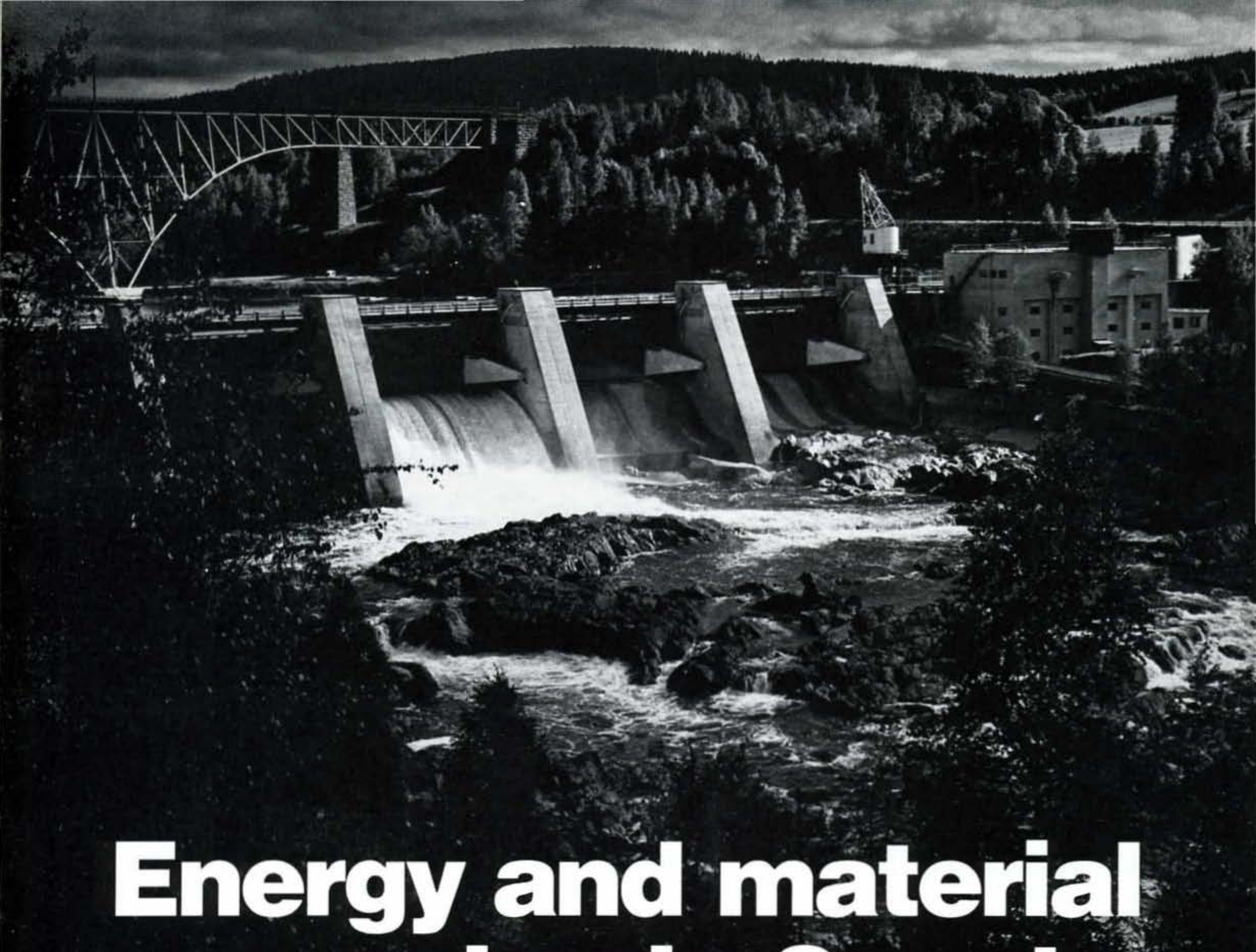

Energy and material conversion in Sweden

by Göran Wall

This article deals with the conversion of energy and material resources in Sweden as a means of illustrating the significance of the concept of exergy in preparing resource balances. A fuller description of this is contained in report No 80-1 entitled ''The Exergy Conversion in the Swedish Society'' published by the Physical Resource Technology Research Group, Chalmers University of Technology, Gothenburg.

The following definition has been formulated in order to derive a quantitative energy measurement which also takes account of its quality:

> **The exergy (or ''useful'' energy) of a system in a given environment is the maximum quantity of highest-grade energy (e g work) which can be recovered from the system in that environment.**

Exergy can also be used as a measure of material resources. To demonstrate this clearly, I have chosen to illustrate Swedish energy and material conversion for 1975 in terms of exergy as shown in Fig 1. In the chart, the energy and material resource flows go from left to right. The width of each flow is proportional to the exergy content stated in PJ/year. The inaccuracy of the flows varies from approx 5 per cent for electricity to approx 20 per cent in the case of heating – of both residential and public premises. To avoid drawing a multiplicity of thin lines in the chart, only exergy flows in excess of 5 PJ/year are shown, the only exceptions being solar heat, district heating supplied by back-pressure turbine plants, and electricity for residential heating and transport applications (Swedish Railways). The inflows, which comprise the national resources base, are classified by origin. Thus, sunlight is a renewable, natural exergy flow. Harvested forest, crops and hydropower are renewable, exergy flows from terrestrial funds. Ores, nuclear fuels and hydrocarbons are non-renewable flows from terrestrial deposits. (This rough classification of the various resources is illustrated in Fig 2.) In Fig 1. the empty boxes represent exergy conversions by the community, while the resources which we, as a society, demand, are shown as outflows at the right-hand side of the chart.

Uppermost on the chart is the inflow of sunlight (approx 20 PJ) which is converted to heat. (The total inflow of sunlight received by Sweden is approx 1 million PJ/year.) This heat (approx 1 PJ) covers approx 5 per cent of the national requirement during the heating season as shown in the lower right-hand corner of the diagram. In Stockholm, a south window admits approx 7 MJ/m^2 per day during the heating season. Thus, a south window can be made to act as a small heating element by suitable control of the window shutters.

Shown under the sunlight inflow is an inflow of harvested forests.

In 1975, the estimated net felling in Swedish forests was approx 430 PJ.

The greater proportion of this quantity (200 PJ) went to the sawn timber industry which, in 1975, produced 94 PJ of timber, 61 PJ of by-products for the pulp industry and 14 PJ of by-products such as fuel wood. The pulp mills were supplied with 200 PJ of timber, including the above-mentioned 61 PJ of waste from the wood products industry. Together, the pulp and paper mills consumed 280 PJ of the felled tonnage, 60 PJ of which reappeared as pulp and 86 PJ as paper in the end products. The only losses incurred when sawing trees into timber are in the form of waste and sawdust. In 1975, these losses amounted to 31 PJ. Paper pulp manufacture is extremely wasteful to exergy, due mainly to the amount of heat required for digesting wood chips. This heating requirement accounted for approx 130 PJ of the wood harvested. Together with the 105 PJ of fuel supplied, this combustion process contributed less than 60 PJ of heat and approx 10 PJ of electricity, which was used in the forest industry. The pulp and paper industries accounted for a further 53 PJ of electricity. The exergy content of the end product, which consisted of wood, pulp and paper, was 250 PJ.

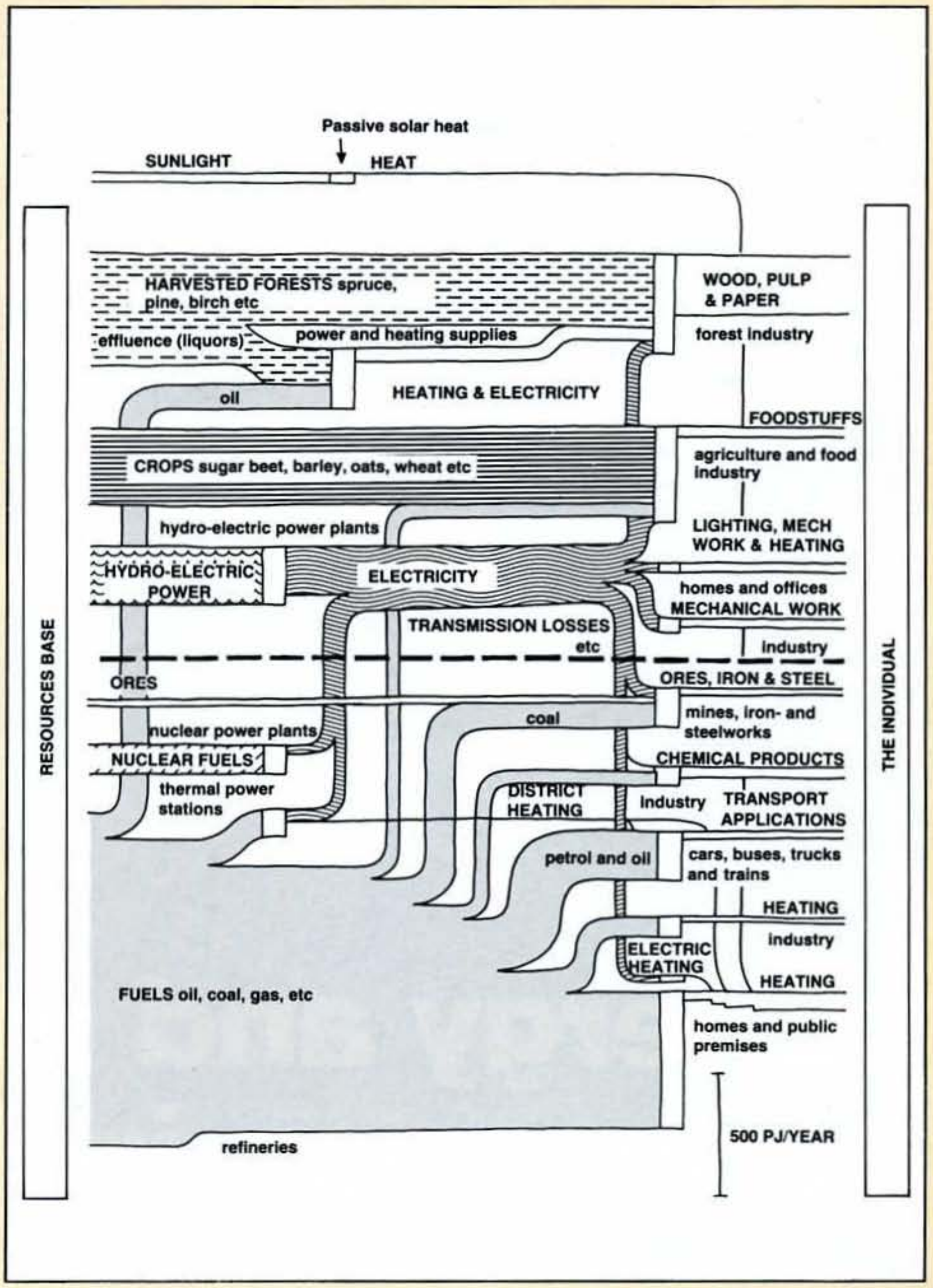

Figure 1. EXERGY CONVERSION IN SWEDEN FOR 1975. Total conversion of resources approx 2 600 PJ or 320 GJ per person. Net yield 520 PJ or 65 GJ per person.

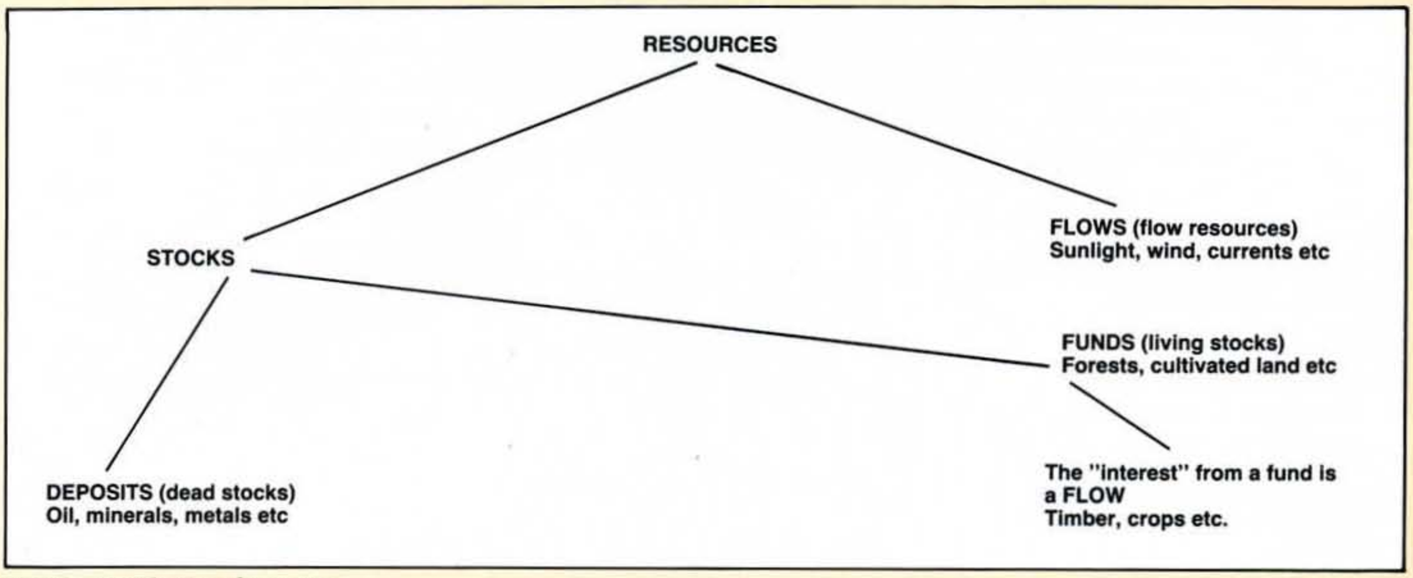

Figure 2. Classification of resources.

The next conversion process in the chart shows agriculture and the foodstuffs industry. With the aid of fuels and electricity, harvested crops are processed into food in the form of both vegetable products such as vegetables and bread, and animal products such as milk and meat. The chart shows clearly that the food yield is extremely small in comparison with the inflow of harvested crops. This is due to the fact that we eat relatively large quantities of animal products and small quantities of vegetable products. Even worse, approx a third of all foodstuffs produced is thrown away.

The total exergy content of the products of cultivation was 105 PJ. In addition, fodders and waste accounted for an estimated amount of the order of 200 PJ. Thus, the total annual crop exergy was approx 300 PJ. In addition to crops, agriculture and the foodstuffs industry accounted for the conversion of a further 31 PJ of fuels and 3 PJ of electricity for machine power and heating applications. In this sector, the end product is food and a daily intake of 2 850 kcal per person is equivalent to an annual conversion of 36 PJ for the country as a whole.

Hydro-electric power is the next conversion process shown on the chart and is used to produce electricity which, as we have seen earlier, is used in the forest industry and in food production. In 1975, the electricity was also used for lighting, domestic power supplies etc (64 PJ). The engineering industry used a great deal of electric power (54 PJ) to drive machines i e to perform mechanical work (approx 36 PJ). The remainder was used in the mining, iron and steel industries (36 PJ), the chemical industry (21 PJ), in transport applications (7 PJ) and for electric heating (22 PJ).

In 1975, the production of electricity from hydro-electric power sources amounted to 208 PJ. If we assume the losses incurred in converting the potential energy of the water in the reservoir into electricity from the power station to be 15 per cent, this corresponds to a total exergy requirement of 244 PJ.

Nuclear fuel (U-235) and fuels such as oil were also used for generating electricity, the conversion being carried out in condensing power stations and district heating power plants. Apart from generating electricity, the latter type of plant supplies district heating at the design back pressure. The chart illustrates how this flow of district heating (6 PJ) is distributed as a heating outflow to homes and public premises. The chart also shows that only one-third of the nuclear fuel is converted to electricity, the remainder being lost in the conversion process itself. The losses in nuclear, condensing and district heating power plants are of the order of 60 per cent.

In 1975, the production of electricity from nuclear and hydrocarbon fuels amounted to 43 and 40 PJ respectively. To this must be added the power station house loads including losses in power transformers and pumping losses in pumped storage plants. Thus, total production of electrical energy in 1975 amounted to 295 PJ, of which a net 4 PJ was imported. Of this production, 260 PJ was actually consumed, the remainder being represented by transmission and step-down losses in transmission and distribution to the consumer.

In Sweden, iron ore accounts for almost all of the ores converted. On average, Swedish iron ore has an iron content of approx 60 per cent by weight and normally consists of apatite ore represented by the chemical formula Fe_3O_4 (magnetite).

Iron ore production in Sweden in 1975 amounted to approx 31 Mtonne. Assuming that all of this consists of magnetite ore, the total quantity of exergy involved is 16 PJ.

In the same year, Swedish iron and steel production amounted to approx 6 Mtonne, representing an exergy content of roughly 41 PJ. The materials used to achieve this production consisted of approx 10 Mtonne of ore (equivalent to 5 PJ), 36 PJ of electricity and 110 PJ of coal, coke and other fuels.

The commonest fuels used in Sweden are crude oil, oil products, coal and coke. In 1975, imports of these products amounted to a total of 1 370 PJ.

Fuels are used as feedstocks in the chemical industry. In 1975, 65 PJ of oil and 21 PJ of electricity were converted into 43 PJ of rubber, plastics etc. Thus, the chemical industry is an example of how a traditional energy resource such as oil is used as a feedstock and how the product itself can be used as an energy source at the end of its life. Naturally, this also applies to many other "used" materials such as wood and paper.

As we can see from the chart, transportation accounts for a major proportion of the fuel inflow (200 PJ). Petrol and oil are converted to motive power in cars, buses and trucks. Approx 10 per cent of the exergy content of the fuel is used to propel a motor vehicle (approx 1 tonne of steel) forwards. The remainder is either lost or is expended in wearing out the exhaust system, engine and tyres of the vehicle.

As regards the remainder of the originally-listed areas of consumption, 36 PJ are supplied to the oil refineries, approx 586 PJ for direct conversion to heating in homes and other premises, 115 PJ for the production of electricity and heat in thermal and district heating power plants, and 86 PJ for the production of heat etc in industry.

The largest conversion — that of fuels, solar heat, district heating and electricity to heat — is illustrated at the bottom of the chart. As we can see, this conversion, which is divided between industry, homes and public premises, entails appreciable losses. In a conventional oil-fired boiler, less than 5 per cent of the fuel is used to produce heat. Half of the imported oil is used for heat production.

The exergy content of heat is determined by its temperature as defined by the formula:

$$E = \frac{T - T_O}{T} \cdot Q$$

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

If we now wish to use this heat for heating homes, we must also allow for the fact that the ambient temperature is subject to seasonal variations. Thus, Swedish residential heating requires a net exergy flow of 0.05 times the quantity of heat (energy) supplied. This means that the exergy contents of the various heating flows will be: solar heat 1 PJ, district heating 2 PJ, electric heating 1 PJ and heating produced by fuel firing 19 PJ. The latter figure also includes other direct energy losses such as flue gas losses (amounting to approx 35 per cent).

Let us now use the chart to examine the following chain of resources: nuclear fuel — electricity — heat. In the conversion of nuclear fuel to electricity, 30 per cent of the exergy content of the fuel is recovered. If we then follow the electricity flow to its conversion into electric heating using resistive elements, we see that only 5 per cent of its exergy content is produced as heat.

Thus, taking the conversion process as a whole, only 1.5 per cent of the exergy content of the nuclear fuel is converted to heat. (Furthermore, considering the fact that only 3 per cent of the total exergy content of the fuel is used in a modern nuclear power station, the actual net yield is only of the order of 0.05 per cent.) The conversion of fuel oil to electricity to heat gives a somewhat better yield of 2.0 per cent. As a comparison, a good stove (which is only capable of burning wood to produce heat) has an exergy efficiency of about 1 per cent. The obvious conclusion is that electric heating is an unsuitable use of electricity. Instead, a heat pump should be employed to improve the efficiency of converting electricity to heat to over 30 per cent or, best of all to make savings by introducing energy conservation measures. The chart obviously shows many other resource chains which could be subjected to similar analyses. Unfortunately, however, electric heating is becoming increasingly more common although it represents an enormous waste of resources.

Of the total national inflow of energy and material resources (approx 2 600 PJ) in Sweden in 1975, only 20 per cent or just over 500 PJ was used. The loss which this represents can be rescued appreciably by active conservation at all levels of society. Looking at the utilization of commercial energy resources alone, the efficiency is somewhat lower (approx 12 per cent).

To maintain the conversion of resources in a society over a long period, it is required that the resources base of that society be almost exclusively comprised of natural flows, and flows which can be tapped and converted from terrestrial funds. As the conversion of Swedish national resources in 1975 clearly shows, this is definitely not the case and we are, therefore, in a situation which will be untenable in the long term.

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.