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EXERGY CONVERSION IN THE JAPANESE SOCIETY

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Abstract—The exergy concept is reviewed as a tool for resource accounting. Conversions of energy and material resources in the Japanese society 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 are described in some detail.

INTRODUCTION

Today, the use of energy and other resources in the industrialized world has reached a level never reached before. This we see as increasing lack of natural resources and as increasing destruction and pollution of our natural environment. At the same time, the resource conversion network is becoming very complicated. Technical improvements are often concentrated towards less important resource conversions, which do not improve the total resource use. Technical solutions sometimes even become more sophisticated rather than efficient, e.g., nuclear-produced electricity used for space heating or air-conditioning. By describing the use of resources in society in terms of exergy, we may gain important knowledge and understanding. We may find important areas where large improvements should be undertaken by applying efficient technology in the sense of more efficient resource conversions. We would then see how to change the resource base towards renewable resources. Even though this method may be regarded as simple and approximate, it is an effective tool in the study of physical-resource use in society, with the goal of improving resource use. This study is based on concepts and methods presented in earlier work.[1] Similar studies to improve the use of natural resources by applying the concept of exergy to societal systems have been suggested by Szargut.[2]

A CLASSIFICATION OF RESOURCES

Physical resources, such as energy and material resources, appear partly as *flows* and partly as *stocks* (see Fig. 1). A natural flow has a limited size or power but usually lasts for a very long time. An ecosystem such as a forest forms a living stock. It is built up of natural flows and gives rise to a flow (yield) that can be taken out of the system without decreasing the stock. On the other hand, dead stocks such as oil deposits can only yield a flow if they are gradually depleted. Flows from deposits also pollute the natural environment.

We therefore differentiate between dead stocks or *deposits* and living stocks or *funds*. Deposits and funds are defined with regard to the time of reproduction. Natural flows and flows from funds are often also called renewable flows.

ENERGY AND EXERGY

Energy is often defined as work or the ability to perform work. Energy should instead be defined as motion or the ability to produce motion. This is certainly a less specific but a more correct definition. Energy is conserved in all processes. Energy is thus most often an all too hazy concept.

In 1824, Carnot[3] published a relation between heat and work, which later resulted in formulation of the second law of thermodynamics. Gibbs expressed the general relation for work as early as 1873.[4] But not until 1953 did Rant[5] suggest the name exergy and a general definition was given by Baehr in 1965.[6] These four investigations have yielded an adequate definition of the exergy concept and have established the foundations for this thermodynamic quantity.

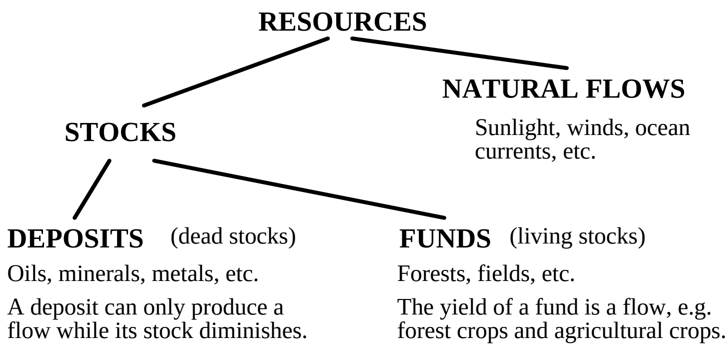

Fig. 1. A classification of resources.

We may express the energy and exergy concepts in the following simple terms: (1) energy is motion or ability to produce motion and (2) exergy is work or ability to produce work. The laws of thermodynamics may be formulated accordingly: (1) energy is always conserved in a process (1st law, law of energy conservation) and (2) exergy is always conserved in a reversible process, but it is always consumed in an irreversible (real) process (2nd law, law of exergy).

The exergy E of a system may be written as

$$E = S(T - T_0) - V(p - p_0) + \sum_i n_i(\mu_i - \mu_{i0}), \tag{1}$$

where the extensive parameters are entropy S, volume V and number of moles of substance i n_i, and the intensive parameters are temperature T, pressure p, and chemical potential of substance i μ_i for the system; the subscript 0 describes the reference state when thermodynamic equilibrium is established with the reference environment. We clearly see that exergy approaches zero as the system approaches equilibrium. The effects of electricity, magnetism, gravity, radiation, etc. can also easily be added to this expression.

Analogously, the exergy of a flow can be written as

$$E = H - H_0 - T_0(S - S_0) - \sum_i \mu_{i0}(n_i - n_{i0}), \tag{2}$$

where H is the enthalpy. Reference states are based on definitions by Morris and Szargut.[7]

EXERGY AS A GENERAL RESOURCE CONCEPT

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. The exergy concept could therefore, in this sense, be used systematically to describe such systems scientifically.

The exergy concept is mostly used within energy engineering, where you work with energy of varying qualities. However, the field of application can be extended to the totality of energy and material conversions in the society. This yields a uniform description of the use of physical resources and the environmental impacts in connection with this use.

Natural resources are traditionally divided into energy resources and other resources. This separation is often 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, thus, 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 (Table 1).

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/m^3 or J/kg. This would be the beginning of an expanded resource budgeting and a first step towards an integration with the traditional energy budgeting. Thus, exergy per unit quantity is the *physical* value of a resource which can be compared to the price which is the *economical* value of a resource. And, both values are affected by the environment in question.

Table 1. The quality of some common energy forms.

Energy form	Quality factor
Mechanical energy	1.0
Electrical energy	1.0
Chemical energy	about 1.0†
Nuclear energy	0.95
Sunlight	0.93
Hot steam (600°C)	0.6
District heat (90°C)	0.2 - 0.3‡
Heat at room temperature (20°C)	0 - 0.2‡
Thermal radiation from earth	0

†May exceed 1, with proper definition of system boundaries and final states
‡Depend strongly on the outdoor temperature

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.

RESOURCE CONVERSIONS IN THE JAPANESE SOCIETY

The population in Japan has been steadily increasing during this century apart from a small drop due to the Second World War (Fig. 2). However, the population is assumed to reach a limit of about 136 Mpeople by the year 2010 and then slightly decline. The population in Japan was 1985 about 121.05 Mpeople.[8]

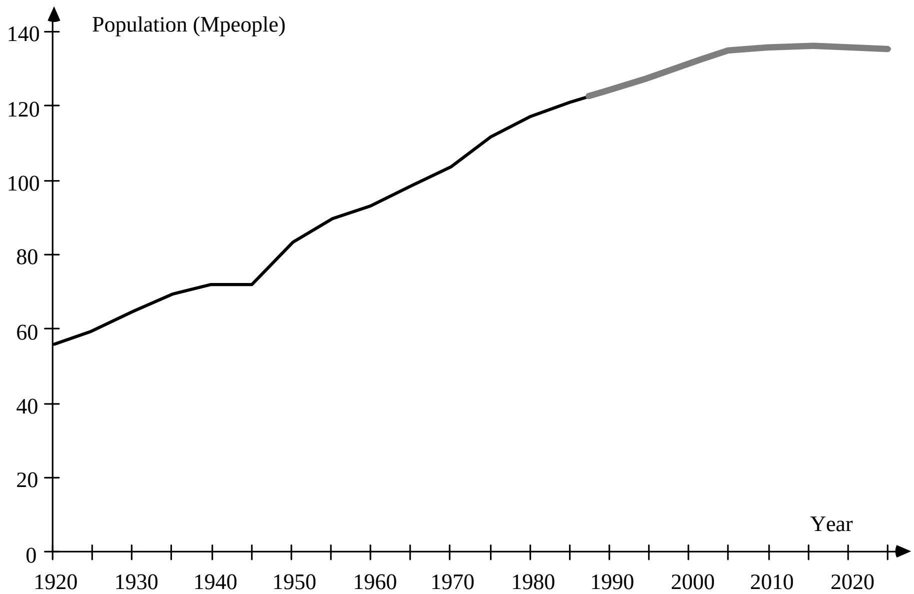

Fig. 2. The population from 1920 to 1986 and estimated from 1987 to 2025.

The use of natural resources has increased dramatically since the end of the second world war. Figure 3 shows the use of energy resources. From this figure we also see that the total use has been more or less constant since the first dramatic oil price increase and that the use of fuel oil is being substituted by other resources such as nuclear fuels.

The main conversions of energy and materials in the Japanese society in 1985 is shown in Fig. 4. The flows of resources go from left to right in the diagram, i.e., from the *resource base* to *the individual*. The width of the flows is defined by their exergy content and the unit of the flows is J/yr. (Since the flows vary in time a great deal during the year the unit J/yr is preferred to W.) The inaccuracy of the flows varies from 5% for electricity to about 20% for the heat flow to houses and other premises. In order not to make the diagram too complicated only major exergy flows are included. The inflows are ordered according to their origins (Fig. 1). Sunlight is thus a natural flow. Harvested forests, agricultural crops, and hydro-power are flows deriving from funds. Metals, nuclear fuels, and fossil fuels are flows from deposits. Exergy conversions are represented by the unfilled boxes. The resources actually demanded in society, by individuals, appear as outflows on the right-hand side of the diagram. The total inflow of resources during 1985 accounts to 18 EJ or 150 GJ/capita and the net output becomes 3.8 EJ or 31 GJ/capita. The same values for the Swedish society in 1980 were 2.5 EJ or 305 GJ/capita and 0.5 EJ or 60 GJ/capita.[9] The large difference is explained by a larger use of wood and paper in Sweden, about 40 GJ/capita in Sweden compared to about 5 GJ/capita in Japan.

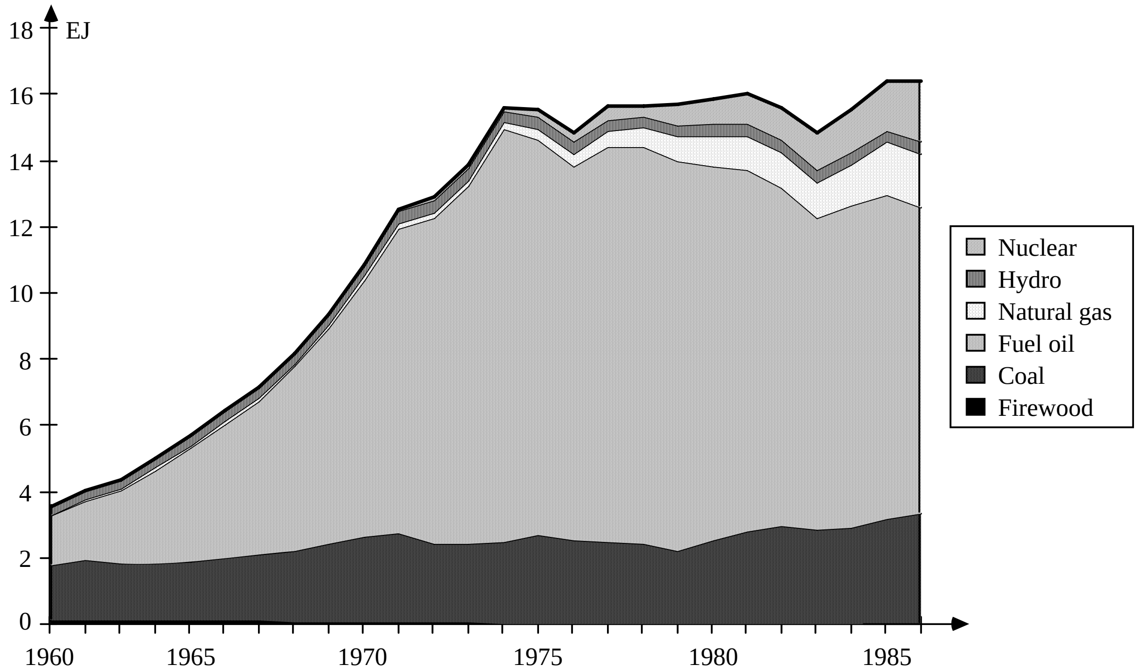

Fig. 3. Energy-resource use between 1960 and 1986.

Solar heating

The inflow of sunlight, a few PJ, is converted into heat in solar panels. (The total inflow of sunlight over the area of Japan is about 900,000 PJ/yr.) The converted flow of solar heat supplies the use of heat for water heating, mainly in households, that can be seen at the very bottom on the right in the diagram. The exergy content of heat and cold is treated in some detail below. A solar panel could produce about 20 m^3 of warm water (40°C) per year and m^2.

Forestry and industry based on forests

In the *Statistical Yearbook of Japan*[8] the stocks of timber and the raw materials derived from the forests are generally quantified in m^3. Wood is here used as a unifying name of many different kinds of wood, e.g., cedar, pine and cypress.

The exergy of wood is assumed to be 8 GJ/m^3. The exergy content of wood is, in principal, 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 materials. This part is of great value for certain materials such as proteins or cellulose fibres. 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. In practice, the structural exergy is, however, often a very small part of the total exergy content of a material but never the less very useful.

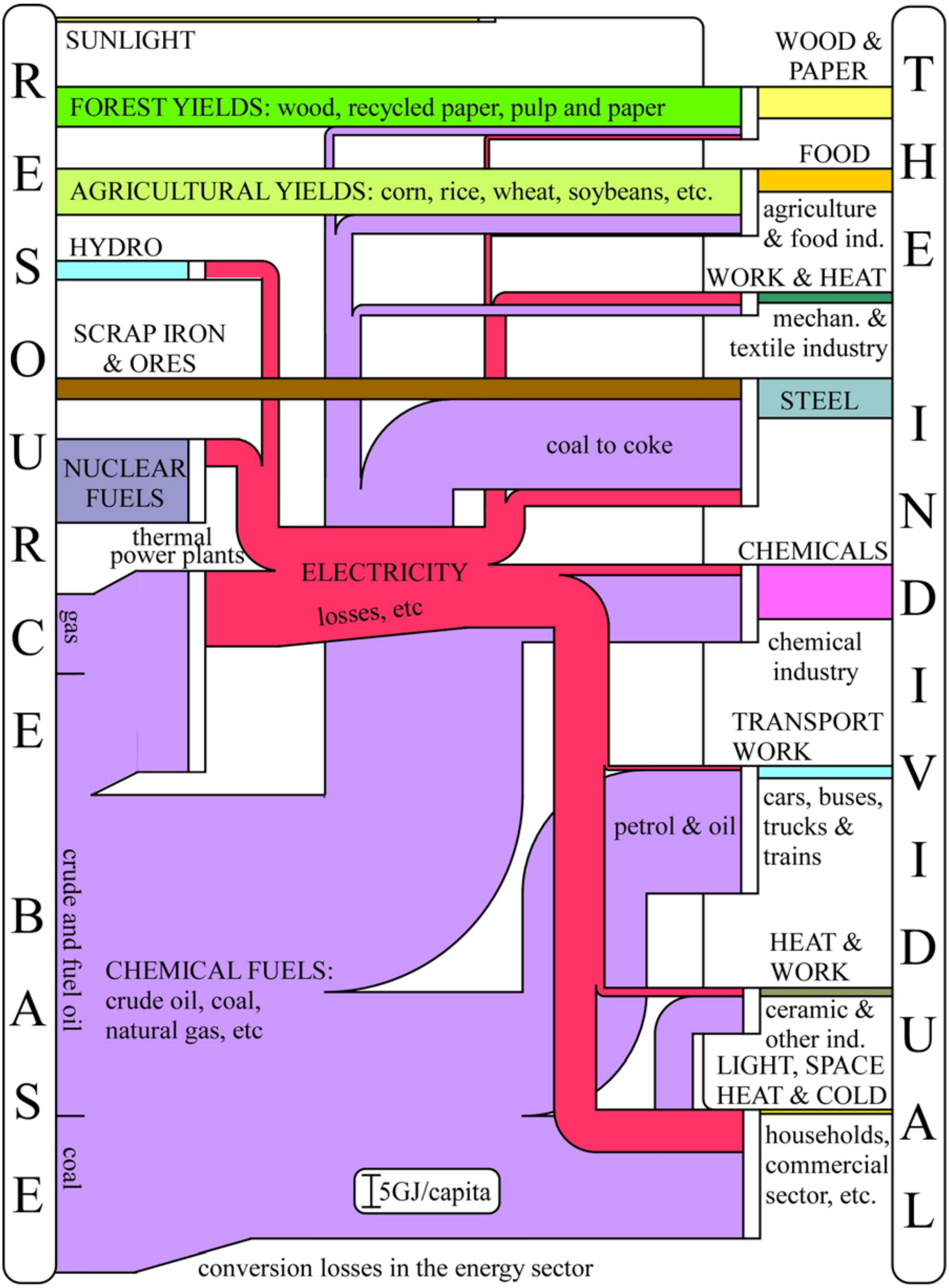

Fig. 4. The exergy-conversion system in the Japanese society in 1985. The total input was about 18 EJ or 150 GJ/capita and the net output 3.8 EJ or 31 GJ/capita.

In 1985, the forest crops were used according to Fig. 5. Japanese timber-cutting was 41.3 Mm^3 (including branches and bark) or 330 PJ and 32.9 Mm^3 (excluding branches and bark) or 264 PJ. (The stock of forests is about 2700 Mm^3 or about 82 times the yearly cut.) The import adds 261 PJ of wood.

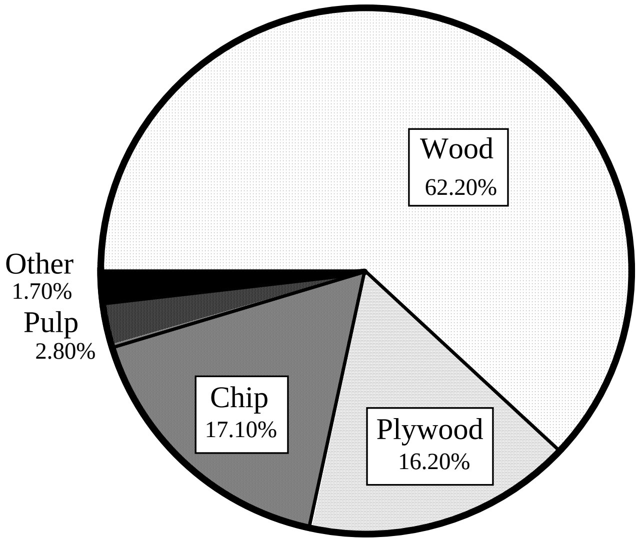

Fig. 5. The use of forest products in Japan 1985

The pulp and paper industry also used 178 PJ of recycled paper. The pulp production was 158 PJ and the import of pulp was 39 PJ. The production of paper was 348 PJ of this 16 PJ were exported and the import of paper was 13 PJ.[10]

In the pulp production there are great losses of exergy due to the conversion of chemical exergy into heat at the boiling of pulp. Thus, 118 PJ of the forest crops (lignin) together with 166 PJ of other fuels (see below) were lost mainly in the production of heat. Also 102 PJ of electricity were delivered to the wood and paper production. The exergy content of the outputs, consisting of wood products and paper, was 637 PJ. The use of firewood amounted to about 4 PJ according to the statistics.

Agriculture and food production

Harvested crops are converted into food. The input in agriculture and food industry is not only solar radiation but also fertilizers, fuels, and electricity. The food consists partly of vegetable substances such as rice and greens, partly of animal substances such as fish and meat.

The agricultural land of Japan covers at present about 53,790 km^2 or 14% of the total land area. The yield may vary a lot which is compensated by support from stocks and trade exchanges. For instance, in 1980 the rice support from stocks was about 2.2 Mton whereas the total harvest was 9.8 Mton. The production and trade of rice in Japan is completely governed by the state. About 60% of the food supply in Japan are based on import. Only the import of corn amounted to 233 PJ or about 300 g/capita-day. In Table 2, the exergy content of the most common Japanese food is to be found.

The exergy content of the total amount of domestic crops was 236 PJ. In addition to this there were residues such as straw and harvesting losses which is estimated to be about the same amount, i.e., 236 PJ. The exergy from fossil fuels, mainly kerosene and fuel oil, and electricity used in agriculture and food industry, was 198 and 64 PJ. Another 184 PJ of fuel oil was used in the fishing industry to produce 55 PJ of fish. Mostly corn, wheat and soybeans were imported mainly to supply the domestic animal production (Table 2). The export could be neglected. The indirect use of exergy in the form of fertilizers is not included here. The output from this sector is food.

The food consumption in Japan is estimated according to the daily intake stated to be on average 2573 kcal/day-person. This adds up to 3.94 GJ/capita or 476 PJ, which is indicated by the outflow from the food production system in Fig. 4. The food production system of Japan seems more efficient than that of Sweden.[9] But, a large amount of food in Japan is imported, so a considerable loss occurs outside of Japan. However, because of a higher consumption of animal products in Sweden, Japanese food production will be more efficient.

Table 2. Vegetable and animal products in Japan 1985.

Products	MJ/kilogram	Mton	PJ
Vegetable products			
Domestic production:			
Rice	15.2	11.66	177
Rice stock	15.2	- 0.81	- 12
Red beans	16.9	0.97	16
Wheat	17.4	0.87	15
Greens etc.	0.4 - 24	24.12	40
Total domestic production:			236
Assumed amount of residues:			236
Import:			
Corn	16.4	14.23	233
Wheat	17.4	5.51	96
Soybeans	16.6	4.91	82
Fruits etc.	0.8 - 25	1.59	6
Total import:			417
Total vegetable products			889
Animal products			
Domestic production:			
Fish	2.5 - 6.5	12.17	55
Beef	14	0.56	8
Pork	15	1.56	23
Chicken	5	1.36	7
Egg	7	2.15	15
Milk	2.7	7.38	20
Total domestic production:			128
Import:			
Beef, pork, chicken, etc.	5 - 15	0.83	1
Total animal products			138

Electricity from hydro-power and thermal power

Electricity was used within forest industry and in food production, see above. Furthermore, electricity was used for lighting, electrical domestic appliances, where air-conditioning accounts for about one third of the total use, and other not specified use within households and commercial sector, 854 PJ. About 88 PJ was used in ceramic industry, of which cement industry accounts for 31 PJ, and for not specified use in industry. Within textile and mechanical industry most of the electricity, 265 PJ, was used for driving machines, i.e. mechanical work. The rest of the electricity went mainly into the mining and steel industry, 364 PJ, the chemical industry, 190 PJ, construction and other not specified industries, 116 PJ and transports. The use of electricity for trains amounts to 68 PJ.[11-13] Modern trains in Japan are usually equipped with regenerative braking, thus use less electricity.

In 1985, production of electricity from hydro-power was 326 PJ. If we assume 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 to be 15%, the gross exergy supply becomes 384 PJ, as hydro-power.

Nuclear fuel (U-235) and fossil fuels such as natural gas, oil and coal are also used to produce electricity. These conversion processes occur in condensing power plants and also in combined power and heating plants (cogeneration).

The production of electricity was 545 and 1398 PJ respectively from nuclear and fossil fuels. The total production of electricity was then 2269 PJ. Of this production 1979 PJ was used as specified above. The rest, 290 PJ, was lost along its way to the consumer due to electric resistance and imperfect adaptation between production and consumption or used by the energy sector.

Metals

The Japanese metal industry is totally dominated by steel. The domestic production of iron ore in 1985 was approximately 0.34 Mton whereas the import was 116.36 Mton. The exergy content is assumed to be 0.5 MJ/kg,[1] thus, the total iron ore amounted to 58 PJ.

The production of steel was about 105 Mton, representing an approximate quantity of 712 PJ. To produce this steel ore was needed (see above) together with, domestic steel scrap 262 PJ, imported steel scrap 20 PJ, 276 PJ of electricity, 1705 PJ of coal for coke production, and 91 PJ of other fuels.

The rest of the metal sector is mainly aluminum. The use of aluminum amounts to about 53 PJ, of which the import is 46 PJ. Other metals such as copper and zinc add another 7 PJ to the metal use.

Nuclear fuel

The exergy content of nuclear fuel (enriched uranium) is estimated on the basis of how much energy that is released as heat in a thermal reactor for a certain amount of produced electricity. At an efficiency of 32%, this becomes 1703 PJ. Japan has strongly increased its use of nuclear fuel as can be seen from Fig. 3.

Chemical fuels

Chemical fuels are here oil and oil products, such as kerosene and petrol, coal and coal products, such as coke, and natural gas.

The most commonly used chemical fuels in Japan are natural gas (LNG), crude oil, oil products and coal. The total import of these goods was in 1985 equal to 1535, 7597, 1499 and 2750 PJ whereas the domestic supply of these resources was 91, 24, 0 and 420 PJ. Also 179 PJ of oil products and 68 PJ of coke were exported.[11, 14, 15]

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. 1289 PJ of oil, 31 PJ of gas and 72 PJ of coal were converted into asphalt, grease, lubricants, rubber, plastics, fertilizers etc. The chemical industry is thus an example of how traditional energy goods like oil are used as materials. Often, the used material can then be used as an energy 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.

As we see from the diagram, the transportation system uses a great deal of the fuel inflow, 2515 PJ. Petrol and oil are converted into transport work in cars, buses, trucks etc. Only, about 10% of the exergy content of the fuel is used to run a vehicle.

About 680 PJ were used by the energy sector, e.g., oil refineries and 1740 PJ for direct conversion into heat in households, commercial sector, etc. 4082 PJ were used for the production of electricity and heat in combined power and heating plants and in condensing power plants and, beside what is already accounted for, 916 PJ for mainly heat production within the ceramic industry.

Exergy losses at the conversions into heat and cold

At the bottom of the diagram in Fig. 4, we have the largest aggregate of conversions which is that of fuels, electricity and solar heat into mainly heat at room temperature (space heating) in households. This conversion is shared between apartment houses, family houses, and other premises. As we see, heavy losses appear here.

The exergy content of a heat transfer Q at temperature T is

$$E = \left| \frac{T - T_0}{T} \right| Q \,, \tag{3}$$

where T_0 is the reference temperature. The ratio $(T - T_0)/T$ is also known as the Carnot efficiency. This is illustrated by the black line in Fig. 6 below.

In Fig. 6, we can also see how the exergy content depends on the temperature of a limited heat content,

$$E = \left| 1 - \frac{T_0}{T - T_0} \ln \frac{T}{T_0} \right| Q \,, \tag{4}$$

which is illustrated by the gray line. Exergy becomes almost equivalent to energy at very large values of temperature. In Fig. 6, also some common forms of heat are marked. The reference temperature is 15°C.

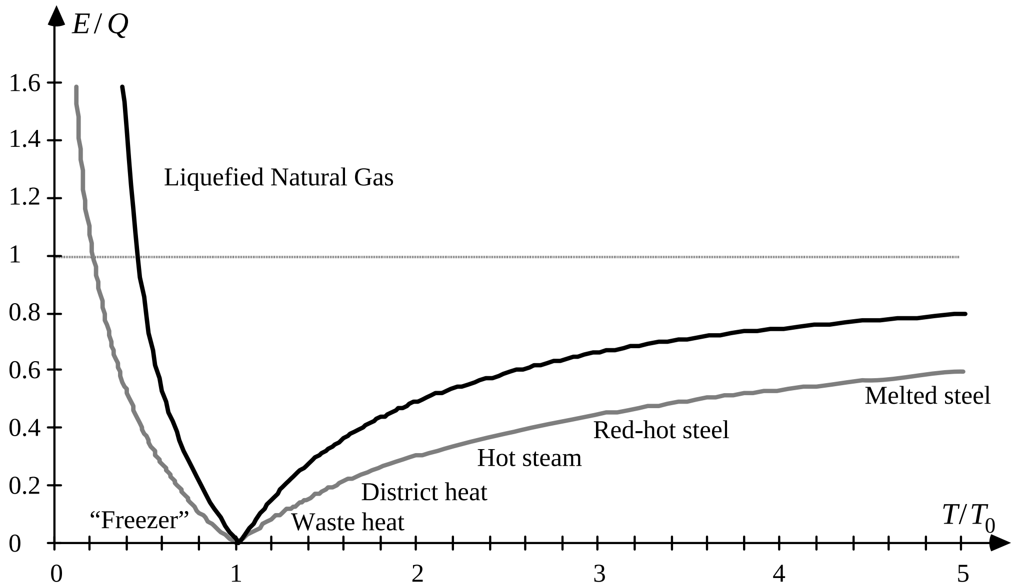

Figure 6. Exergy as a function of temperature.

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.

Figure 7. The exergy content of the indoor heat as a function of the outdoor temperature.

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 dependant on the ambient temperature. If, we consider the indoor temperature, 20°C or 293 K, as constant, then the exergy content of the indoor heat varies with the outdoor temperature according to Fig. 7.

However, the exergy content will be lower, since, due to poor insulation of the houses, the indoor temperature varies with the outdoor temperature. With a temperature difference between indoor and outdoor of 10°C the exergy content of the indoor heat becomes about 3% of the energy value. Three percent are therefore assumed to be a reasonably good exergy value of the indoor heat during the heating season in Japan. Other losses such as exhaust gases are neglected in comparison with these losses.

The flow of exergy for the Japanese space heating is thus obtained by multiplying the supplied heating quantity (energy) by 0.03.

CONCLUSIONS

Of the total inflow of energy and material resources into the Japanese society of about 18 EJ in 1985, only about 21% reached final use. Heavy losses could be considerably reduced by an active resource budgeting and economizing at all levels in the society. In particular, building technology needs to be improved. Better insulation would decrease the need of space heating and air-conditioning. This insulation would also improve indoor comfort.

In the long run, exergy needs of a society must be supplied almost entirely from renewable resources. As we can clearly see from Fig. 4, 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 using natural resources. This type of knowledge can be used to 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 a more equitable distribution of resources.

However, in order to generalize the use of this technique statistical data must be improved. Necessary steps should therefore be undertaken by national authorities to establish international agreements to facilitate the gathering and sharing of information.

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