface with its material cycles, or a society, i.e. metabolic processes. The exergy concept could and should therefore, in this sense, be used systematically to describe such systems scientifically.

The exergy concept has mostly been used within heat and power technology, where one works with thermal energy of varying qualities. The field of application can be extended to the totality of energy, material and information conversions in the society. This yields a uniform description of the use of physical resources and the environmental impacts in connection with this use. Also, there is a lack of a useful common scientific measure of substances, which is a serious problem in many environmental accounting methods practiced today, e.g. Life Cycle Assessment or Life Cycle Analysis (LCA) and Environmental Economics. (Gong and Wall, 1997)

Natural resources are traditionally divided into energy resources and other resources. This separation often can be only approximate. Oil, for example, is usually looked upon as an energy resource and wood is regarded as a material resource. This distinction is not very meaningful, however, because oil can also be used for producing useful materials and wood can be used as a fuel. It would be more appropriate to consider these resources together. The exergy concept is, in this connection, an adequate resource measure. The exergy content of the energy resources may be given by their energy content multiplied by a quality factor that applies to the energy form in question. Energy resources are usually measured in energy units, i.e. the same unit as exergy. Other resources are usually measured in purely quantitative units as weight, volume, or number.

In principle, a material can be quantified in exergy units just by multiplying its quantity with a transformation factor for the material. The unit of such a transformation factor could then be e.g. J per m^3 or J per kilogram. This would be the beginning of an expanded resource budgeting and a first step towards an integration with the traditional energy budgeting.

Exergy per unit quantity is in fact the physical value of a resource relative to the environment. This can be compared to a price which is also partly defined by the environment through, for instance demand. (Gong and Wall, 1997)

Exergy can only denote *one* extensive physical quality of goods. The exergy content *does not* imply anything about intensive physical or biological qualities like electric conductivity, nutritive value, toxicity, or the like. However, when a material is used as an exergy converter the efficiency is then related to the quality of interest of the material. A material with bad electric conductivity gives a greater exergy loss than a material with good electric conductivity gives when being used as an electric conductor. In a similar way we may distinguish biological qualities with regard to their effect on the natural exergy conversions in the environment.

In Fig. 3, we see how the exergy flow through human society is maintained, cf. Fig. 2. The greater part of the exergy requirements are seen to from the terrestrial exergy stocks. Man only uses a very small part of the exergy flow from the sun, e.g. within agriculture and forestry. In society there is thus, on the whole, a continuous exergy loss. Some exergy flows, such as flows of ores, increase their exergy when passing through society. However, other flows decrease their exergy all the more. The exergy flow in the Swedish society will be presented below.

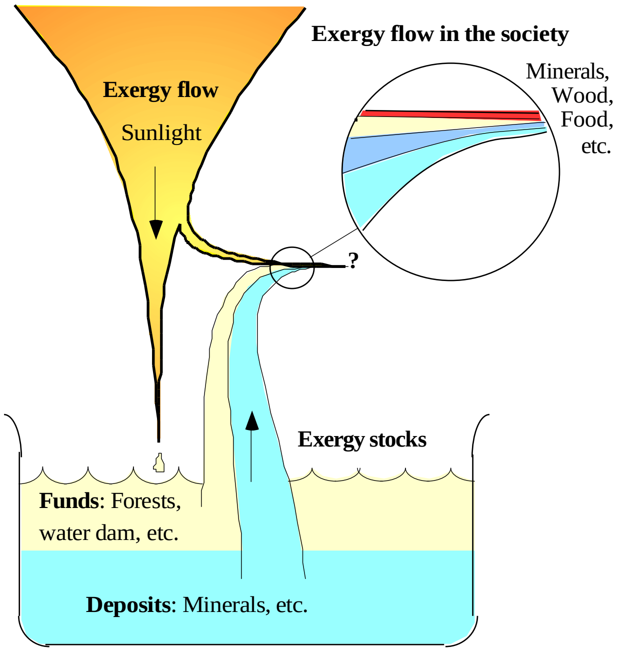


Figure 3 The exergy flow from the sun, and the exergy stocks on earth create the resource base for human societies on earth.

RESOURCE CONVERSIONS IN THE SWEDISH SOCIETY

The use of energy resources in Sweden from 1960 to 1994 is shown in Fig. 4 below. Nuclear is here defined by the amount of energy being released as heat in the nuclear power plants. This amount is about three times the amount of produced electricity. As we can see, the total energy resource use has increased over the period, where fuel oil as been decreased from early 70's and nuclear increased from mid 70's. The use of these and other physical resources will be described below.

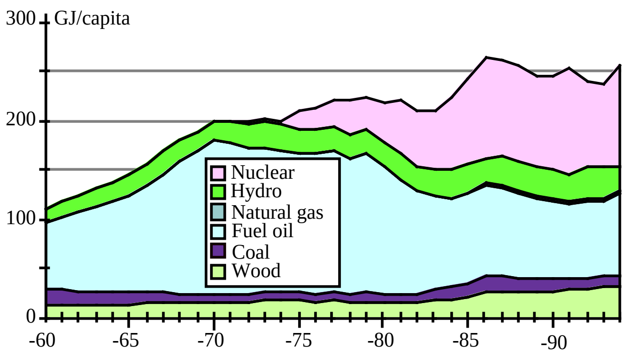


Figure 4 The use of energy resources in Sweden, 1960 to 1994.

The main conversions of energy and materials in the Swedish society in 1994 is shown in Fig. 5. Data was available from *Statistical Abstract of Sweden 1996* and *Statistical yearbook of industry 1994*. 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 basically represents the resource supply sector. The width of the flows is defined by their exergy content and the unit of the flows is J/year. (Since the flows vary a great deal during the year I prefer to use the unit J/year instead of W.) The inaccuracy of the flows vary a lot between the different areas. For the electricity system the accuracy is quit high, whereas for sectors related to agriculture and forestry we have, from obvious reasons, a different situation. In order not to make the diagram too complicated only exergy flows exceeding 5 PJ/year are included. The inflows are ordered according to their origins. Sunlight is thus a renewable natural flow. Besides, a minor use of wind power, far less than 5 PJ/year, this is the only direct use of a renewable natural flow. Harvested forests, agricultural crops, and hydropower are renewable exergy flows deriving from funds, which of course are founded 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 full of toxic substances. Exergy conversions are represented by the unfilled boxes, which in most cases represents a huge number of internal conversions and processes. The resources actually demanded in society appear as outflows on the right side of the diagram. The total inflow of resources during 1994 accounts to about 2720 PJ or 310 GJ/capita and the net output becomes 380 PJ or 40 GJ/capita. Thus, the over all efficiency of the supply sector can be estimated to less than 15%, which must be regarded as too poor. As we will see, some sectors has a far less efficiency, in some cases ridiculously poor.

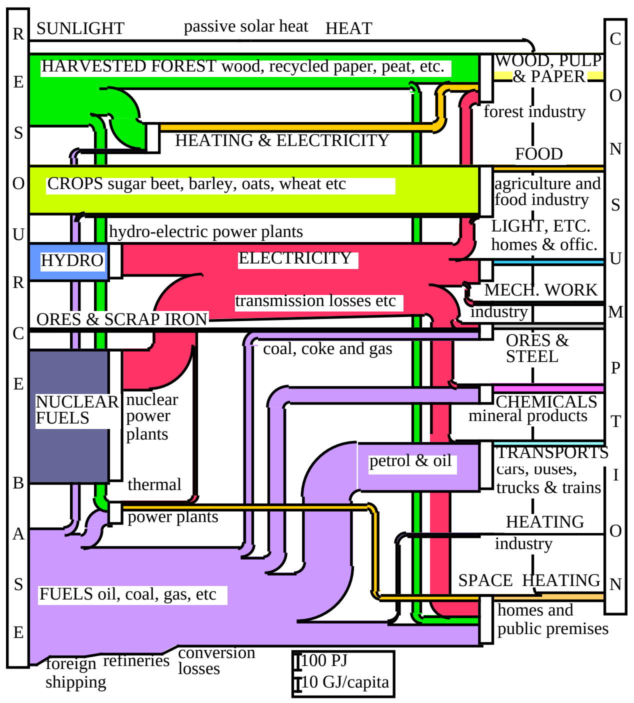


Figure 5 The exergy conversion system in the Swedish society in 1994. Total input about 2720 PJ or 310 GJ/capita and output about 380 PJ or 43 GJ/capita.

It is also recommended to compare this diagram with earlier studies of Sweden (Wall 1987) as well as other countries like

Japan (Wall 1990), Finland (Wall 1991), Italy (Wall et al. 1994), and Brazil (Schaeffer 1990 and Schaeffer et al. 1992). Let us now look closer into each sector starting from the top of the diagram.

Solar heating

The inflow of sunlight, about 20 PJ, is converted into heat. (The total inflow of sunlight over the area of Sweden is about 1 000 000 PJ/year.) The converted flow of solar heat is about 1 PJ which supplies about 5% of the use of heat for space heating, that can be seen at the very bottom on the right in the diagram, during the heating season. The exergy content in heat is treated below. A south window lets in about 7 MJ/m^2 and day during the heating season in Stockholm. With an adequate regulation by shutters a south window can be equivalent to a small heat radiator. The average solar inflow in Sweden is about 1000 kWh/m^2 and year, or 3.6 MJ/m^2 yr in energy units. With an exergy factor of 0.93 the exergy inflow becomes 930 kWh/kWh/m^2 yr, or 3.3 MJ/m^2 yr. (Wall 1977) 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 need of heat for space heating of about 5 in energy units and 93 in exergy units. 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 used by the energy system in the future. An example of such a house is presented in Fig. 13 below.

Forestry and industry based on forests

In forestry the stocks of timber and the raw materials derived from the forests are generally quantified in m^3 wood without bark. Wood is here used as a unifying name of many different kinds of wood.

The exergy of wood is about 18 MJ/kilogram dry solid. The natural water content of wood is about 25%. With an average value of density equal to 450 kilograms of dry solid per m^3 we get an exergy of 8 GJ/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 as lack 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 never the less very useful.

In 1992/93, the 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 about 60 Mm^3 or 480 PJ.)

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

Table 1 Calculated annual gross fellings, by assortment in the felling-seasons and use of forest products

Assortment	Mm^3	PJ
Saw-logs	25.0	200
Pulpwood	21.5	172
Fuel wood	3.8	30
Other wood	0.9	7
Total net felling	51.2	410
Cut whole trees, left in forest	1.8	15
Gross felling	53.0	424
Chips for pulp production	19.9	159
White deal	4.7	38
Red deal	4.1	33
Deal		70
Product	Mton	PJ[1]
Bleached pulp	2.4	41
Paper	2.3	39
Unbleached paper	1.1	19
Other paper	0.3	5
Pulp and paper		104

[1] 17 PJ/Mton

Agriculture and food production

Harvested crops are converted into food. The input in agriculture and the food industry is not only solar radiation but also fertilizers, fuels, and electricity. The food consists partly of plant substances such as vegetables and bread, partly of animal substances such as milk and meat. We see that the outflow of food is very small, mainly due to losses in the production of animal products.

The agricultural land of Sweden covers at present about 2.8 million hectares. The yield is very stable from an international point of view. It varies only a few percent per year and this is compensated by trade exchanges. In Table 2 below, the vegetable yield in exergy of the most common Swedish crops are to be found.

The total exergy content of the vegetation products was about 160 PJ. In addition to this there were residues such as straw and harvesting losses, about 140 PJ. The amount of residues that was brought back into cultivation was estimated to 30 PJ. Exergy from fossil fuels, mainly diesel fuel and fuel oil, and electricity were used in agriculture and in greenhouses, and in the food industry. The export and import of agricultural products were approximately equal in exergy terms. Mostly cereals were exported and feeding-stuff for animals were imported. The indirect use of exergy mainly in the form of fertilizers is not included here. The output from this sector is food.

The food consumption in Sweden for 1994, with approximately 8.8 million inhabitants, can be estimated in different ways. According to the recommended daily intake, the people in Sweden should consume 31 PJ with considerations taken to the age-distribution. In the statistical yearbook there is stated an average of 2862 kcal/day and person. This adds up to 38 PJ for the food consumption.

Table 2 Vegetable yield in Sweden 1994.

Yield in metric tons	Mton	PJ/Mton[1]	PJ
Winter wheat	1.1702	16.0	18.7
Spring wheat	0.1747	16.0	2.8
Rye	0.1734	15.5	2.7
Barley	1.6609	15.5	25.7
Oats	0.9906	17.9	17.7
Hay	4.6275[2]	16.1	74.6
Potatoes[3]	1.0628[2]	3.5	3.7
Sugar-beets	2.3498	2.8	6.6
Winter rape	0.1	19.1	1.9
Spring rape	0.069	19.1	1.3
Winter turnip rape	0.001	19.1	0.0
Spring turnip rape	0.025	19.1	0.5
Total yield			156.2

[1]There is a large uncertainty in the precise composition of the materials, especially concerning the water content.
[2]Partly estimated
[3]Table potatoes and potatoes for processing

Electricity from hydro power and thermal power

Electricity was used according to Tables 3 and 4 below.

Table 3 Electricity: generation and consumption in Sweden.

Electricity		TWh	PJ
Hydro, pump and wind	*gross*[1]	*59.172*	*213.0*
Hydro, pump and wind	net	57.954	208.6
Nuclear	*gross*	*73.589*	*264.9*
Nuclear	net	70.151	252.5
Fossil fuels	*gross*	*9.876*	*35.6*
Fossil fuels	net	9.546	34.4
Import		6.681	24.1
Total supply		144.33	519.6
Export		6.419	23.1
Farming, forestry, etc. (1993)		3.279	11.8
Industry		48.258	173.8
Power plants etc.		7.769	28.0
Rail transports and buses		2.577	9.3
Housing (1993)		35.192	126.7[2]
Other consumers		32.209	116.0
Total domestic use		130.731	470.6
Transmission losses		7.182	25.9

[1]The difference between gross and net equals to own consumption in power stations incl. transformer losses at power stations and pumping in pumping stations.
[2]Of which 104.8 PJ was used for space heating

The forest and paper industry used electricity for manufacture of wood and wood products, 6.9 PJ and for manufacture of paper and paper products, printing and publishing, 70.4 PJ, summing up to about 77 PJ. In the food production electricity was used at the farms, 11.8 PJ and in the manufacture of food and beverages, 8.9 PJ, i.e. in total 20.7 PJ. The manufacturing industry used totally about 21 PJ in textile, wearing apparel and leather industries, 1.0 PJ, manufacture of machinery and equipment, 6.5 and other manufacturing industries 13.1 PJ. Much of this electricity was used for driving machines, i.e. mechanical work. The rest of the electricity went mainly into mining, 8.4 PJ, basic metal industries and manufacture of fabricated metal products, 31.5 PJ. Thus, mining and basic metal industries, which is mainly the iron and steel industry, used about 40 PJ. The chemical industry divided into manufacture of chemicals, petroleum, coal, rubber and plastic products, 22.6 PJ, and manufacture of non-metallic mineral products except products of petroleum and coal, 4.4 PJ, used about 27 PJ. Transports, i.e. rail transports and buses, used about 9 PJ. Electricity, gas, heat and water plants used 28 PJ, and the waste treatment sector used about 3 PJ. Furthermore, electricity was used in households, for space heating, 105 PJ and for housing, services etc., 146 PJ, mainly for lighting, heating, mechanical work etc.

Table 4 Consumption of electricity by industry.

Industry	TWh	PJ
Mining	2.335	8.4
Manufacture of food and beverages	2.485	8.9
Textile, wearing apparel and leather industries	0.267	1.0
Manufacture of wood and wood products	1.907	6.9
Manufacture of paper and paper products, printing and publishing	19.569	70.4
Manufacture of chemicals, petroleum, coal, rubber and plastic products	6.287	22.6
Manufacture of non-metallic mineral products except products of petroleum and coal	1.210	4.4
Basic metal industries and manufacture of fabricated metal products	8.753	31.5
Manufacture of machinery and equipment	1.806	6.5
Other manufacturing industries	3.639	13.1
Total	48.258	173.8

In 1994, production of electricity from hydro, pump and wind power was 209 PJ. If we include conversion losses of potential energy in the dam into electricity supplied by the power plant, and transformer losses at the power stations and pumping in pumping stations, the actual supply becomes 248 PJ, which is more than the gross supply, i.e. 213 PJ, given in Table 3.

Nuclear fuel (U-235) and fossil fuels like oil and coal are also used to produce electricity. These conversion processes occur in condensing power plants and, for oil, also in combined power and heating plants. A combined power and heating plant furnishes, not only electricity, but also district heating by a so-called back-pressure process. We can see from the diagram how this flow of district heating, 26 PJ, goes into the outflow of heating for housing and other premises.

The production of electricity was 253 PJ and 34 PJ respectively from nuclear and fossil fuels. The total production of electricity was then 514 PJ, of which 1 PJ was net imported electricity. Of this production 471 PJ was used according to Table 3 and 4 above. The rest, 26 PJ, was lost due to electric resistance and imperfect adaptation between production and consumption, i.e. transmission losses.

Iron ore

The Swedish mining industry is totally dominated by iron ore. The Swedish iron ore has an average iron content of about 60% (weight percentage) and it usually consists of magnetite in which the iron ore has the chemical composition Fe_3O_4. The molecular weight for iron is 55.8 grams, which implies that 1 kilogram (kg) of iron ore consists of 600/55.8 = 10.7 moles of iron.

Let us assume that Fe and O are represented as Fe_2O_3 (hematite) in solid form at the mole fraction of 2.7×10^{-4}, and O_2 in gaseous form at the partial pressure of 20.40 kPa in the standard environment (Szargut 1980).

The chemical potential for iron in magnetite and hematite then becomes:

$$\mu(Fe_{magnetite}) \approx \frac{1}{3}(1014.2 + 2 \times 3.84)\,\mathrm{kJ/\,mole} \approx 335.5\,\mathrm{kJ/mole}$$

$$\mu_0(Fe_{hematite}) \approx \frac{1}{2}(741.0 + 1.5 \times 3.84)\,\mathrm{kJ/\,mole} \approx 367.6\,\mathrm{kJ/\,mole}$$

Where 3.84 kJ is the amount of exergy released when the partial pressure of one mole of oxygen decreases from 101.325 kPa to 20.40 kPa at 15°C.

The exergy content of magnetite iron ore then becomes[2]:

$$e_{ironore} \approx 10.7\left\{[-335.5 - (-367.6)] \times 10^3 + \right.$$
$$\left. + 8.31 \times 288 \times \ln\left(\frac{0.83 \times 0.43}{2 \times 2.7 \times 10^4}\right)\right\} \approx 0.51\,\mathrm{MJ/\,kilogram}$$

$$e_{iron} \approx 17.9\left\{[0 - (-367.6)] \times 10^3 + 8.31 \times 288 \times \ln\left(\frac{1}{2 \times 2.7 \times 10^4}\right)\right\}$$
$$= 6.90\,\mathrm{MJ/kilogram}$$

since 1 kilogram of Fe is equivalent to 17.9 moles.

The Swedish production of iron ore in 1994 was approximately 19.9 Mton of which about 15.3 Mton were exported. If we assume all this ore to be magnetite iron ore, since most of the Swedish iron ore is, then the ore represents a total exergy quantity of 10 PJ.

The production of iron was about 4.5 Mton, representing an approximate quantity of 31 PJ. To produce this iron about 4.6 Mton of ore was needed, corresponding to 2 PJ together with 1 Mton scrap iron, i.e. 7 PJ, 29 PJ of electrical exergy and 50 PJ of coal, coke and other fuels.

Nuclear fuel

The exergy content of nuclear fuel (enriched uranium) is estimated on the basis of how much exergy that is released as heat in a thermal reactor for a certain amount of produced electricity. At an efficiency of 30%, this becomes about 840 PJ. However, this is only about 1.5% of the available nuclear exergy, see Fig. 6. (Wall 1993) Then, the total nuclear exergy being handled in Sweden is about 55000 PJ or 55 EJ. Figure 6 shows the exergy utilization when the electricity is used for space heating by direct conversion through short circuiting, which becomes less than 0.025%. From a physical approach this is a disaster, but still economically and politically justified. This also gives a better understanding of the problems of nuclear waste management, since most of the exergy is left in the waste. In the world today most of the nuclear fuel is used at an incredibly poor efficiency.

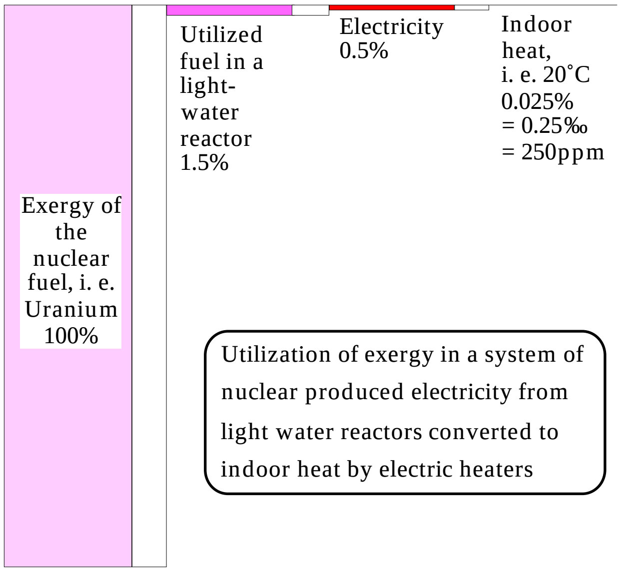


Figure 6 Nuclear fuel in Light Water Reactors for space heating by short circuiting.

Chemical fuels

Chemical fuels or, shorter, *fuels*, are oil and oil products, such as paraffin (kerosene) and petrol, coal and coal products, such as coke and urban gas, natural gas, and peat.

The most commonly used fuels in Sweden are crude oil, oil products, pit coal and coke. The exergy content of these are 42.3, 41.2-43.2, 27.4 and 28.1 GJ/ton respectively (Wall 1983). The total import of these goods was in 1994 1094 PJ, see Table 5.

Table 5 Import, export, and stock changes of chemical fuels.

Chemical fuel	Import	Export	Changes in stocks, etc.	Domestic use
Coal and coke	101.4	1.4	2.1	97.9
Crude oil, oil products	1096.0	389.4	-30.1	736.7
Gaswork gas, natural gas, coke-oven gas, blast-furnace gas	31.6	0	0	31.6
Total	1229	390.8	-28	866.2

Within the chemical industry, fuels are also used as raw materials. This means that a large fraction of the exergy remains in the products, i.e., the relative conversion losses are moderate. About 8 PJ of fossil fuels, see Table 6, 3 PJ of biofuels and 23 PJ of electricity were converted into rubber, plastics, fertilizers etc. The chemical industry is thus an example of how a traditional energy resource like oil is used as material. The used material can then be used as an energy

[2] 1 kg of iron ore = 0.6 kg Fe = 10.7 mole Fe = 10.7/3 mole Fe_3O_4 = 0.83 kg Fe_3O_4.

resource. (We have, however, to consider the problem with special pollutant emissions.) This is of course also true for many other used materials like wood and paper.

Table 6 Consumption of chemical fossil fuels by industry.

Industry	PJ
Mining	5.5
Manufacture of food and beverages	13.7
Textile, wearing apparel and leather industries	1.7
Manufacture of wood and wood products	2.7
Manufacture of paper and paper products, printing and publishing	30.5
Manufacture of chemicals, petroleum, coal, rubber and plastic products[1]	7.7
Manufacture of non-metallic mineral products except products of petroleum and coal	15.7
Basic metal industries	51.6
Manufacture of fabricated metal products, machinery and equipment	3.2
Other manufacturing industries	8.2
Total	140.6

[1]Exclusive refineries.

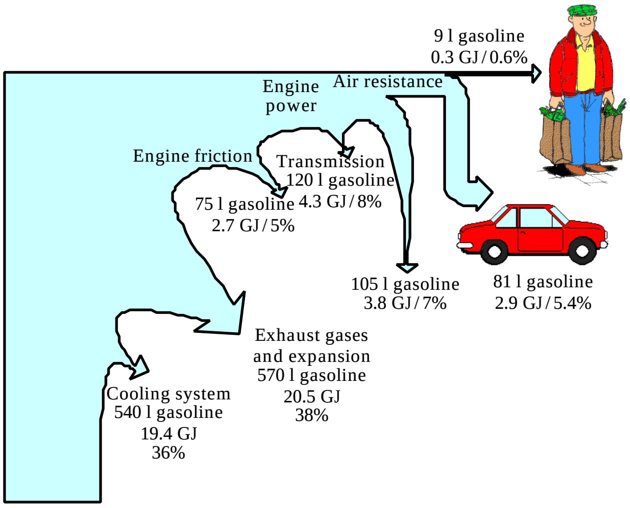


Figure 7 Exergy efficiency of a car.

As we see from the diagram in Fig. 5, the transportation system uses a great deal of the fuel inflow, 301 PJ. Gasoline and oil are converted into transport work in cars, buses, trucks etc. About 13% of the exergy content of the fuel is used to run a vehicle, i.e. for acceleration and to overcome the air resistance, see Fig. 7. We see that the net output as transport of people and goods is only 0.6%. However, too this we should add about the same amount of exergy for manufacturing and maintaining cars, roads, etc. The efficiency for the car then becomes about 0.3%. Thus, to achieve a transportation work of 1 kJ we need approximately 170 kJ of gasoline (100/0.6) plus another 170 kJ from production and maintenance of cars and roads, i.e., a total of approximately 340 kJ.

In addition, 26 PJ was used in the oil refineries, 45 PJ for bunkering for foreign shipping, 54 PJ was lost in the conversion of fossil fuel into other forms of fuel, e.g. coke and blast furnace gas, 134 PJ for direct conversion into heat for housing and other premises, 87 PJ for the production of electricity and heat in thermal power plants, and 13 PJ for heat production within the industry.

Exergy losses at the conversions into heat

At the bottom of the diagram we have the conversion of fuels, electricity, solar heat and hot water (district heating) into heating in industry and heat at room temperature for space heating. The conversion into space heating is shared between apartment houses, family houses, and other premises. As we see, heavy losses appear here. This, leads us to look closer into thermal exergy.

The exergy content of heat is

$$E = \left| \frac{T - T_0}{T} \right| Q \qquad (3)$$

where Q is the quantity of heat and T its absolute temperature (Kelvin). T_0 is the absolute temperature of the environment. The ratio $(T - T_0)/T$ is also known as the Carnot efficiency.

In Fig. 8, we see Eq. 3, i.e. how the exergy content depends on the temperature, as the upper curve. Exergy becomes almost equivalent to energy, i.e. $E \rightarrow Q$, at very large values of temperature. The temperature of the environment is assumed to be 15°C. The lower curve we will introduce below.

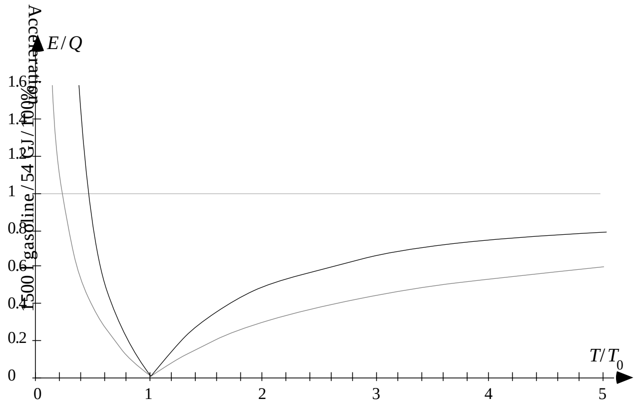


Figure 8 The exergy factor of heat and cold as a function of ratio of temperature to environment temperature for a heat reservoir and a limited body of heat.

Let us now look upon two common exergy conversion processes, fuels converted into heat in industrial processes and fuels or electricity converted into heat in space heating.

In the first case, we have a constant need of heat independent of small variations in the ambient temperature. This means that the exergy content of the produced heat is fairly well defined.

In space heating the situation is more complicated as the need of heating is entirely dependent on the ambient temperature. We now consider the indoor temperature, 20°C or 293 K, as constant. The exergy content of the indoor heat then varies with the outdoor temperature according to Fig. 9.

In order to apply this to space heating we must take the variations of the ambient temperature into consideration.

Assume that the ambient temperature varies harmonically during the year and during the day, then the average exergy factor, E/Q is

$$\frac{E}{Q}=\frac{\left(a^2+\frac{b^2}{2}+\frac{c^2}{2}\right)d+\frac{b}{\omega}\left[\frac{b}{2}\sin(\omega d)-4(a-c)\sin\left(\frac{\omega d}{2}\right)\right]}{T\left[ad-\frac{2b}{\omega}\sin\left(\frac{\omega d}{2}\right)\right]} \tag{4}$$

where
Q = heat (energy)
T = the indoor temperature (in Kelvin)
a = $T - T_0$, where T_0 is the annual average outdoor temperature
b = $T_0 - T_{min}$, where T_{min} is the minimum five-day mean temperature
c = $(T_{day} - T_{night})/2$, the diurnal amplitude
d = the length of the heating season (in days)
ω = $2\pi/365$ per day

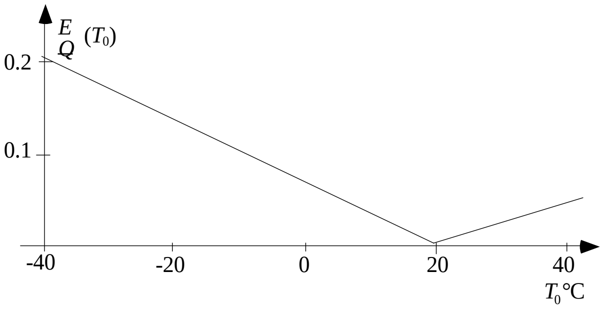


Figure 9 The exergy content of the indoor heat as a function of the outdoor temperature.

Based on this relation a value has been calculated for the exergy factor for space heating in Sweden. (Wall 1986) The exergy factor E/Q, decreases when we go from north to south of Sweden, and this is also reflected in the decreasing heating needs. By summing up relative exergy values of different areas, we get the total amount of exergy in space heating for the whole country. The result was that 5.0% of the supplied heating energy represents exergy. (In addition to this there are of course furnace losses etc.) This estimation of the exergy content in heat for space heating could also, of course, have been estimated from a diagram over the cumulative annual heat load variation. However, an estimate of the exergy content in heat for space heating has also been made from data over the number of hours during the year that the outdoor temperature is below the temperatures: –29.5, –24.5 –19.5, –16.5, –13,5. –9.5, –4.5, and –0.5°C, and above the temperatures: 14.5, 9.5, 4.5 and –0.4°C. When the temperature reaches 11°C, the heating needs are assumed to vanish. From this estimation we get that the total amount of exergy in the space heating is 6.3%. (Wall 1986) The earlier estimated exergy value, 5.0%, was lower, mainly because the estimation did not include the irregular temperature fluctuations which are included here. However, these fluctuations are often very short and are then, in practice, evened out because of the heat load capacity in the buildings. 5% is therefore assumed to be a reasonably good exergy value of the indoor heat during the heating season.

The flow of exergy for the Swedish space heating is thus obtained by multiplying the supplied heating quantity (the energy) by 0.05. This results in the figures: 1 PJ solar heat, 2 PJ from fire wood, 6 PJ of district heat, 5 PJ of electric heat, and 5 PJ of heat from fuels. The figure for heat from fuels also includes other losses, about 30%, such as hot exhaust gases. The minimum physical need of exergy for space heating is thus only 19 PJ. The total exergy supply is, however, more than 400 PJ.

Let us also look closer into the situation for district heating and to maintain systems at a constant temperature, which partly must be treated somewhat different.

The exergy factor of energy transferred as heat from a system with a limited heat content at temperature T, e. g. a substance m with specific heat $c_p(T)$, becomes

$$\frac{E}{Q}=\left|\frac{\int_{T_0}^{T}\frac{T'-T_0}{T'}mc_p(T')dT'}{\int_{T_0}^{T}mc_p(T')dT'}\right| \tag{5}$$

If we assume that the specific heat is a constant this becomes

$$\frac{E}{Q}=\left|1-\frac{T_0}{T-T_0}\ln\frac{T}{T_0}\right| \tag{6}$$

see the lower curve in Fig. 8.

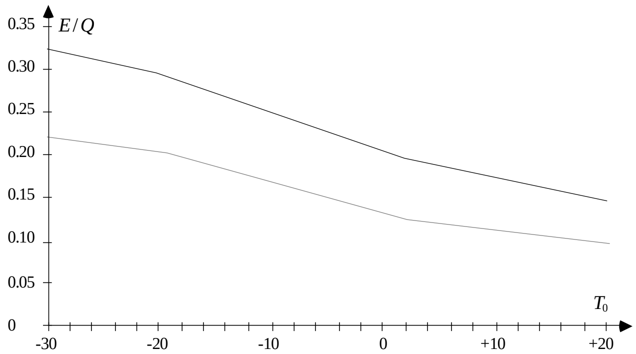


Figure 10 The exergy factor of district heat.

In Sweden space heating based on district heating, a network of hot water distribution for several houses, is common. The exergy factor of district heat becomes

$$\frac{E}{Q}=1-\frac{T_0}{T_d-T_0}\ln\frac{T_d}{T_0} \tag{7}$$

where T_d is the temperature of the delivered heat, i.e., the temperature of the hot water used by the consumer for space heating. This temperature is maintained at about 85˚C (T_d = 358.15 K) at outdoor temperatures above +2˚C (T_0 = 275.15 K) and is subsequently raised in inverse proportion to the outdoor temperature, up to 120˚C (T_d = 393.15 K) at an outdoor temperature of –20˚C (T_0 = 253.15 K). The exergy factor will thus vary with the outdoor temperature according to the lower curve in Fig. 10, above. But, since only a part of the delivered heat is used by the consumer, i.e., the water is returned at a temperature above the outdoor temperature, the exergy factor of the actually used heat becomes

$$\frac{E}{Q} = 1 - \frac{T_0}{T_d - T_r} \ln \frac{T_d}{T_r} \quad (8)$$

where T_r is the temperature of the returned water. When this is 55˚C (T_r = 228.15 K) we instead get the upper curve in Fig. 10.

Chains of resource conversions

As we have already indicated we may follow a chain of resource use to find the total resource use for a specific purpose, e.g. nuclear fuel to electricity for space heating, as was described in Fig. 5. In this regard the diagram gives a complete picture of the total resource use. This makes it possible to compare different systems, within the same system boundaries. The conversion of fossil fuel (oil) via electricity to heat utilize about 2.0% of the exergy, to be compared with the nuclear to space heat system. There are many other chains of conversions in the diagram that could be discussed. However, the use of nuclear for space heating is becoming increasingly common. In 1975, the use of electricity for this purpose was 22 PJ, and at this time it was often compared with cutting butter with a chain-saw.

Of the total inflow of energy and material resources into the Swedish society of about 2720 PJ in 1994, only 14% or 380 PJ reached final use. If we consider the actual use of nuclear fuel, the situation would be much worse, or about 58000 PJ and 0.65%. In 1980 the same numbers were about 2500 PJ, 20% and 500 PJ. Heavy losses could be considerably reduced by an active resource budgeting and economizing on all levels in the society. If we had looked only at the use of commercial energy resources (hydropower, nuclear fuel, and fossil fuels), the efficiency would have been less than 10%.

CONCLUSIONS AND RECOMMENDATIONS

In the long run, exergy needs of a society must be supplied almost entirely from renewable resources. As we can clearly see from the diagram over the exergy conversion in the Swedish society, this was not at all the case.

Analyses of this nature provide us with knowledge as to how effective and how balanced a society is in the matter of conserving natural resources. This type of knowledge can identify areas in which technical and other improvements should be undertaken, and indicate the priorities which should be assigned to conservation measures. Making comparisons of this type between various societies throughout the world and studying the international system should also be of fundamental interest if we are serious in our efforts to work towards an equitable distribution of resources.

It is also of essential importance that the present resource use in the society, see Fig. 11, is moved towards a more natural system, see Fig. 12. From ecological point of view, the present resource use in the society is a dead end technology, Fig. 11, creating nothing but dead in the long run. Deposits are exploited, used and become waste in a one-way flow. Instead we need to develop a vital and sustainable engineering, similar to what is practiced by nature, see Fig. 12. (Wall 1993) From Figs. 11 and 12 it is also obvious that our culture works against the recycling of energy and matter, which is practiced by nature, to create exergy and life on the earth through the natural evolution.

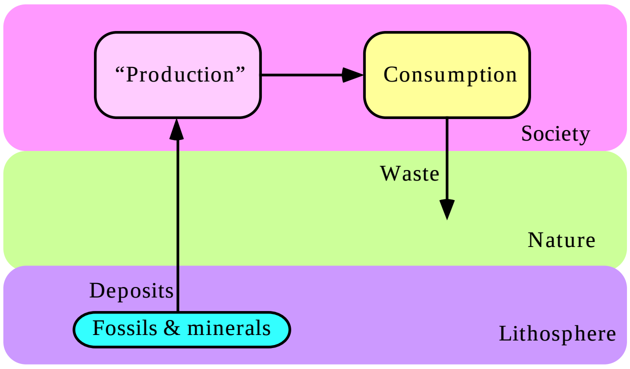


Figure 11 The society takes deposits from nature and returns wastes.

The nature's engineering has so far generated ability of self reproduction, i.e. life, and ability of awareness practiced by higher forms of organism of which man is only but one example. We call this natural evolution, and it was first described by Darwin. Present societal evolution is governed by increased Gross National Product (G.N.P.). This is when rain forests are replaced by asphalt, concrete, smokestacks and electric cables, or when rice fields being farmed for more than 5000 years convert to golf greens. This myth of development must be questioned.

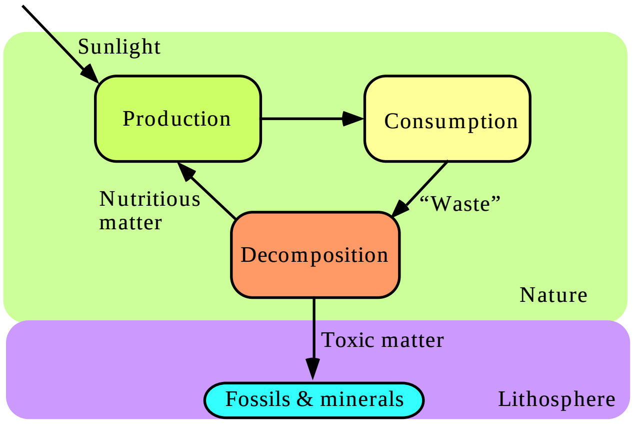
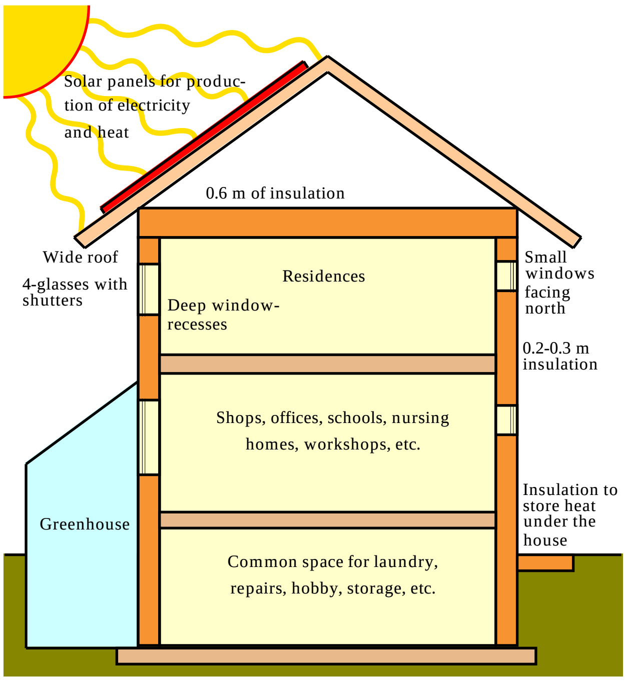


Figure 12 The natural evolution is forced by sunlight and is "self cleaning".

Important solutions to these problems may be found just by regarding ordinary housing in Sweden, see Fig. 13 below. Most of the resource use in the society is linked to a poor management of housing. During the 60's the nearness in the Swedish society was destroyed by concentration of areas for living, working, shopping, etc, thus increasing the distances. This, in turn made the private car into a necessity, which in turn satisfied and increased the producers of cars, gasoline, roads, etc. By making better use of our houses, during the whole day and night, we could both reduce the heating needs and the transportation needs. Also, I believe that this would have a positive impact on our social welfare. However, this is completely against the policy of some major and powerful industries, with large resources for lobbying, etc. Just by addressing ourselves the question: Who will gain and who will lose if we adopt the solutions presented in Fig. 13?, it is obvious where we have the obstacles for a change. Unfortunately, this is rarely expressed or concluded. Partly, it is also rejected by the scientific society, since it reduces the problems of our society to common sense and simple solutions, which is not supporting large research budgets. (Wall 1996) Besides, solving the problems of energy supply through better housing we must also develop technique to use human waste as urine and faeces within the agricultural sector. Here, also common sense and simple solutions are the most profitable ways to approach the problem. In order to support these necessary changes in a sustainable direction an exergy tax has been suggested. (Wall 1993, Gong & Wall 1997)



Plus:
- Fermentation and compost of sewage and garbage
- Recycling of paper, glass, metals, plastic, etc.
- Plantation of fruits and vegetables in the neighborhood
- Local democracy, etc.

Figure 13 A sustainable house for a sustainable society.

ACKNOWLEDGMENTS

The author is grateful to Dr. Darwish M. K. Al Gobaisi, International Centre for Water and Energy Systems in Abu Dhabi, U. A. E. who made this work possible.

REFERENCES

Georgescu-Roegen, N., 1971, *The Entropy Law and the Economic Process*, Cambridge. Mass: Harvard Univ. Press.

Georgescu-Roegen, N., 1975, *Southern Economic Journal*, Chapel Hill, N.C. 41.

Gong, M. and Wall, G., "On exergetics, economics and optimization of technical processes to meet environmental conditions", International Conference on Thermodynamic Analysis and Improvement of Energy Systems, Beijing, China, June 10-13, 1997.

Schaeffer, R., 1990, "Generalization of the concept of exergy at a national level: A tool for energy planning using Brazil as a case study", Thesis, University of Pennsylvania, .

Schaeffer, R. and Wirtshafter, R. M., 1992 *Energy*, Vol. 17, No. 9, pp. 841-855.

Statistical Abstract of Sweden, 1996, the Central Bureau of Statistics, Stockholm.

Statistical yearbook of industry, 1994, the Central Bureau of Statistics, Stockholm.

Szargut, J., 1980, *Energy*, vol. 5, pp. 709-718.

Szargut, J., Morris, D. R., and Steward, F. R., 1988, *Exergy Analysis of Thermal, Chemical, and Metallurgical Processes*, Springer.

United Nations, *Report of the United Nations Conference on Environment and Development*, Rio de Janeiro, 3-14 June, New York, 1992

Wall, G., 1977, "Exergy — a useful concept within resource accounting", Institute of Theoretical Physics, Göteborg. Report no. 77-42.

Wall, G., 1986, "Exergy — a Useful Concept", Thesis, Chalmers University of Technology, Göteborg.

Wall, G., 1987, "Exergy conversion in the Swedish society", Resources and Energy, Vol. 9, pp. 55-73.

Wall, G., 1990, "Exergy Conversion in the Japanese Society", *ENERGY*, Vol. 15, No. 5, pp. 435-444.

Wall, G., 1991, "Exergy Conversions in the Finnish, Japanese and Swedish Societies", Report, Turku School of Economics, Finland.

Wall, G., 1993, "Exergy, Ecology and Democracy — Concepts of a Vital Society", presented at "ENSEC'93 International Conferens on Energy Systems and Ecology", 5-9 July, 1993, Cracow, Poland, publ. in Szargut, J., et al., Eds., pp. 111-121.

Wall, G., Sciubba, E. & Naso, V. 1994, "Exergy use in the Italian society", *ENERGY*, Vol. 19, No. 12, pp. 1267-1274.

Wall, G., 1996, "Energy, Society and Morals", submitted for publ. in *Journal of Human Values*.