EXERGY

– A USEFUL CONCEPT

Göran Wall

Physical Resource Theory Group

Göteborg 1986

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To my Mother, to my Wife, and to all my Friends

EXERGY – A USEFUL CONCEPT

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Abstract: This thesis demonstrates the usefulness of the exergy concept for analyzing systems which convert energy, material and/or information, e.g., a society or an industrial process. The first paper, *Exergy – a Useful Concept within Resource Accounting*, deals with the theory of exergy in a new and simple way. Exergy is applied to matter, is related to other thermodynamic potentials and to information theory.

Paper II, *Exergy Conversion in the Swedish Society*, presents, in terms of exergy, the conversions of energy and material resources in the Swedish society in 1980. 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. Compared to the situation in 1975, described in Paper I, the change is mainly the increased use of nuclear power and the decreased use of fuel oil.

Paper III, *Exergy Flows in Industrial Processes*, describes the exergy flows in a pulp and paper mill and in a steel plant. Steam data are calculated on a micro-computer with the accuracy of ordinary steam tables. Also, a simple method for calculating the exergy of different substances is presented. For the purpose of comparison, the Swedish house heating system is described using the exergy concept. The energy and exergy prices of several common energy forms are also compared.

Thermoeconomics is an effective method of making technical systems efficient by finding the most economical solution within the limits of the technically possible. At the same time it may indicate how research and technical development should be directed. In Paper IV, *Thermoeconomic Optimization of a Heat Pump System*, a simple heat pump process is chosen as an example to illustrate the method. The physical treatment of the refrigerant and the optimization of the system is done with a specially developed computer program. The result shows, among other things, that the driving source should be made more efficient, thus saving both money and exergy.

Keywords: Exergy, resource conversion processes, applied thermodynamics, thermoeconomics, energy analysis, efficiency, processing industry, energy management, cost engineering.

This thesis is based on the work in the following papers:

I Wall, G., 1977, *Exergy - a Useful Concept within Resource Accounting,* report no. 77-42, Institute of Theoretical Physics, Göteborg.

II Wall, G., 1981 revised 1986, *Exergy Conversion in the Swedish Society*, report no. 80-1, Physical Resource Theory Group, Göteborg. (To appear in *Resources and Energy* in 1987.)[1]

III Wall, G., 1983 revised 1986, *Exergy Flows in Industrial Processes*, report no. 83-11, Physical Resource Theory Group, Göteborg.[2]

IVa Wall, G., 1985, *Thermoeconomic Optimization of a Heat Pump System*, report no. 85-5, Physical Resource Theory Group, Göteborg. (Published in *Energy*, vol.11, no. 10, pp. 957-967, 1986.)[3]

IVb Wall, G., 1985, *Thermoeconomic Optimization of a Heat Pump System– Computer Programs*, report no. 85-5, Physical Resource Theory Group, Göteborg.

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[1] *RESOURCES and ENERGY*, Vol. 9, pp. 55-73 (1987)

[2] presented at “the Fourth International Symposium on Second Law Analysis of Thermal Systems”, Rome, 25-29 May, 1987, I00236, pp. 131-140, ASME and published in *ENERGY*, Vol. 13, No. 2, pp. 197-208 (1988)

[3] presented at “the Fourth International Symposium on Second Law Analysis of Thermal Systems”, Rome, 25-29 May, 1987, I00236, pp. 89-95, ASME and at “the 1988 IIR Meeting”, 18-21 July, 1988, Purdue University, West Lafayette, U.S.A., David R. Tree and Douglas C. Hittle Eds., *Progress in the Design and Construction of Refrigeration Systems*, pp. 91-97, Purdue Univ and published in *International Journal of Refrigeration*, Vol. 14, pp. 336-340 (1991)

Preface

This thesis treats the exergy concept and its applications to technical and societal systems. The purpose is to develop descriptive methods which are based on fundamental theory and to show their usefulness in different applications. The exergy concept often implies a new picture of energy and material conversion systems. The concept is not new but for a long time it was nearly forgotten. As is shown by the large number of publications during the last years it has now been rediscovered. One reason for this is the increasing interest in efficient energy techniques deriving from the problems related to energy use in the society. Exergy is a concept originating from an engineering problem. It is by now a firmly established concept in physics with well-defined relations to the information concept of information theory. That it takes time for a less familiar concept to be understood and accepted is shown by the fact that still to-day there is opposition against using exergy instead of energy in physical descriptions of resource conversions.

Hopefully, this thesis demonstrates the importance of the exergy concept for analyzing systems which convert energy, materials and/or information, e.g., a society or an industrial process. The large losses which are revealed in an exergy treatment of a process should be seen not as an insurmountable obstacle but as a challenge to achieve technical improvements. I hope that the exergy concept will reach further understanding and acceptance within science and education, research and development in the society.

I will here express my gratitude to all of those who have made this work possible. I will name some of them in particular. Karl-Erik Eriksson has always been of great help in many respects. Björn Eriksson and Kåre Olsson inspired the early tentative steps in this work. Sten Karlsson has, throughout the years, closely watched and criticized my work. Myron Tribus and Yehia El-Sayed guided me into my present field of research during my stay at Massachusetts Institute of Technology. The financial support of the Energy Research and Development Commission, the National Swedish Board for Technical Development, the Swedish Natural Science Research Council, and the Swedish Council for Planning and Coordination of Research is gratefully acknowledged. Finally, I am deeply grateful to my wife Kerstin for her help and patience.

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Bibliography on Exergy

Papers

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II **Wall, G., 1981 revised 1986, *Exergy Conversion in the Swedish Society.***

III **Wall, G., 1983 revised 1986, *Exergy Flows in Industrial Processes.***

IVa **Wall, G., 1985, *Thermoeconomic Optimization of a Heat Pump System.***
IVb **Wall, G., 1985, *Thermoeconomic Optimization of a Heat Pump System– Computer Programs.***

1. INTRODUCTION

On the 18th of November, 1975, an article by Hannes Alfvén was published in the Swedish daily newspaper Svenska Dagbladet. The headline of the article was “Exergy report may create a new energy policy”. The report that he was referring to was a preliminary draft of a paper (B. Eriksson, K.-E. Eriksson, K. Olsson, and G. Wall 1976), and a summary of this paper was published in the same newspaper on the 6th of December, 1975 (B. Eriksson, K.-E. Eriksson, K. Olsson, and G. Wall 1975). In his article, Alfvén compared the energy accounting, irrespect of different energy values, with a cashier counting his cash only by the number of coins or notes, and neglecting their value. This comparison has a striking similarity with what is happening in the energy description of a space heating system. Here one describes the exchange of an “one hundred kronor note” (SEK 100), i.e., electricity, into a “five kronor coin” (SEK 5), i.e., heat at indoor temperature, as if their value did not matter. Unfortunately, the pedagogical content of these newspaper articles is still as much relevant as it was eleven years ago.

Few areas of science and technology have been so closely related to public debate as energy research. Since the 1973 oil price rise the debate on new energy sources, energy conservation, and energy-environment relations has continued. Recent events, such as the nuclear power plant accident in Chernobyl and the increased effects of acid rain on forests, have put new fuels into the debate. No simple solutions exist, mainly because the situation is strongly related to the goals of the modern society. Large use of energy and material resources based on mineral exploitation, with today’s technology, cannot continue together with a healthy environment. This situation can only be changed by changing the aims and the direction of today’s society. Fundamental scientific concepts and methods to describe reality must play an important part in this process of change. Some ideas are presented in this thesis.

Chapter 2 gives a short description of physical resource theory, a new scientific field which has connections to several other research fields, such as physics and economics. This description also gives a background to the research area covered in this thesis.

Chapter 3 describes the milestones in the development of the exergy concept, which is further treated in the first paper of the thesis, *Exergy – a useful concept within resource accounting,* described in Chapter 4. Paper I also includes a first attempt to apply exergy to the energy and material resource conversion system of a society (Sweden 1975). This application has been developed further (Wall 1978 a, 1978 b, and 1983 b) in Paper II, *Exergy conversion in the Swedish society*, which is also described in Chapter 4. In order to give a historical perspective of today’s resource use in Sweden I have also included a description of the situation in Sweden in 1920 (Wall 1982).

Chapter 5 (Papers III and IV) presents two rather straightforward applications of the exergy concept to technical systems. Paper III, *Exergy flows in industrial processes,* is one example of how industrial processes could be described in terms of exergy and what the benefit would be of such a study. The paper includes all necessary tools, even lists of computer programs. Paper IV, *Thermoeconomic optimization of a heat pump process,* goes a bit further in its analysis by including economic objectives. This is an important improvement, since it immediately answers the question: Is a particular technical improvement also economical? The method is basically simple, but, applications to real systems imply large and sometimes even impassable obstacles. Numerical treatment may partly solve this problem, as is shown in the paper.

Also, a bibliography is added as a step towards the development of a data base in this field.

2. PHYSICAL RESOURCE THEORY[†]

2.1. Definition

In nature there are physical systems which process **energy** and various **materials** and which thereby build up and maintain **ordered structures**. Examples of such systems are *living organisms* and *ecosystems with living organisms in interplay with one another and with the non-living environment*. Also in *human settlements and societies* a similar conversion of energy and materials is taking place.

Structural organization in matter is most appropriately described in **information-theoretical** terms. Furthermore, the systems often have control systems which process information. This information is physically tied to relatively small amounts of energy and matter. An important example is the genetic information in living organisms.

Energy, materials, and information will in this context be denoted by the common term **physical resources**.

Physical resource theory is the science dealing with physical resources and their conversion in various systems. The systems can be *societal* (e.g., technical, such as energy conversion systems or an industrial process), *geophysical* (e.g., the atmosphere or a mineral deposit), or *ecological* (e.g., an ecosystem or an organism). Special attention should be given to *the conversion of physical resources in societal systems*. This has to be studied with reference to human needs, availability of resources and the possibilities of incorporating these conversions in the natural system. Another important task for physical resource theory is to develop *methods to optimize resource conversion processes*. The systems are described and analyzed by means of the methods of mathematics and the natural sciences.

2.2. Why physical resource theory ?

2.2.1 Questions that arise within science

Thus, physical resource theory deals with questions that arise *within science itself* and with problems *in connection to* the resource handling of the *society*.

Never before in the history of science have **macrocosmos** and **microcosmos** been so *intimately tied together*. There is as yet no complete theory of elementary particles, and structures of dimensions from 10^{-19}m down to 10^{-35}m still remain to be

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[†] This chapter is a revised version of an early description of this field (Eriksson, Islam, Karlsson, Månsson, Peressutti, and Wall 1981)

explored. (The smallest dimensions may be inaccessible to observation due to difficulties in achieving the enormous energies needed to penetrate into this region.) Even if new and surprising phenomena are observed they will not separate the physics of microcosmos from that of macrocosmos but rather tie them more strongly together in an effort to understand the beginning of the universe.

A frontier of physics which is becoming increasingly important, besides the microcosmos and the macrocosmos, is *the physics of the complex*. This could involve branches of physics that have become sciences of their own, e.g., atomic and molecular physics, solid state physics, nuclear physics, astrophysics. However the frontier which may change scientific thinking most is rather the physics of **self-organizing systems**.

Prigogine (1980) also uses the term "**dissipative structures**" to denote self-organizing systems, thereby indicating that such systems dissipate energy to build up new structure. Haken (1980 ed., 1983, and 1984) has shown how many degrees of freedom are tied to ("slaved by") a few degrees of freedom, described by a few *"order parameters"*. Structure may also be described in information theoretical terms: *dissipative structures create new information while dissipating energy*. Dissipation of energy can also be described as *consumption of* **exergy**, i.e., of energy weighed according to quality. Thus dissipative structures use exergy as an "input" to produce structure/information. Some of the exergy is tied to the structure, some is consumed in the process.

Since information increases, dissipative structures are *inherently indeterministic*, the information content of a system at one time is in general insufficient to predict the state of the system at later times. Small unpredictible fluctuations may have a decisive influence on the whole system. The system builds *"order through fluctuations"* (Prigogine 1980).

Exergy can thus be destroyed ("consumed") but not created – except at a cosmic scale due to changing local equilibrium conditions in a changing universe (Eriksson, Islam, and Skagerstam 1982). This is a consequence of the second law of thermodynamics. All this means that *exergy is the resource*, consumed by dissipative structures that use exergy to produce **structure/information**, as well as by decaying structures or non-structured systems which go towards equilibrium or towards a stationary state. "Structure" is here a spatial or temporal order describable in information-theoretical terms (Eriksson and Lindgren 1986).

There is a good reason why exergy should be used as a resource measure rather than negentropy, as has often been suggested. The reason is that mechanical work W is pure exergy E, $E = W$, whereas the negentropy Σ contained in work depends on the ambient temperature T_o, $\Sigma = W/T_o$. It is also convenient to use *a concept that is directly related to mechanical work.*

2.2.1.1. The origin of resources and their conversion in various systems

According to the current theory of the origin of the universe, at 0.01 second after the start (the Big Bang) thermal equilibrium prevailed everywhere. The exergy was zero, since in the absence of any gradients no work could have been extracted. Now the situation is different. In an overall cold and thin gas very hot and dense bodies like our sun move around. There is now exergy. The water cycle of the earth uses the sun as a boiler and the space as a cooler to extract work. There are many levels on which resources are converted and exergy is consumed: galaxies, quasars, stars (including super novas).

When did this exergy arise, and how? The answer is that the cosmic exergy is mainly nuclear and that its creation started during the first three minutes described by Weinberg (1977) and Eriksson, Islam, and Skagerstam (1982).

Our planet is itself a resource converting system. Several subsystems can be identified and they are worth special studies: the interior of the earth and the crust of the earth, its surface and the atmosphere. The last two systems are of particular interest since they contain the life-supporting system, the biosphere, which includes the water cycle and other similar cycles and in which the human society is embedded. Next come ecosystems and their populations of various species. Finally we come down to the metabolic cycles of the living cell.

At all levels there is creation of information. For instance, the solar radiation impinging on the earth is a photon gas very near equilibrium and containing very little information in the sense that it is very simple to describe (Chaitin 1979). (We disregard here the information on the sun’s surface which is irrelevant for this context.) But the solar radiation is much hotter than the earth’s surface, it has relative to the earth a lot of exergy. And out of this exergy (information capacity) comes new information in a continuous coding process – a truly creative process. Most of the systems that use the terrestrial exergy have long been studied within the natural sciences. Such studies include the turn-over and transfer of energy and matter (materials) and accumulation of information in the systems under study. However, a consistent accounting, exergetics, seems to be lacking in most of the relevant study areas.

Human societies are – among many things – also physical systems, converting resources. To view them as such is therefore a valid point of view, see Section 2.2.2.

2.2.1.2. Various forms of resources

So far, we have been discussing resource-converting systems. In order to understand those it is necessary to have a clear picture of the relations between physical quantities within a given system. This is necessary before systems studies can be made successfully. We shall now focus on the exergy concept’s relation to various forms of resources and to other physical quantities.

Even the simplest forms of energy, mechanical energy and heat, have not been studied in detail until recently with regard to this relationship. However other energy forms are in greater need of study with respect to their convertibility into work. Such studies are included in what we call **exergetics** (Eriksson 1982 a). The following areas are then of importance:

- Exergetics of systems with various equations of state, in particular radiation (Karlsson 1982 a)
- Exergetics of solids and fluids (Månsson 1981)
- Chemical exergetics (Månsson 1985 a)
- Nuclear exergetics
- Applications to living systems, the atmosphere (Karlsson 1982 b), the earth’s crust

Such work also serves the purpose of giving a more firm physical foundation to the description of societal resource conversions, see Section 2.2.2, where uncertainties and ambiguities clearly have political implications.

2.2.1.3. General thermodynamic and information-theoretical problems

The concepts and relations of **statistical mechanics** and **information theory** are so general that they may be applied to a large class of systems irrespective of the details of those systems. This opens the possibility of combining statistical mechanics/ information theory with another general theoretical framework, **system theory,** into a general description of resource-converting systems, e.g., ecological systems (Eriksson and Kåberger 1984). The above-mentioned work on self-organizing systems, called **synergetics** by Haken, is of great importance here. Relevant concepts and models have also been developed within ecology and economics. It would be very valuable if one could develop a simple *diagrammatic description* of resource-converting systems.

The following questions naturally arise within this context (**system exergetics**):

- How should one characterize basic system components and their functions?
- How should one characterize forms of exergy consumption?
- What is the minimum exergy consumption for a steady or cyclic process which runs at a certain speed?
- What is the minimum exergy cost of information transfer, given the speed and the required accuracy? (Bennet and Landauer 1985)
- What is the exergy cost and the information gain when macroscopic order is created in a dissipative structure? (Eriksson and Lindgren 1986)

2.2.1.4. A comment

The above discussion may give the impression that physical resource theory covers almost everything. In a way this is also true – as it is true that physics covers almost everything. But then one must bear in mind that this can only be so because *the aspect is very limited*. Physics can deal with such a wide realm of phenomena only by choosing one or a few very limited general aspects. The same is true for physical resource theory. The arguments given here support the view that those limited aspects are *relevant to the natural sciences*. We shall now argue that they are also relevant for the description and understanding of processes in society.

2.2.2. Questions that arise within society

As stated already, a society may – among many other things – be viewed as a physical system. As such it is embedded in and draws its resources from one or several natural systems.

During the 1970's it became increasingly clear that what is commonly called "energy" is a crucial resource for a society. Whereas matter is conserved (disregarding radioactive decays and nuclear reactions, the chemical elements are conserved) and, in principle, possible to use over and over again, energy, although it is also conserved, can be used only up to a point where it has lost its quality. Also degradation or spreading out of matter (materials) can easily be described in exergy terms.

The *intimate connection between "energy" and materials* is obvious in a variety of cases:

- The competitive use of the same resource, as a material or as a fuel.
- The large energy use in industrial countries for the processing industry and for transportation of materials.
- Energy savings from better – and better use of – insulation materials.
- The maximum temperature, and thus the Carnot efficiency, in the conversion from heat to work, as in a steam turbine, is largely a problem of material properties.
- Agricultural land may carry energy crops or fiber crops as well as food crops.

If resources are so closely tied together it seems reasonable to try to study them within a *unified theoretical framework.*

In the discussion above, we have tried to outline such a framework and describe its place among other natural sciences. We have also discussed questions that arise, and possible applications of the answers to those questions or the methods developed.

What can be of interest in a societal context are those applications that refer to natural systems and processes which are of great importance to the society or those which concern various components of the society's resource system. Methods developed and tested within a natural science context may also be useful when applied to the society.

Exergy has to be spent in any process which takes place at a non-zero rate. The exergy exspenditure can – to a large extent – be steered by will. Exergy is thus *a physical measure of the action potential* of the one (or those) who command it. Clearly it is by no means a complete measure. Availability of efficient technical equipment as well as relevant know-how and rational organization are of great importance, and the action potential may, accordingly, involve the option to invest in equipment, know-how, or organization.

This comment, although very sketchy and incomplete, indicates that exergy is a concept of high relevance to economics. Since exergy is a measure of contrast within a system or between a system and a given environment it comes very close to *a measure of value.* (With this measure, environmental disturbances like pollution have an immediate exergy cost, since the contrast is reduced when there is partial mixing (between different systems).)

2.2.2.1. Resources within an economy

It is an important task for physical resource theory to develop useful *physical methods for describing stocks and flows of resources within an economy*, including the flows in and out of it and the transformations within it.

Although basically physical, such descriptions should be designed to be as consistent as possible with economic terminology. In the literature, various degrees of crudeness or fineness have been applied in the characterization of resources. One approach to this is the method known as **energy analysis** (Johansson and Lönnroth 1975, Thomas 1977, Gilliland 1978, and Chapman and Roberts 1983). In our case it would rather be an **exergy analysis** (B. Eriksson, K.-E. Eriksson, Olsson, and Wall 1976 and Wall 1977), which would use the results of the **system exergetics** (Grubbström 1980 and Eriksson 1982 b). A general description method could probably be developed, which can be used to achieve an arbitrary fineness in the resource characterization.

Since the society draws its resources from and returns residuals to some natural system, some descriptions of the natural system or parts of it should be included.

2.2.2.2. Resource use over time

During the 1970's, economists, inspired by the big world models, discussed intensively how to *describe and optimize resource use over time*, and many models were designed for the handling of this problem (Meadows and Meadows 1972 and 1977). As pointed out by, e.g., Ayres (1978), the physical constraints on the efficiency have not always been properly taken into account in this modelling.

This sort of work is nevertheless important as a basis for the discussion on resource planning. One problem, besides *physical constraints*, that needs further elaboration is the *interplay between non-renewable and renewable resources*. There are also many questions that could be given new answers in this context and which should therefore be open to discussion:

- Should the future really be discounted?
- How should utility be defined?
- Should some absolute limits be set (ecological limits, basic needs fulfilled)?
- Could the models be further disaggregated but still remain possible to handle?

2.2.2.3. Efficiency in resource use

The usefulness – or the utility – of certain goods is not directly a function of the goods themselves but rather of the services that they can provide. For a *given set of services or functions*, one can then analyze its *costs in terms of exergy and materials or labour*. Various ways to provide the same set of services may then be compared, and their *technical and organizational efficiency may thus be evaluated*. For instance, the same indoor climate may be achieved in several ways at widely different resource costs.

Due to structural, administrative, or legislative restrictions, or even lack of imagination, the optimal way may often not be able to compete on a market. One aim in a study of organizational efficiency is to provide information which cannot be transferred by the market. We may also look for and take into account *constraints from ecological or ethical limits.* An important problem is to minimize resource costs for a given set of services under such constraints.

2.3. Relations to other fields

Physical resource theory, originating from physics, has to process knowledge from many fields of science. The main sources of theory are **statistical mechanics**, **system theory**, including **synergetics** (the theory of self-organizing systems, Haken 1980 ed., 1983, and 1984), and **economics** (see Fig. 2.1). In order to investigate different systems one also has to collect information from other branches of physics and other natural sciences.

With **human ecology** (Eriksson, Islam, and Tengström 1981 and Tengström 1985) the relations are a bit different. Human ecology is the study of the interactions between man and his/her total environment. The relations between a society and its natural environment is of fundamental importance. So are the relations between societies. A study of this kind must be interdisciplinary in a broad sense. A close cooperation and integration is necessary between natural sciences on one side, and social sciences and humanities on the other. The two sciences have similar aims, and the conceptual problems are partly the same in both sciences. Human ecology is the one with the broader scope, and physical resource theory is the one which is more method-oriented. Physical resource theory could serve as an auxiliary science to human ecology, and human ecology could help setting values to be applied in physical resource theory. The integration of knowledge and the development of concepts should be done in close collaboration between the two.

Although there is no arrow in the chart back into the economic box, one may hope that developments in physical resource theory will lead to results which benefit **economics**. Work by Grubbström (1980) and Månsson (1985 b) indicate this.

Systems analysis has a very wide definition (Patten 1971, Pantell 1976, Bell et al. 1977, and Bennet and Chorley 1978) and is more related to engineering and social sciences. However, several of the methods and applications used in physical resource theory also play a role in systems analysis (Wall 1981, 1983 a, and 1985).

Thermoeconomics, which is described in Chapter 5, is strongly related to exergy analysis and applied exergy analysis (El-Sayed and Tribus 1983, Wall 1985 and 1986).

The boxes in Fig. 2.1 are marked with numbers indicating where the papers in this thesis belong.

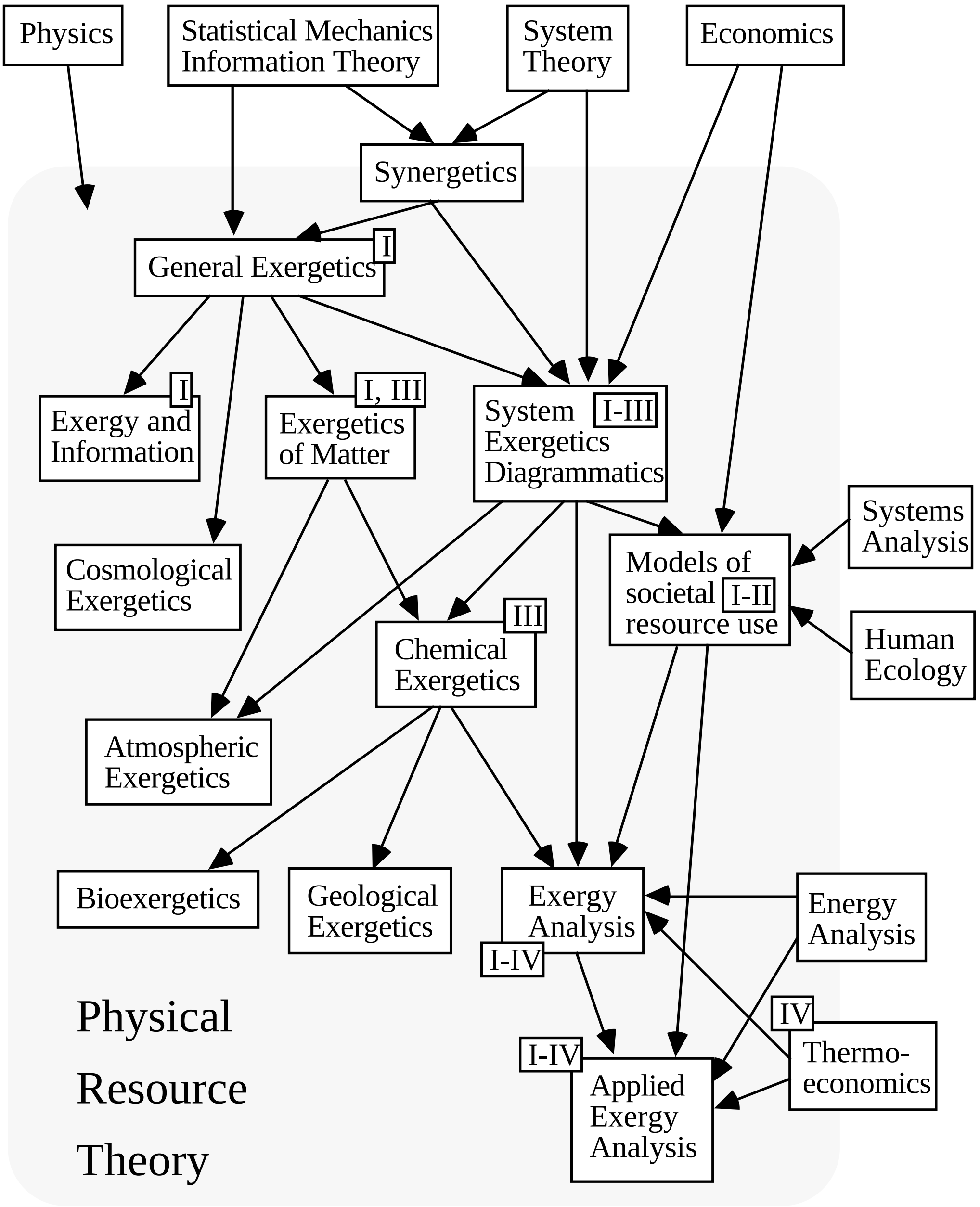

Fig. 2.1. Schematic chart of physical resource theory and related fields.

3. DEFINITION OF THE CONCEPT OF EXERGY

In 1824, the French engineer Sadi Carnot published a relation between heat and work which later resulted in the formulation of the second law of thermodynamics. J. Willard Gibbs was the first to express the general relation for work as early as 1873.

“We will first observe that an expression of the form

$$-\varepsilon + T\eta - Pv + M_1 m_1 + M_2 m_2 \ldots + M_n m_n$$

denotes the work obtainable by the formation (by a reversible process) of a body of which ε, η, v, m_1, m_2, … m_n are the energy, entropy, volume, and the quantities of the components, within a medium having the pressure P, the temperature T, and the potentials M_1, M_2, … M_n. (The medium is supposed so large that its properties are not sensibly altered in any part by the formation of the body.)”

Not until 1953 did Z. Rant suggest the name exergy.

“Aus diesen Forderungen geht hervor, daß „ie“ die zweckmäßigste Nachsilbe sein wird. Da es sich bei dem untersuchten Begriff um eine Arbeit handelt, muß als Stammsilbe (als genus proximum) das griechische Wort erg (on) hierfür erscheinen. Nun ist noch die richtige Vorsilbe zu wählen, die die spezifische Eigenart, die differentia specifica, hervorhebt. Hierfür gilt die Forderung, daß der neue Begriff die Arbeit bezeichnen soll, die aus einem System herausgeholt werden kann. „Aus“ heißt auf Griechisch „ek“ vor Konsonanten bzw. „ex“ vor Vokalen.

Damit lautet der neue Begriff Exergie: er erfüllt praktisch alle aufgestellten Forderungen, und der Buchstabe x unterscheidet ihn klar vom verwandten Begriff der Energie, so daß trotz der Analogie in der Wortbildung jede Verwechslung ausgeschlossen bleibt. Der Ausdruck kann in jede germanische, romanische oder slawische Sprache eingeführt werden, er lautet z. B. auf deutsch Exergie, auf englisch exergy, auf französisch exergie, auf spanisch exergia, auf italienisch essergia und auf slawisch eksergija.”

A general definition was given by H. D. Baehr, 1965:

“Die Exergie ist der unbeseschränkt, d. h. in jede andere Energieform umwandelbare Teil der Energie.”

These three works constitute an adequate definition of the exergy concept, thus establishing a foundation. However, some later publications deserve to be mentioned, such as a special issue of *Energy* (Penner 1980) and some textbooks: Gaggioli (1980), Ahern (1980), Edgerton (1982), Gaggioli (1983), and Moran (1982). Richard Gaggioli makes the following statement (1980):

“The concept of exergy is crucial not only to efficiency studies but also to cost accounting and economic analyses. Costs should reflect value, since the value is not in energy but in exergy, assignment of cost to energy leads to misappropriations, which are common and often gross. Using exergy content as a basis for cost accounting is important to management for pricing products and for their evaluation of profits. It is also useful to engineering for operating and design decisions, including design optimization.

Thus, exergy is the only rational basis for evaluating: fuels and resources, process, device, and system efficiencies, dissipations and their costs, and the value and cost of systems outputs.”

In science and technology one has used, for a long time, thermodynamic potentials similar to exergy but more limited in scope. Gibb’s free energy, Helmholz’ free energy, and enthalpy are all special cases of exergy (Evans 1969, Wall 1977, Andersson, Fredriksson, Ljung, Söderström, and Wall 1981).

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* (First law, the law of energy conservation) and (2) *Exergy is always conserved in a reversible process, but is always consumed in an irreversible process* (Second law, the law of exergy).

The historical development of the concept of exergy should be documented. I see this as an important task especially after preparing the bibliography which indicates that a lot of scientific work is never accepted in society or applied to real processes. Thus, I strongly recommend this as a topic for a study in the history of science.

4. PRESENTATION OF PAPERS I AND II

It is important to investigate the basic physical premises for human societies on earth. Questions concerning the resource situation and the state of the environment play an increasing role in the society. It is therefore important to have an adequate description of the resource conversion processes in a society and a general method to make such descriptions.

In Paper I, *Exergy – a Useful Concept within Resource Accounting*, the exergy concept is discussed in this respect. It deals with the theory of exergy applied to matter, its relation to other thermodynamic potentials and to information theory, the calculation of exergy of an ideal monatomic gas and the comparison of information transfer efficiency between technical and biological systems. In Paper II, *Exergy Conversion in the Swedish Society,* this is described more in detail. Paper I describes the situation in 1975 and Paper II describes the situation in 1980. The difference is mainly the increased use of nuclear power and the decreased use of fuel oil for space heating. This method of description is an improvement over conventional energy flow diagrams in two ways. First, since material flows are included, it gives a more complete picture of the resource conversion in a society. Secondly, since energy quality is taken into account, the method immediately reveals in which conversions it is physically possible to improve the efficiency.

Since Paper I is an early paper, a few minor modifications are motivated such as a unit shift to J instead of Wh, and the following comments:

(1) Table 2.1. on p. 12: Note that for some substances the exergy content may even exceed the chemical energy content, due to definitions of system boundaries and final states.

(2) Table 2.2. on p. 13: Note that matter in an ordered form also may include biological organisms, e.g. a living plant.

(3) Figure 3.7 on p. 27: By using the reference states of Paper II for iron, Fe and O are represented as Fe_2O_3 (hematite) in solid form at a mole fraction of $2.7 \cdot 10^{-4}$ and O_2 in gaseous form at a partial pressure of 20.40 kPa in the standard environment, we get a different description of the Swedish iron production in 1975. The Swedish production of iron ore in 1975 was approximately 36 Mtons. If we assume all this ore to be magnetite iron ore, as most of the Swedish iron ore is, then the ore represents a total exergy quantity of 18 PJ. The production of iron was roughly 6 Mtons, representing an approximate quantity of 41 PJ. To produce this iron, about 10 Mtons of ore was needed, corresponding to 5.1 PJ together with 36 PJ of electrical exergy and 110 PJ of coal, coke and other fuels. The exergy efficiency in the iron production process then becomes $\eta_{ex} \approx 27\%$. Figure 4.1. illustrates the situation.

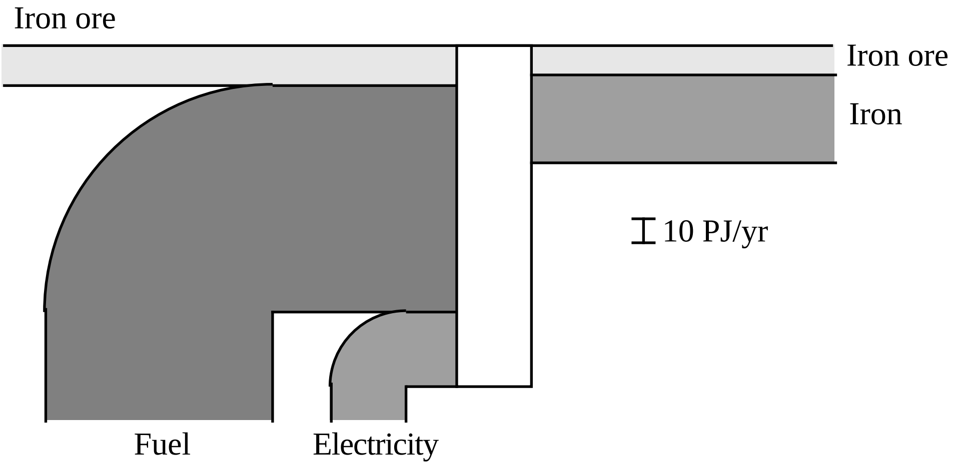

Fig. 4.1. The Swedish iron ore conversion in exergy units in 1975

(4) A diagram of exergy flows can be constructed for the total conversion of energy and material resources which takes place in the Swedish society during one year. This will look like the diagram in Fig. 4.2. This description differs somewhat from that of Paper I (Fig. 3.9, p. 31), but corresponds better with later studies. The inflows of energy and materials origin from the resource base, which is represented as a box in the left part of Fig. 4.2. The outflowing "products" are difficult to define in a uniform way. The individual, however, plays an important role as the final user, by directly or indirectly demanding the "products". This is indicated as a box in the right part in Fig. 4.2.

The total conversion of resources is about 2500 PJ/yr or 300 GJ/yr per person and the net yield is about 450 PJ/yr or 55 GJ/yr per person. At the top of the chart is the inflow of sunlight (about 20 PJ/yr) which is converted to indoor heat, about 1 PJ/yr. The next conversion in the diagram concerns the forest industry. The stock of forest, a fund, is harvested each year and the timber is used either as timber raw material or converted into paper pulp and paper. At the conversion of timber into pulp, large amounts of heat is used to boil wood chips in the processing of paper pulp. This heat is produced by burning effluence (liquors) and fuel oil.

In 1975, the estimated net felling in Swedish forests corresponded to about 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 firewood. The pulp mills were supplied with 200 PJ of timber, including the above-mentioned 61 PJ of which reappeared as pulp and 86 PJ as paper in the end products. The main 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 as far as exergy is concerned, due mainly to the amount of heat required for digesting wood chips. This heating requirement accounted for about 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 about 10 PJ of electricity, which was used in the forest industry. The pulp and paper industries accounted for a further 53 PJ of electricity.

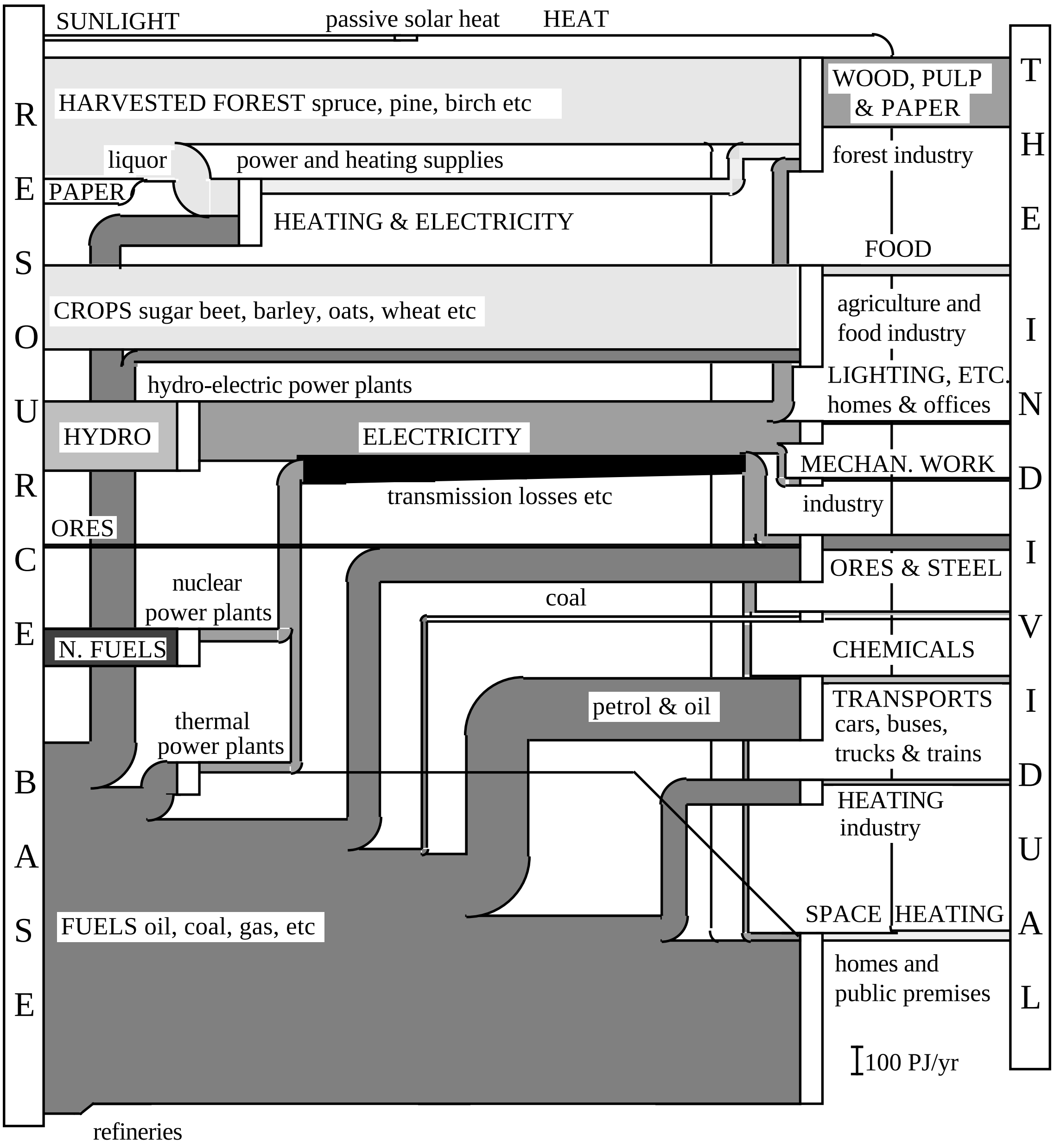

Fig. 4.2. Conversion of energy and matter in the Swedish society in 1975 in exergy units. (The total conversion was about 2 500 PJ/yr.)

The exergy content of the end product, which consisted of wood, pulp and paper, was 250 PJ. The efficiency of the conversion for the whole of the forest industry was thus about 42%.

The next conversion processes shown in the chart are agriculture and the food industry. 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 about 300 PJ. In addition to crops, agriculture and the food industry accounted for the conversion of a further 50 PJ of fuels and 13 PJ of electricity for machine power and heating applications. In this sector, the end product is food and a daily intake of 12 MJ per person is equivalent to an annual conversion of 36 PJ for the country as a whole. This means that the food which is thrown away is not included in the food flow, but is represented as a loss in food processing. Approximately as much as 25 - 30% of the food that leaves the shops is thrown away. Large parts of the losses in agriculture are also inevitable since some parts of the crops are not edible to humans, such as straw. Regrettably the use of straw in animal production has decreased considerably the last few years. This depends to a large part on the shift in the consumption of animal products from milk and butter to pork and poultry. Therefore, the efficiency of the conversion within food production becomes quite low, only about 9%. Also, the exergy content of the agricultural produce is lower than the exergy content of the inputs such as fertilizers, machine wear, and fuels. About a third of the inputs of fuel and electricity in food production is used in the food processing industry.

Hydro-electric power is the next conversion process shown in the chart. In 1975, the electricity was also used for lighting, domestic power supplies etc (82 PJ). The engineering industry used a great deal of electric power to drive machines, i.e., to perform mechanical work (about 26 PJ). The use in the forest industry and in food production was mentioned earlier. 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 in converting the potential energy of the water in the reservoir into electricity from the power station to be 15%, 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 combined power and district heating plants. Apart from generating electricity, the latter type of plant supplies district heating by a so-called back-pressure process. The chart illustrates how this flow of district heating (6 PJ/yr) is distributed as a heat 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%.

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 pumping stations. 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 losses in transmission and distribution to the consumer.

In Sweden, iron ore accounts for almost all of the ores converted. In Fig. 4.1 the Swedish iron ore conversion process was presented. We see this conversion process in its context in the diagram in Fig. 4.2.

The most common fuels used in Sweden are crude oil, oil products, coal and coke. In 1975, imports of these products amounted to a total of 1 323 PJ.

Fuels are used as feedstocks in the chemical industry. In 1975, 18 PJ of oil and 21 PJ of electricity were converted into about 30 PJ of rubber, plastics etc. Thus, the chemical industry supplies 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 (220 PJ/yr). Petrol and oil are converted to motive power in cars, buses and trucks. About 10% of the exergy content of the fuel is used to propel a motor vehicle (about 1 ton 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, about 583 PJ for direct conversion to heating in homes and other premises, 115 PJ for the production of electricity and heat in thermal and combined power and district heating plants, and 86 PJ for the production of heat etc in industry.

The largest conversion process – 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 process, which is divided between industry, homes and public premises, entails appreciable losses. In a conventional oil-fired boiler, less than 5% of the fuel exergy content goes into the heat produced. 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:

$$E = \frac{T - T_0}{T} \text{ Q} \tag{8}$$

where Q denotes the quantity of heat and T its temperature in Kelvin. T_0 is the ambient temperature. The ratio $(T–T_0)/T$ is also known as the Carnot coefficient.

If we now wish to use this heat for heating homes, we must also allow for the fact that the environmental 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 were: solar heat 1 PJ/yr , district heating 2 PJ/yr , electric heating 1 PJ/yr and heating produced by fuel burning 19 PJ/yr. The latter figure also includes other direct energy losses such as flue gas losses (amounting to about 35%).

Of the total national inflow of energy and material resources (about 2 500 PJ/yr) in Sweden in 1975, only 18% or just over 450 PJ/yr was used. The loss which this represents could be reduced appreciably by active conservation in the society. Looking at the utilization of commercial energy resources alone, the efficiency is somewhat lower (about 12%).

(5) It is difficult to apply the concept of information to biological systems. In a sense it is meaningless (biologically) to speak about the information content of a chromosome without regarding at least the system surrounding the chromosome, i.e., the biological

organism. However, all biological organisms are related within the biospere. The ecological evolution is a result of interactions within this system. Thus, to extract a part of this system and evaluate it in physical terms has, of course, only physical meaning. The protein biosynthesis presented in the information rate versus power diagram in Fig. 4.1, p. 39, occurs in an environment difficult to define, and the information is transferred in packages of information. A package of information can, naturally, be transfered (transported) between systems with hardly any exergy. An information content may thus be transfered well below the line indicating the ambient temperature in Fig. 4.1. In technical systems this may be done e.g. by cooling the components. The visualization must, however, occur well above this line.

(6) In relation to the discussion on human utilization of exergy and information (Eq. (12), p. 37), the following simple calculation might be added. The total inflow of information since the creation of the earth accounts for about $4 \cdot 10^{54}$ bits, an incredible amount of information. After a few billion years life began on earth and just recently homo sapiens entered. The immense information capacity inflow plays a crucial role for the existence of these phenomena on earth.

In order to give a historical perspective of today’s resource use in Sweden, given in Paper I and II, I also add the descriptions of the exergy conversion in the Swedish society in 1920 (Wall 1982).

4.1. Exergy conversion in the Swedish society in 1920

4.1.1. Introduction

This description is based on a study from the Centre for Interdisciplinary Studies of Human Conditions at the University of Göteborg (Egnéus et al.1978).

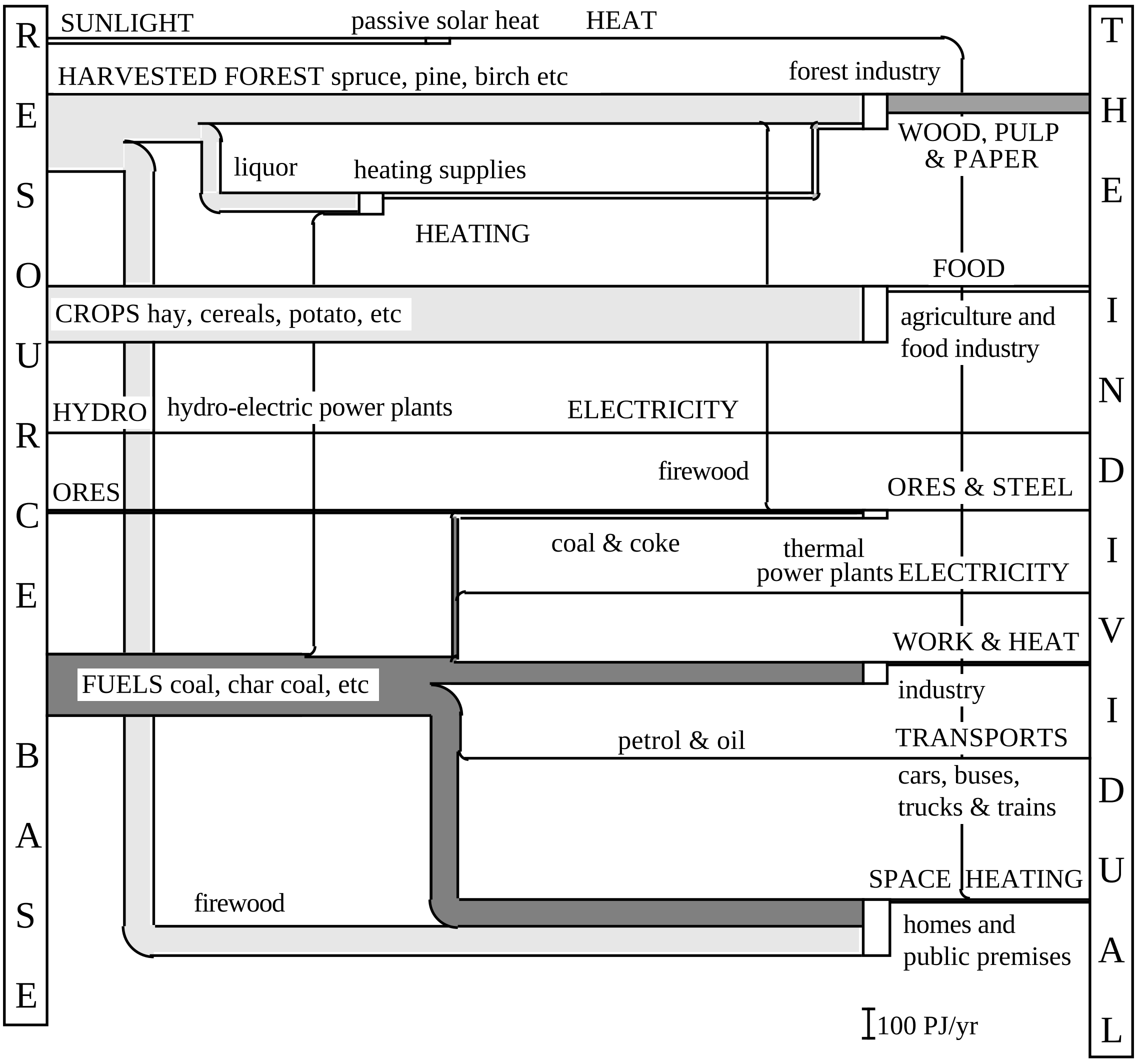

Fig. 4.3. The Swedish energy and material conversion in 1920, in terms of exergy. (The total conversion was about 670 PJ.)

For the Swedish population the increased use of resources meant an increased material standard at this time. In 1920 there was no longer any self-sufficiency on a household level. About half of the population depended on a monetary income and had to pay for the greater part of their basic material needs, such as food, clothes and living quarters. The food that they bought was very satisfactory measured by the standards of the 1970's. The construction of new houses increased and older houses were improved. Better living conditions and better hygiene were to eliminate certain diseases later on, mainly tuberculosis. The improved standard of living removed the soot and ashes from the living quarters to the surrounding air, and human waste was removed from the privy in the backyard to the water courses. The people of the 1920's did not see the negative consequences of this.

The supply of energy and material resources was important for all these changes. Exergy was necessary to take care of the flows of resources, to convert them into useful commodities, and to transport these to the consumer.

In the towns, there was a shift from the use of Swedish resource flows to using imported deposit resources such as coal and coke. The car brought with it imports of fuel from abroad, mainly USA. However, firewood was still important locally. Both industry and households were thus well prepared for a reduction of imported fuels. Water power became more and more important both in industry and in households during the 1920's. Industry produced more commodities for ready consumption out of raw materials.

When resources were increasingly fetched from peripheral areas, and all values were translated into SEK, people's awareness of scarcity, of the need to limit the extraction from funds and of the finite nature of deposits, decreased.

In the flow diagram below, the Swedish energy and material conversion in 1920, in terms of exergy, is illustrated. Some of the figures are only estimated. A more detailed description of the resource conversion follows below.

4.1.2. Technical uses of natural resources.

The first technological revolution came with the introduction of a new source of power, the steam engine, the second with electricity, which brought with it a new technique for the transfer of power as well as the combustion engine, and the third which occurred after World War II (WWII), with electronics and computerization.

Electricity: The first real breakthrough in the use of electricity in industry came with the development of the three-phase system during the 1890's. It was this system that was the important factor in the industrial revolution at the turn of the century. At first, electric lighting was introduced with the light bulb, and electricity was produced in thermal power plants. Electricity, however, could also be derived from hydro-electric power. The use of electricity for driving industrial machines became, with the three-phase system, an interesting alternative to the more direct use of water wheels and steam engines. However, the factories had to be rebuilt. The use of electricity in industry created a base for an expansion of hydro-electric power to the larger and more distant waterfalls. The use of electricity in industry, the possibilities of using large amounts of electricity to power electric furnaces as well as for electrolysis, put those countries that had plenty of large waterfalls, such as Norway and Sweden, in a more favourable position.

The electric furnace, the process of electrolysis, and the use of electricity to produce several of the most important semi-manufactures in chemical industry – ammonia, calcium carbide, chlorine, chlorate – were also part of the great industrial revolution. But electrical energy was expensive to produce, and electric furnaces, electrolysis and electricity in the chemical industry needed a lot of energy per product unit. Therefore, they only became interesting when power plants and the distribution network had been built, and the electric power plants had reached a surplus capacity.

The operation of railways and trams is yet another use for electrical energy. Apart from small industrial railways and short tramways, it was not until well into the 20th century that electric locomotives and trams became common. This is partly because there was not enough electrical energy at first to run larger railways, and partly because the addition of railways to a common distribution network caused disturbances in both electric and telephone networks.

Petroleum: The use of petroleum was another important factor in the great industrial revolution at the turn of the century. Small quantities of oil were already used for lighting (paraffin oil for lamps and paraffin stoves) and for greasing, but there were no uses for the lightest fractions, i.e., petrol, and the large-scale use of the heavier fractions as fuel had not yet started in the 1870's. Society was adapted to the use of solid fuels, and before petroleum was able to compete on a large scale a distribution system needed to be established and drilling techniques needed to be improved and to become cheaper. These investments were not made as long as there was still plenty of coal in the industrial centra of the world and fuel-wood in its peripheral parts.

In the 1920's, oil was still little used as compared with coal, but the breakthrough can still be said to have come during the decade. The cause of the breakthrough was the possibilities that oil had in new areas. One was the ability to use existing machines better. This was interesting, for example, in the case of steam turbines used to generate electricity. Turbines have advantages over, for example, the steam engine, in driving an electric generator, mainly because they can produce the higher speed needed by the generator directly. As electric power systems were expanding, the need to regulate the production of electricity to answer demands became greater. The cost of fuel for this production of "peak power" was not so important if one could get away with low investment costs. Another possibility was to attach oil furnaces onto steam boilers usually fueled with coal, which could then produce more steam at a higher pressure and temperature through the more efficient oil combustion.

The internal combustion engine: The use of petroleum was, however, influenced by the development of the combustion engine for boats and cars, more and earlier than the possibilities for increased effect in some machines. The decisive factor was that engines with internal combustion could be made more compact and lighter in relation to the driving force produced than steam engines or other engines with external combustion. The weight and the space required for the brought fuel made the combustion engines quite superior to electrical engines.

During WWI, diesel engines were introduced on larger ships. This and the use of steam engines run with oil created better performance and less work on board, but were not as revolutionizing as the introduction of combustion engines, e.g. compression- ignition engines, on small motorboats. Fishing boats at sea, by coasts, and on lakes and rivers were fitted with engines.

New materials: Even if the introduction of electricity and the combustion engine were those aspects of the industrial revolution that meant most to development, there were several other aspects.

New materials were put into use. The use of electrolysis for the production of aluminium made clay into a technically and socially useful natural resource. The electric furnaces made it possible to produce alloys for steel in large quantities.

The effect of the alloying materials (as well as that of coal) on the properties of the steel were thoroughly studied from the beginning of the 1890’s. Alloys with greater tensile strength, flexibility, and hardness were looked for. Soon also the interest in rust resistance increased.

Manganese steel was used early for certain construction purposes that required a high tensile strength. Chromium steel, which was very tough, was used for tools, machines, and military equipment. Wolframite or wolframite/molybdenum steels, which were very hard even after heating and cooling in air, were used for cutting.

Several alloys were known and used earlier as well, but then they were very exclusive because the components were rare and expensive laboratory products until the electric furnace was invented.

Special alloys made a much more effective workshop technology possible, and a new generation of machines was developed: milling machines, the turret lathe and the grinding machine were added to the traditional lathe, the planing machine and the drilling machine. Also, a simple automization of the machines was done so that they no longer needed the complete observation and skills of one worker. The workshops could work with a much higher degree of precision. New measuring instruments were developed, for example the so-called gauge block. Through the increased precision it was possible to produce screws, nuts, shafts, cogwheels, belt pulleys and even more complicated machinery in specialized workshops, to be assembled in other factories. It became important to standardize machinery if the specialization was to work, and this was achieved, especially in Germany. Completely new machinery was also developed, such as ball bearings.

4.1.3. Agriculture

Table 4.1 shows the agricultural production for vegetable consumption. Here farming acreage, production in tons, and the amount of exergy are given. Losses in the form of plants consumed by insects, fungi and bacteria, or as straw, tops and subterraneous parts of plants, have not been estimated.

Table 4.1. Farming acreage, production and estimated exergy content of the harvest in 1927.

	Acreage (1000 hectares)	Production (1000 tons)	Exergy content (PJ)
Cereal for bread	503	802	12
Potatoes and sugar beets	90.5	1968	8
Other plants	22	34	about 1
Total	615.5	2804	21

Table 4.2 shows the agricultural products of plant matter which is converted by animals before consumption.

Table 4.2. Farming acreage, production and estimated exergy content of a certain harvest in 1927.

	Acreage (1000 hectares)	Production (1000 tons)	Exergy (PJ)
Cereal for fodder	1049	1661	26
Roots and potatoes for fodder	174.5	3275	12
Hay	1569	5965	91
Total	2792.5	10901	129

The exergy content of the straw can be estimated at 38 PJ, since the production of straw was about as large as the harvest.

The figures of production given in the tables are gross figures. This means that not all is consumed by animals or humans, e.g. planting seed, losses in connection with flour-making and treatment of the plant matter, and storage losses.

Table 4.3. Animal products in 1927.

	Production (1000 tons)	Exergy (PJ)
Cattle	103	1.6
Swine	141	2.3
Other animals	11	0.2
Dairy products	4077	12.6
Eggs		0.2
Total		16.9

It is the primary exergy flow from plants to man that has been presented here. The inputs of exergy needed to set this exergy flow in motion, for example, the production of fertilizers, concentrated fodder, and tools, are absent. These inputs were, however, much smaller than today.

Other important contributions were pastures for cattle, sheep and goats in natural fields and in woods, as well as berries, mushrooms and game animals.

The estimates presented here are not complete, but they show the possibility of estimating the total exergy flows. The exergy flow from agriculture was more than 180 PJ/yr. The part that was consumed by domestic animals had an exergy content between six and eight times the part which was consumed directly by man.

4.1.4. Forestry

Physical usefulness: The physical properties which form the basis of a description of the Swedish forest are: (1) the area of forested land, (2) the geographical distribution of the forest, (3) the amount of timber in different forest regions, and (4) the combination of tree species in different forest regions. These factors also influence the site quality class.

More than half of the total area of Sweden was forested in the 1920's. The proportionally largest area of forested land was in the southern part of Sweden. In absolute numbers, however, the largest area of forested land was in the north of Sweden. But large areas in the north are bare mountains, and if this is excluded, over 70% of the remainder is forested.

Certain parts of forest growth cannot be utilized by man. Part of the forest ecosystem is destroyed by fire. About 0.4 M m^3 of forest was lost through fire each year. However, this loss was small compared to the total biomass of the forest, about 1700 Mm^3.

Another factor which can be of greater importance is the effect of wind on the crops, i.e., storms. About 5 Mm^3 of timber was felled during two bad storms in 1931 and 1933. The dead trees also become breeding ground for various harmful insects.

Parts of the forest waste is used by humans, mainly as fuel. In 1927, about 12 Mm^3 of stump wood (stumps and tops) was left in the forests. About 3 Mm^3 of branches were obtained, and about half of this was used as fuel.

The felled timber is used (1) as fuel (see Section 4.1.5), (2) for building and wood industry (saw mills), about 15.4 PJ/yr, and (3) for the pulp and paper industry, about 12.8 PJ/yr.

4.1.5. Solid fuels

In the 1920's one spoke mainly of fuels and power in connection with energy, where fuels meant both sources of heat and chemical raw materials. Power included steam engines, water wheels, oil combustion engines, etc, which was used directly, as well as electric engines. The installed power capacity was mostly given in units of horse power, while the energy they converted was less interesting. No uniform concept of energy was used.

The different fuels used in the 1920's had, of course, different properties and *could not easily replace each other*. In statistics, they were instead reported as the heat of combustion that can be obtained from them. To simplify the figures the heat of combustion was often compared with that of "good English coal" and then expressed as so-called coal equivalents, see Table 4.4. This table also shows those solid fuels which were used at this time.

The heat content per ton obviously varies a great deal. The heat content of coal is 28 GJ/ton while that of coniferous wood is only 11 GJ/ton. The variations are especially great when the heat content is shown per unit of stacked cubic volume. We see that the fuels obtained from forestry are much more voluminous than those based on coal with respect to the heat content. In comparison with coal and firewood (trunk wood), the waste fuels are very voluminous. This is especially true of wood shavings. This means that as soon as there is a question of transporting waste fuels a longer distance, transport conditions are far more unfavourable than for firewood or coal fuels. Since the waste fuels in certain industries, mainly the wood industries, are as great as the total production by weight, the wood waste (including potential waste fuel) caused a storage problem.

Table 4.4. Some important "energy properties" of solid fuels.

Type of fuel per mass unit (GJ/ton)	Heat content per volume (GJ/m^3 stacked)	Heat content coal volume (m^3)	Equivalent
Coal	28	23	1.0
Coke	27	12	1.9
Airdry birch wood	15	7	3.4
Raw birch wood	13	6	3.6
Airdry coniferous wood	16	5	4.2
Raw coniferous wood	11	5	4.2
Charcoal	26	4	6.0
Peat	14	3	7.0
Saw dust		2	11
Wood chips		2	10
Wood edgings		3	7
Wood shavings		1	20

When used for heating, the fuels can replace each other in equal amounts of coal equivalents. But if a high combustion heat is needed, the fuel has to have a high enough energy density (i.e., combustion heat per kilogram). For a metallurgical process it can also be important to use a fuel that gives off low amounts of certain pollutants, such as sulphur.

Firewood: In the 1920's, firewood was still a very important source of energy. It contributed to about one third of the yearly fuel requirements and corresponded to about 4 million normal tons of coal equivalent, i.e., the same as the yearly import of coal. Table 4.5 gives a general summary of the use of firewood by the main users in 1913-1935. It shows how the use of fuel decreases, apart from during WWI.

Table 4.5. The use of firewood in Sweden in 1913-1935 (Mm^3).

Sector	1913	1916	1925	1935
Industry	0.8	1.4	1.0	0.9
Transports	0.1	0.4	0	0
Domestic sector	15.3	16.8	13.4	11.1
Total	16.2	18.6	14.4	12.0

Peat: The maximum production of peat in Sweden was about 700 000 tons, in 1920. The increase in the peat production from 1916 to the peak year 1920 was about 500%. The decrease after the peak of 1920 was even faster than the increase, and in 1922 the production was again the same as in 1916. The increase and the following decrease of industrially produced peat for selling followed quite closely the changes in price of coal.

Peat replaced coal and coke for certain uses in certain geographical areas. The main characteristic of the peat production during the period of 1913-1930 is the extremely fast increase during the energy crisis and the following equally fast decrease after the crisis to a slowly vanishing production around 1930. Before and after the energy crisis, approximately half of the peat production was used in industry and the other half for domestic purposes and heating of premises.

Coal: Sweden had her own flow sources of energy, i.e., forests and water, and, in relation to the population, these were vast. In spite of this the country imported stored energy resources from deposits. The most important commodity imported was coal, the most important commodity exported was paper pulp. Before WWI, 99% of all coal imported to Sweden came from Great Britain, which also received most of our exported paper pulp. During the war Sweden also imported a great deal of coal from Germany.

During the years 1921-1925, Great Britain almost monopolized the Swedish import of coal. This had been the case before the world war as well. 1920 is the only year when a large part of the import came from USA. 1920 was the year of the great coal strike in Great Britain. Sweden had to get coal from other countries, mainly Germany and Poland, and after 1926 Great Britain no longer had monopoly of the export of coal to Sweden, but from this time besides Britain the imports mainly came from Poland and Germany. The situation was the same when it came to coke.

The industry consumed about 50% of the coal used in the 1920's. Coal and coke were mainly used by gasworks, the paper and paper pulp industry, and the manufacture of non-metallic mineral products except products of petroleum and coal. Industry used coal and coke partly for power generation, partly for heating. Another great consumer was the railways. They consumed about 20% of the total consumption. The rest was shared approximately evenly by shipping, gasworks, public works, institutions and households.

4.1.6. Liquid fuels

The import of petroleum increased during the 1920's from 50 million kilograms (1920) to 160 million kilograms (1930). During the same period, USA's part of this decreased from 91% to 36% and the price from 0.31 SEK/kilogram to 0.06 SEK/kilogram.

The industrial consumption of oil as fuel did not at all increase as fast as the import. The industrial consumption was at most 20-25% of the import. The remaining consumption is difficult to trace.

The state did not take any initiative whatever to encourage or discourage oil imports. Oil was allowed to flow freely into the country. This was not the case with *petrol*.

The consumption of petrol in 1920 was 43 million kilograms of which 80% came from USA, and in 1930 410 million kilograms of which 43% came from USA and 40% from Great Britain. The price was 0.72 and 0.11 SEK/kilogram respectively.

The import of petrol increased throughout the 1920's. From 1920 to 1930, the import of petrol increased by a factor of eight. The main consumers (about 90%) of petrol were, of course, the cars, which increased rapidly in number during the 1920's.

The liquid fuel which has been used longest in Sweden is paraffin. During the 1920's the imported paraffin competed with electricity that was produced within the country.

The import of paraffin in 1920 was 62 million kilograms of which 91% came from USA, and in 1930 79 million of which 35% came from the USA and 45% from Great Britain. The price changed from 0.47 SEK/kilogram to 0.12 SEK/kilogram.

During the 1920's the Swedish import of liquid fuels increased rapidly. Sweden thus became more and more dependent on the import of liquid fuels, and the increasing portion of our fund resources such as paper pulp in exports was needed to pay for the import of fossil fuels and vehicles. It was only in the case of petrol that the state tried to impose restrictions to decrease the import and, to a certain degree, the negative effects on the trade balance. In 1924, tax and import duty on petrol were introduced, the first energy tax in Sweden.

4.1.7. Electric power

The use of electrical energy was well established and increased greatly during the 1920's. The industrial use increased from 2.1 PJ/yr on 1920 to 3.6 PJ/yr in 1930. The increase within the domestic sector was particularly great and rose from 0.2 PJ/yr in 1920 by a factor of three to 0.6 PJ/yr in 1930.

During the period 1915-1935, the use of electrical energy within the domestic sector increased, on average, by 10% per year. This rapid increase is probably connected with the shortage of fuel during and after WWI.

The main part of the electrical energy in the domestic sector was used for lighting in the towns. But it was during the 1920's that the absorption refrigerator was invented by von Platen and Munthers. The number of refrigerators increased from 500 in 1920 to 4000 in 1930.

The very rapid increase in the use of electrical energy was due not only to the decrease in price relative to fuels, but also to the fact that the state actively encouraged the expansion of electric power plants and power lines – especially in rural areas. However, electrical energy was still mostly too expensive to be used for other purposes than for lighting. The power plants and those industries which produced electric machines made strong propaganda for an increased use of electrical energy.

4.2. Comparison of the presented societies

In all the diagrams of societies exergy resource use the inflowing resources come in an order with natural flows at the top, followed by flows from funds and flows from deposits. The inflow of solar heat is thus a direct exergy flow from the sun. Then follow the inflows of forest crops, agricultural crops and hydro-electrical power. The remaining inflows of ores, nuclear fuel and other fuels come from dead stocks, deposits, on earth.

In Table 4.6, the figures for Sweden in 1920, 1975, and 1980 are given. We can see that, besides an increased resource use, the resources today origin from mostly deposits instead of funds as in 1920.

Table 4.6. The exergy flows per capita in Sweden in 1920, in 1975, and in 1980.

	$\frac{\text{Total inflow}}{\text{capita}}$	from funds	from deposits	$\frac{\text{Net outflow}}{\text{capita}}$	$\frac{\text{Net outflow}}{\text{capita}}$
	GJ/yr capita	%	%	GJ/yr capita	%
Sweden 1920	120	69	28	30	25
Sweden 1975	300	40	59	55	18
Sweden 1980	305	40	59	60	20

5. PRESENTATION OF PAPERS III AND IV A-B

5.1. Paper III

Paper III, *Exergy Flows in Industrial Processes*, gives a detailed description of the exergy flows in a pulp and paper industry and in a steel plant, two kinds of industries with heavy flows of matter.

The ability to find new solutions is often limited by the existing technology. Current technology is often overestimated in relation to past technology and to future alternatives. Thus, today's most sophisticated computers are mere "steam engines" when compared to the simplest biological cell or to future computers as is also illustrated by the rapid developments in the computer field. This paper emphasizes therefore the importance of defining the problem in scientific terms, that is, unhindered by the limitations of current technology. Such a description must, of course, be based on clearly defined scientific concepts. If not, we might be evaluating a false picture of the problem that may become an obstacle to important technological advances.

This paper presents in more detail the energy and exergy flows of two typical Swedish industries, a pulp and paper mill and a steel plant. These are also described in relation to Sweden's space heating system. The pulp and paper industry which I have studied produces unbleached kraft liner. After the wood is cleaned, debarked and chipped, the wood chips are processed in a continuous digester to a sulphate pulp. The separated bark is combusted together with fuel oil to produce steam and electricity, both of which are used in the process. The chemicals and the stripping (or draw-off) liquor leave the digester after processing. A major part of the chemicals is recovered in the flash and heat exchangers, evaporators, soda recovery unit and lime sludge reburning kiln, while the liquor is used to produce steam. The washed sulphate pulp is then transported to the paper mill where it is formed, dewatered, pressed, dried, reeled and cut for delivery. Approximately 36% of the energy losses are incurred in the soda recovery unit, ~17% in the steam plant (or steam production unit), and ~34% in the paper mill. In terms of exergy losses, ~40% are incurred in the soda recovery unit, ~31% in the steam plant and ~16% in the paper mill. The sum of the energy losses and the sum of the exergy losses in these three subprocesses are the same, but the relative proportions in the two treatments vary considerably. Furthermore, seen from an energy point of view, the unutilized outflows (or waste flows) amount to 57% of the total losses as compared to an exergy loss of only 7%. It can be seen that these flows constitute a considerably smaller resource than an energy account would lead us to believe, and it may thus be concluded that an energy balance paints an incorrect picture of the process.

The steel plant produces reinforcing steel from scrap iron. The scrap iron is smelted in two electric steel furnaces and then undergoes continuous casting. The steel is subsequently cut into blanks which are then reheated in a pusher type furnace and then rolled to circular crossections with diameters from 6 to 32 mm. The major part of the energy losses is incurred in the electric steel furnaces and during continuous casting, and amounts to ~44% of the total losses. The picture of the losses is more or less the same when we look at the exergy losses. Nearly half of the exergy losses are incurred in these two subprocesses. The difference between the energy and the exergy treatments increases when we look at the unutilized flows in the process such as exhaust gases and heat. These account for about 65% of the energy losses but only for about 28% of the exergy losses. What appears as a substantial unutilized resource flow in terms of energy is thus shown to be considerably less in terms of exergy, which is mainly due to the temperature of the flows. Thus, only a minor improvement in efficiency can be achieved by utilizing the existing unutilized flows. It is only by introducing new and more efficient processes that major improvements can be achieved.

As a comparison to the industrial processes, the study also describes the Swedish space heating system. This comparison reveals many interesting differences. The Swedish space heating system represents the largest single exergy saving potential in the country. The efficiency in the conversion to heat is estimated to be about 5% for Sweden as a whole. Two observations can be made: (1) current-day systems are highly inefficient, and (2) new technology offers enormous potential for improving Sweden’s space heating system. Modern nuclear energy technology, which utilizes only a small fraction of the exergy content of nuclear fuel yields an extremely low over-all efficiency for space heating.

Finally, the study provides a short description of the price of several of the most common energy forms in relation to energy and exergy content. This is relevant since the design of the energy system mostly depends on the price of different energy forms. The approximate energy price of electricity in SEK/GJ is about 70, the price of petrol about 110, of fuel oil about 50, and of wood about 20, and district heat about 60. The high price of gasoline can be justified by its special area of use, the low price of wood can be explained by the fact that efficient energy conversion from wood is expensive. In terms of exergy, we obtain instead the following prices. (SEK/GJ): electricity about 70, gasoline about 120, fuel oil about 50, wood about 20, and district heat about 340. The very high exergy price of district heat is difficult to justify but can be explained by today’s rather inefficient heat production technology. This means that it will hardly be possible to maintain the price of district heat as heat pump technology develops further. In the future, when heat pumps have reached a coefficient of performance (COP) of about 5, today’s relative price of district heat would be too high.

The method presented in this paper is also valuable for long-term planning of, for example, research efforts on more efficient allocation of resources since it reveals the real losses.

A computer program is developed to calculate steam data on a micro-computer with the accuracy of ordinary steam tables. Earlier, this had only been done on large computers.

Also, a simple computer based method is presented for calculating the exergy of substances.

5.1. Paper IV a-b

For several years Myron Tribus and Yehia M. El-Sayed (1983) at the Center for Advanced Engineering Study, M.I.T., have been developing a method which they call "**Thermoeconomics**", to optimize the cost under prevailing thermodynamic conditions. The method has been applied with great success to industrial processes in the processing industry. The purpose of thermoeconomics is to improve analyses of systems by introducing ways of concurrently suggesting improvements to the analyzed system. One way in which Tribus justifies the method is as follows:

"It is much more important to be able to survey the set of possible systems approximately than to examine the wrong system exactly. It is better to be approximately right than precisely wrong."

The starting point is to consider a system surrounded by both a physical environment and an economic environment, see Fig. 6.1. The physical environment is described in terms of pressure, temperature and the chemical potentials of the substances involved. The economic environment is described in terms of the prices of the goods in question and the interest on loans.

The two environments are interconnected via cost relationships describing how the costs depend on physical quantities.

The method can be described briefly as follows:

1. Draw up a concise description of the process studied.
2. Define the system, the system limits, various system zones, components etc (detailed flow chart or sketch of the process).
3. Define the physical environment or alternatively the local physical environment.
4. State the sources of thermodynamic data.
5. Draw up a thermodynamic calculation algorithm with clearly identifiable inflows and outflows. The algorithm is based, among other things, on material and energy balances for the system. It must constitute a complete thermodynamic description of the system (under the given conditions).
6. Indicate cost functions for the relevant zones or components and state the target function of the system (optimization conditions).
7. Calculate the exergy flows in the process and state the entropy sources, i.e., where exergy is lost in the system. Then relate these losses to the inflow and outflow of exergy.
8. Calculate the value flows (based on internal prices) in the process.
9. State any proposals, based in items 7 and 8, for improvements to the system configuration, and adjust the affected relationships (item 5).
10. Carry out an optimization of the process.

11. Carry out a sensitivity analysis.
12. Propose improvements and areas for research and development.

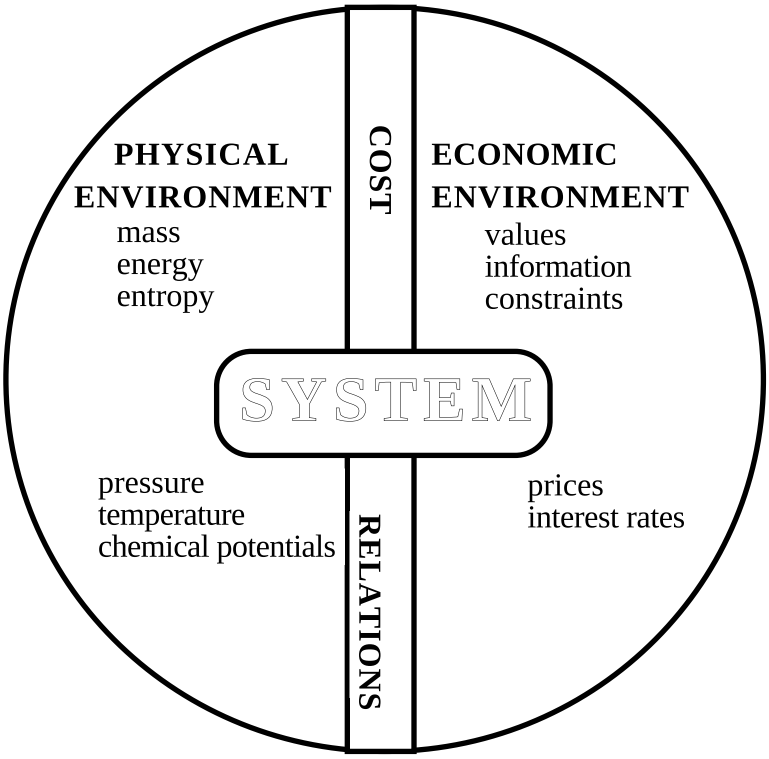

Fig. 6.1. The system in two environments.

The initial stages of this working method are obviously self-explanatory and generally accepted. The most important improvements is the introduction of the environment and its effects on the process. The concept of exergy which can then be applied makes it possible, among other things, to calculate the technical losses in the system, item 7.

An engineer designing a system is expected to aim for the highest possible technical efficiency at minimum cost under the prevailing technical, economic and legal conditions (sometimes also with regard to ethical, ecological and social consequences). Scope for the following should be taken into account when doing this work:

- Different operating modes (different pressures, flow rates etc)
- Different configurations (addition or removal of components, rearrangements etc)
- Different purposes (by-products, sale of waste heat etc)
- Different environments (change of environmental conditions, energy price, environmental requirements etc)

Thermoeconomics is a method of analysis that makes this work a great deal easier.

Paper IV a, *Thermoeconomic Optimization of a Heat Pump System*, is an application of thermoeconomics to a single stage heat pump, which gives unexpected and interesting results. The heat pump is assumed to be made up of a compressor, a condenser, an expansion valve, an evaporator and an electric motor, i.e., a very simple assumption. The refrigerant is R12, and the heat transfer medium to the environment in the condenser and evaporator is water. The free decision variables to be chosen optimally are the efficiencies of the compressor, the condenser, the evaporator and the electric motor. The system is completely determined except as far as these variables are concerned.

The aim is to minimize the total cost of the system for a given heat production. This cost is made up partly of a running cost (electricity) and partly of costs for investment of each component. The running cost increases if the investments decrease and vice versa.

In this example, the values of the dimensioning parameters have been assumed to be: heat output produced 6 500 W (energy), running time of 5 000 hours per year, electricity cost SEK 0.25/kWh, temperature of the produced heat 60°C and temperature of the heat source 10°C. An arbitrarily operating system with all four efficiencies at 70% is assumed as starting point. The calculated total cost will then be SEK 4 221/yr, SEK 3 617/yr of which is for electricity. Optimization now gives the following efficiencies instead: compressor 0.80, condenser 0.83, evaporator 0.73, and electric motor 0.91. The total cost will now be SEK 3 388/yr instead, SEK 2 416 of which is for electricity. So by increasing the investment cost from SEK 604/yr to SEK 972/yr we make a total saving of SEK 833/yr as compared with the assumed system. At the same time the exergy losses are approximately halved from 1 933 W to 979 W, i.e., by 954 W. It is the improvements in the electric motor that account for the largest single exergy saving, so that the optimization saves us both money and exergy. It has been assumed that the electric motor would cost three times as much if its efficiency could be raised from 70 to 91%, a perfectly realistic target. It could, however, even cost nine times as much and still be profitable compared with the assumed system. It may also be added that the coefficient of performance (COP) increases from 2.25 for the assumed system to 3.36 for the optimal system.

Since the choice of the optimum system is influenced by variations in the dimensioning parameters these should also be analyzed. One is the condenser temperature, i.e., the temperature of the heat produced. The total cost is doubled from 2 336 at 40°C to 4 680 at 75°C. The energy output is the same, i.e., 6 500 W, but the exergy output changes from 434 to 713 W, which provides a better explanation of the increase in cost. When the temperature increases from 40 to 75°C, the efficiency requirements for the system as a whole become stricter, but not necessarily for each component. This is clearly shown in this case. In the context of a total increase in component costs, therefore, it is more economical to choose a cheaper evaporator. The reason is simply that an investment gives a better return in other parts of the system. The method does show where an investment is most worthwhile.

Many other relationships can be illustrated in the same way. Other refrigerants or cost relations can be assumed and the heat pump can be modified. The physical treatment of the refrigerant and the optimization of the system is made by specially developed computer programs. These are enclosed in Paper IV b, as they may be easily adapted to other refrigerants as well as other processes. The purpose of this study has been to illustrate the thermoeconomic method by applying it to a heat pump process. The exact results are therefore secondary to the presentation and discussion of the suitability of the method. However, this method for improving technical systems can never replace long practical experience or high technical expertise, but it can be a useful complementary tool to them.

Though this method is principally simple, it is difficult to apply to real processes. The purpose of this investigation, therefore, is to show the importance of applying it to technical systems and how some of the difficulties are avoided.

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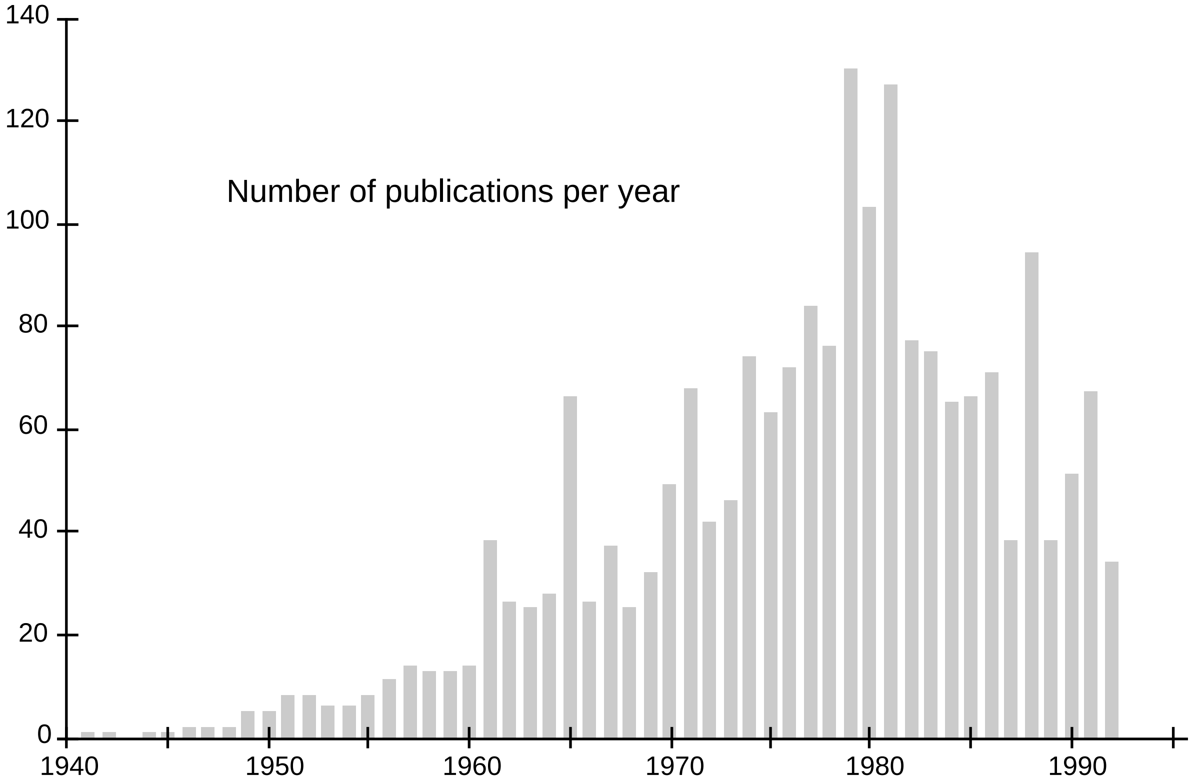
This bibliography contains about 2034 publications most of which are direct references to the concept of exergy published by 1992. Other bibliographies are Wepfer (1979) which covers 404 European publications available before early 1977, Fratzscher and Beyer (1981): 296 publications and Liu and Wepfer (1983): 356 publications, mainly after 1977.

The figure below shows the number of publications per year during the period from 1940 to 1992.



The purpose of this bibliography is to be a data base on exergy. Also, it might be of help to those who work with the exergy concept or would like to penetrate the field.

If you use this bibliography in your work I would be grateful if this is mentioned. I am also grateful for corrections of errors, since this bibliography is subject to continuous revision.

<u>Notes:</u>

Abbreviations:
AIChE = American Institute of Chemical Engineers
JSME = Japanese Society for Mechanical Engineers
BWK = Brennstoff Wärme Kraft
IECEC = Intersociety Energy Conversion Engineering Conference
IVUZ = Izvestiya Vysshikh Uchebnykh Zavedenii
UCLA = University of California, Los Angeles

The references are written: Author,-s/Year/Title/Publication/Comment,-s/Keyword,-s

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EXERGY
- A USEFUL CONCEPT WITHIN RESOURCE ACCOUNTING[1]

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Preface

Anxiety concerning the problems of energy and resources has led to a rapid increase in the interest in describing and understanding the conversion processes of energy and other resources in society. To be able to understand the procedure of these conversion processes it is important that useful concepts are available. I hope that this report will be a help in the development of such concepts.

This report has grown out of earlier collaboration with Björn Eriksson, Karl-Erik Eriksson and Kåre Olsson {1}. The manuscript has been read by Karl-Erik Eriksson and Are Kjeang. I hereby acknowledge my gratitude to them for many important comments and ideas. I am especially grateful to Margareta Ehinger for typing the report with great accuracy. I have received financial support for this work from the Secretariat of Futurological Studies and the Royal Swedish Academy of Sciences.

Of course, I would also be grateful for further comments on and criticism of the content in this report.

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[1] Some text and images are corrected from first version.

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Contents

1. **Introduction**

The purpose of this study is to discuss physical concepts for resource accounting and to suggest a number of basic concepts that could also be valuable in social and economic sciences.

The study has to be considered as a first attempt to summarize fundamental concepts and ideas for an expanded resource budgeting. In order to be able to further develop and establish the basic concepts presented here, however, these must be widely criticized and tested.

Particularly within energy planning, there is now much confusion as to concepts and appropriate delimitations. We often try to solve this concept confusion by introducing new energy units, such as Watt-hours electrical energy (Wh_{el}), tons oil equivalent (toe) etc {2, 3, 4}. Instead, problems arise when comparing energy measured with different units. Furthermore, there is the problem of the different definitions of these units in different countries, depending on how the energy form is produced. For energy conversion processes, completely misleading efficiency concepts are often defined, that reflect reality in a false way {5, 6}. The energy and efficiency concepts used today cannot be applied in an expanded resource budgeting without further notice. The main reason for this is that these concepts lack a fundamental connection to the physical environment. At certain conversions, the environment is of great importance such as, e.g., at the space heating process.

The relationship between the physical resource base and the social and economic structure {7, 8} is a condition often neglected by historians, social scientists and economists. Scientists who have described the physical resource base have, on the other hand, often been little interested in social and economic structures in society.

There are, however, exceptions. There are economists who have tried to take physical factors into consideration as well as economic factors {9, 10, 11}. There are scientists who have taken an interest in catastrophes and threats caused by man’s actions and their squandering of natural resources {12}. Ecological aspects have been of great interest for speculations in this field during the last few years {13,14}. Within the Secretariat of Futurological Studies, two very interesting projects are being carried out in this connection, *Energy and Society* and *Resources and Raw Materials*. From these projects progress reports are continuously published {15} that are of great importance for the comprehension of the energy and material conversion in society {16}. An increased comprehension of the energy and material conversion processes is necessary when planning for the future. Interest in these processes has increased recently in society. The theme of the yearbook of the Swedish Natural Science Research Council 1976/77 is “Natural Resource Cycles” {17}. In order to be able to answer the question about which technology we should choose and how this technology is to be used, knowledge of nature and its cycles is needed. This is because the functions of our own society are integrated in the conversion of energy and matter in nature.

The fundamental concepts that I principally discuss in this study are exergy {18 - 21} and efficiency {22}. The exergy concept has recently appeared more and more often in technical literature {22 - 25}. Exergy represents the useful part of energy for a system in its environment, i.e. the maximum quantity of work that the system can execute in its environment. The exergy concept derives from the entropy concept or rather the negentropy concept {26}, that is more useful in this connection.

The thermodynamic presentation of the exergy concept is given in Sections 2.1 and 2.2. (The derivation of the relevant thermodynamic relations is given in Appendix A.) In Section 2.3, energy and matter are treated as carriers of exergy. In Section 2.4, I discuss the exergy dependence on the environment and the necessity of defining useful standard environments.

Schrödinger {26} says in his book *What is life?* that "we feed on negentropy". He might as well have said "we feed on exergy". Exergy is the fuel for all systems with the ability to maintain themselves, such as the biosphere, an ecosystem, a species, or a living organism. Exergy studies should therefore be useful within those sciences which deal with such systems. In Sections 3.1, 3.2 and 3.3, I give a very brief account of the conversion of exergy on earth. The exergy reaches the earth by means of sunlight, which is then converted, and thus maintains the living conditions for almost all living things on the earth's surface. The sociosphere constitutes the systems of the earth that are created by man. In this sphere world trade is an important exergy flow. There is a short comment on world trade in Section 3.3.

By starting from the energy conversion in a condensing power plant, we can clearly see differences between points of view in exergy and energy studies. These points of view can then be futhered to the energy conversion of a society. This was accounted for in Section 3.4. A first attempt to extend the exergy concept to also describe conversions of matter is made in Section 3.5 and in Appendix 2. To be able to unite the exergy conversion of human society with the global exergy conversion, I account for the exergy flow in Section 3.6. The human society today is dependent on exergy flows from finite deposits of exergy in minerals, such as ores and fossil fuels, but first of all on renewable exergy flows from funds, such as forests and fields, which convert solar energy. Human individuals, groups and societies are constantly dependent on exergy flows to meet their needs. We usually talk about energy resources, material resources such as ores, food and other biological matter, and the environment's ability to purify itself. All these phenomena, however, are examples of exergy flows and can, at least in principle, be quantified in a unified way. This is illustrated in Fig. 3.9, Page 31, where the exergy conversion in Swedish society is presented. From this physical description of a society, we can then start discussing efficiency concepts and comparing different definitions of efficiency. In Section 3.8, I compare energy efficiency and exergy efficiency as concepts of efficiency. The natural consequence of this will then be the question of how effective the total exergy conversion is in society. The aid for such an analysis is described in Section 3.9, Exergy analysis.

In Chapter 4, I discuss the relation between the concept of information, from information theory, and the exergy concept. There is a fundamental relation between these concepts, which are both measurements of order, structure, and contrast.

Chapter 5 is simply a brief concluding remark.

Further, there are five appendixes to the report, which give a more formal description and extension of the concepts presented in the text.

2. **Exergy**

2.1. Energy, matter and quality

Energy and matter cannot be created or destroyed nor produced or consumed. This is a fundamental law of nature. There are no sources or sinks for energy and matter. Energy and matter can only be converted into different forms. This occurs by the consumption of quality. Locally, the quality can be improved, but this can only occur at the expense of a greater deterioration of the quality elsewhere. On the whole it is a question of continuous deterioration in quality. This is also a fundamental law of nature.

The situation is illustrated in Fig. 2.1. Energy and/or matter flow through a system. This must be well defined as to time and space. The motive force of the flow of energy and/or matter through the system is the quality. The quality of the energy and/or matter constantly deteriorates in the flow passing through the system. This is a condition if the flow is to have a definite direction and be defined as to time.

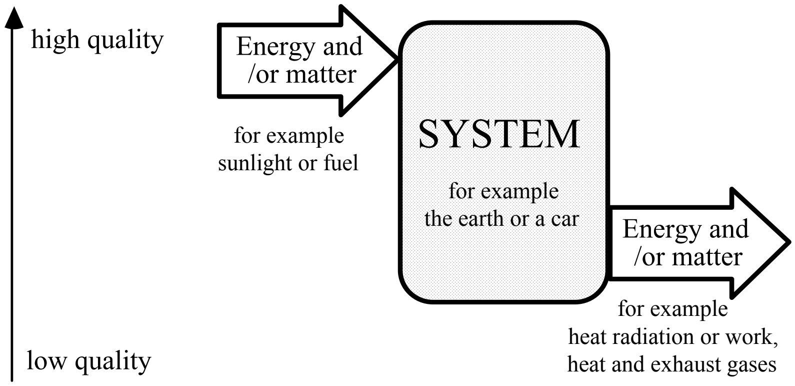

Figure 2.1. The flow of energy and/or matter through a system

When energy and matter flow through a system, a very small part of this is often stored in the actual system. There is usually a balance between inlets and outlets of energy and matter.

Energy and matter only serve as carriers of quality, and it is the quality that is consumed during the conversion of energy and matter. According to this way of looking upon flows of energy and matter it is wrong to talk about the fact that energy and matter are produced or consumed. It is only quality that can be produced or consumed. If an old car stands in the open air getting rusty the material deteriorates in quality but the matter still exists. It will combine with the environment in new chemical combinations, i.e. new materials. From social economic viewpoint, we can say that the car and its material decrease in value and, as time passes, become of no value.

Flows of energy and matter can be regarded as two different phenomena which transport quality. The nonphysical distinction between these is often unclear and approximate. A certain flow can often be regarded both as a flow of energy and as a flow of matter. More about this in Section 2.3 below. The abstract phenomenon of quality is information, which is discussed in Chapter 4.

Instead of saying that the quality decreases, we can say that the lack of quality increases, or that the entropy or disorder increases. It is stated in the second law of thermodynamics that conversions of energy and matter must always take place from a state of low thermodynamic probability to a state of high thermodynamic probability. The energy and matter tend to be distributed over a steadily increasing number of possible states. The quality decreases, and the contrast in a system or a flow is more and more wiped out. An example of this is a warm and a cold flow where the quality and the contrast are determined by the differences in temperature between the flows, which are then mingled to a tepid flow. A tepid flow has no contrast and has, therefore, lower quality than the original flows. This is expressed quantitatively in statistical mechanics as an increase of the entropy for the entire system. The entire system consists of all inflows and outflows as well as all the conversion systems between them. The entropy, represented by an S, can be written as a sum:

$$S = -\mathrm{k}\sum_{j=1}^{\Omega} P_j \ln P_j \tag{1}$$

where k = Boltzmann’s constant, **Ω** = the number of permitted states for the total system, and P_i is the probability for all permitted states which is standardized so that the sum will be equal to one, i.e.:

$$\sum_{j=1}^{\Omega} P_j = 1 \tag{2}$$

The probability for a state can be directly compared to the knowledge of the total system. If we know for certain that the total system is in a certain state, the probability for this state is equal to one. The probability for other states must thus be equal to zero according to Eq. (2). The knowledge of the entire system is thus complete and the entropy for the total system is equal to zero ($S = 0$). Order is complete. On the other hand suppose we do not know anything about the total system. All permitted states must then be equally probable. The number of permitted states is **Ω**. The probability of each state is thus, according to Eq. (2), equal to one divided by this number, i.e. 1/**Ω**. The entropy for the total system becomes $S = \mathrm{k}\ \ln\Omega$. This is the maximum value of the entropy. Disorder is complete.

A conversion of energy and matter which takes place at a finite rate inevitably leads to an entropy production. The entropy production increases with the rate of the conversion. E.g. if we let the conversion take place at a low rate the entropy production becomes less than if the same conversion takes place at a high rate. A conversion which can be reversed is called reversible. Such a conversion is infinitely slow but does not involve a loss, i.e. there is no net production of entropy within the system during the conversion itself. There can, of course, be local changes of the entropy within the system, but on the whole there is no entropy production i.e. no losses of quality. However, a reversible conversion is never completed because of this, and therefore lacks a definite direction of conversion. Reversible conversions only exist theoretically. Real conversions of energy and matter are never reversible. They are always irreversible, which means that they always occur with a loss. Contrary to reversible conversions, irreversible conversions have a definite direction. Losses at real energy and matter conversions are therefore inevitable, and they are also to some extent necessary. Each desired conversion must involve losses, but the losses can be kept down. I have already mentioned a way of keeping down the losses, namely by keeping down the rate of the conversion. There are many other ways, for example choosing the conversion that involves the smallest losses. I will describe this later in connection with energy conversion processes.

The entropy concept is a measurement of the lack of quality. Due to this, the entropy concept gets a negative meaning. We can give a definition of the opposite of entropy, negative entropy or negentropy ($-S$). Negentropy thus becomes a direct measure of quality {26} and has a positive meaning. Negentropy is consumed when quality is consumed or lost.

2.2. The concept of exergy

How shall we measure the quality of a system or a flow of energy and matter? In the technical literature on energy the value of being able to estimate the useful part of the energy, that part that can perform mechanical work, has long been stated {27-30}. In 1953 Z. Rant suggested that the term **exergy** (in German Exergie) {18} should be used to denote “technical working capacity” (in German technische Arbeitsfähigkeit). A complete definition was given by H. D. Baehr {19}:

Exergy is that part of energy that is convertible into all other forms of energy. (Die Exergie ist der unbeschränkt, d.h. in jede andere Energieform umwandelbare Teil der Energie).

The exergy of a system in a certain environment is the amount of mechanical work that can be maximally extracted from the system in this environment. Some examples of systems are a solid, a body of gas, e.g. the air in a heated house in a wintry environment, or a certain quantity of fuel, e.g. the petrol in the petrol tank of a car. The concept of mechanical work below is to be regarded only as an example of a totally ordered energy form, i.e. with the entropy equal to zero. It is only the useful or ordered part of the energy that can be converted into all other energy forms.

Baehr's definition is obviously very general, and can be extended to concern not only energy but also matter. This extension will later be found to be completely justified. An ordinary battery can be used as an example of the conversion of different forms of matter. The matter is converted from one form to another through chemical reaction, and exergy can be derived in the form of an electric current.

Thus, the matter has a greater exergy content in a charged battery than in a discharged battery. The exergy content today is principally used at the optimizing of the steam process within the power industry.

R. B. Evans {20} has shown that exergy (which he calls "essergy") in itself incorporates other thermodynamic concepts such as Gibbs free energy, Helmholtz' free energy, enthalpy (a simplified derivation of this is given at the end of Appendix A), and "availability" introduced by Keenan {30, 31}. Another quite adequate name, "available work" was used by a working team within "the American Physical Society (APS)" in the summer of 1974 {22}.

Exergy is a measurement of how far a certain system deviates from a state of equilibrium with its environment. In Appendix A the exergy E for a system in an environment is written as

$$E = T_0\left(S_{\text{eq}}^{\text{tot}} - S^{\text{tot}}\right) E = T_0\ (S^{\text{tot}}{}_{\text{eq}}\text{-}S^{\text{tot}}) \tag{3}$$

where T_0 is the temperature of the environment, $S_{\text{eq}}^{\text{tot}}$ is the entropy of the total system, i.e. the system plus the environment when the system is in equilibrium with the environment ("eq" stands for equilibrium), and S^{tot} is the entropy of the total system at a certain appropriate deviation from equilibrium. In Appendix A, it is also stated that this concept of exergy is a result of the above definition of exergy. The concept (3) is thus equivalent to Baehr's definition. Exergy is a general concept of quality, i.e. the physical value of a system in the form of how large a quantity of purely mechanical work can be extracted from the system in its interaction with the environment.

By using thermodynamic relations, other concepts of exergy can be derived (see Appendix A).

$$E = U + p_0V - T_0S - \sum_i \mu_{i0}n_i \tag{4}$$

where U, V, S and n_i denote extensive parameters (i.e. quantities that increase with the size of the system) of the system (internal energy, volume, entropy and the number of moles of different chemical elements) and p_0, T_0, μ_{i0} denote intensive parameters (i.e.

quantities which are independent of the size of the system) of the environment (pressure, temperature and the chemical potential of the component "*i*" in its standard state, i.e. in equilibrium with the environment).

Thus, the exergy of a system shows how far the system deviates from the environment. We can see this clearer from the definition (5) below. When the temperature, pressure and chemical potential are the same for the system and for the environment, the exergy of the system is equal to zero. We can also see that the exergy of the system increases when the contrast, the deviation from the environment, increases.

$$E = S\left(T - T_0\right) - V\left(p - p_0\right) + \sum_i n_i\left(\mu - \mu_{\mathrm{i0}}\right) \tag{5}$$

The following formula is very useful for determining the exergy {22},

$$E = U - U_{\mathrm{eq}} + p_0\left(V - V_0\right) - T_0\left(S - S_{\mathrm{eq}}\right) - \sum_i \mu_{\mathrm{i0}}\left(n_i - n_{i\,\mathrm{eq}}\right) \tag{6}$$

where on the right side easily determined quantities appear ("eq" denotes equilibrium with the environment). The derivation is given in Appendix A. It is therefore an easy task to determine the exergy content of a given system in a given environment.

The exergy content in a material can be determined by the formula (see Appendix B):

$$E = \sum_i n_i\left(\mu_i^0 - \mu_{i0}^0\right) + \mathrm{R}T_0 \sum n_i \ln\left(c_i / c_{i0}\right) \tag{7}$$

where μ_i^0 is the chemical potential for the matter "*i*" in its reference state (a state to which all values of the chemical potential for a certain matter are related) and c_i is the concentration of the component "*i*". This way of expressing the exergy makes it possible to determine the exergy content in each type of material theoretically. The exergy content in a given quantity of a certain material can be considered as the quantity of exergy needed to produce this material from the given standard environment by reversible processes.

2.3. Examples of exergy carriers

In Section 2.1, I described how a flow of energy and matter is driven forward by the fact that the flow all the time continuously loses in quality. The quality was also described as the absence of disorder, i.e. of entropy. In Section 2.2, the exergy concept was defined. In this section, I will now link together the two sections by considering energy and material flows exclusively as carriers of exergy, so-called **exergy carriers**.

The quality of an energy form can be expressed as the quantity of negentropy per unit of energy for the energy form in question. The purest energy forms are mechanical and electrical energy, for which the negentropy is zero ($-S = 0$). Energy in the form of heat has a lower quality. The quality decreases with the temperature (provided that the temperature is higher than the environment). Baehr's definition makes it clear that the exergy concept incorporates both the quantitative and qualitative properties of energy.

In Table 2.1 different forms of energy are listed according to their quality, decreasing from "extra superior" to "valueless" {32}. The quality of the energy is indicated by an index giving the approximate exergy content as a percentage of the energy content. The quality index ranges from 100 for potential energy, kinetic energy and electricity (which are pure exergy and thus can be totally transformed into all other forms of energy) to 0 for the exergy-lacking heat radiation from the earth. The quality index of heat energy varies considerably from 60 for hot steam to zero for heat radiation from the earth.

However, not only energy-containing systems carry exergy. If a system is deprived of energy (and thus deviates in this way from the environment) it carries exergy. An ice-block in an environment at room temperature is an example of such a system. (Due to this, the ice represents a negative energy content). When the ice melts, it takes energy from the surrounding air, but we can use the difference in temperature between the ice and the air to run a heat engine and thus extract useful work. This makes the ice a source of exergy. In an analogous manner, an empty container, i.e. a vacuum, surrounded by air and at normal pressure, contains exergy and can be utilized to extract work.

Analogous to the quality of energy, the quality of a certain material can be expressed as the amount of exergy (per unit) for the material in question. The purest form of matter is that consisting of only completely known elements, for which the entropy is almost zero. Diluted and mixed matters have a higher entropy, and therefore have a lower quality. The quality decreases with a greater extent of dilution or mixture. A concentrated mineral deposit has a high exergy content. By mining the mineral deposit and distributing it in the environment, the exergy content decreases. In Table 2.2 different forms of material are listed after decreasing quality. It is difficult to make a classification such as the one in Table 2.1. In any case, there is a clear difference between the upper part of the table, which can be considered as "extra superior" and "superior", and the lower part, which can be considered as "inferior" or "valueless".

Table 2.1. The quality of different forms of energy.

	Form of energy	Quality index (Percentage of exergy)
Extra superior	Potential energy[1]	100
	Kinetic energy[2]	100
	Electrical energy	100
Superior	Nuclear energy[3]	almost 100
	Sunlight	93[2]
	Chemical energy[4]	95
	Hot steam	60
	District heating	30
Inferior	Waste heat	5
Valueless	Heat radiation from the earth	0

[1] e.g. highly situated water resources
[2] e.g. waterfalls
[3] e.g. the energy in nuclear fuel
[4] e.g. oil, coal, gas or peat

The quality of the material form is expressed by an index giving the approximate exergy content i.e., the amount of “elements in an ordered form”, as a percentage of the amount of the material. The definition of the quality index is here analogous to the definition of the quality index for the energy forms in Table 2.1, where the quality index was the amount of “extra superior energy” as a percentage of the amount of energy in question. The exergy for a material is thus the amount of “elements in an ordered form” that can be extracted from a system in its environment. Thus, from a given amount of material, only the part given by the exergy content can be refined into a pure form, provided that no consumption of external exergy occurs. When estimating the exergy content for the material in question, Eq. (7) has been used. As the exergy does not differentiate between “extra superior energy” and “matter in an ordered form”, there is here a clear connection between energy and matter. (Einstein’s relation between energy and matter, $E=mc^2$, the energy is equal to the mass times the speed of light squared, is another more fundamental relation.) Accordingly, we can exchange extra superior energy for the same amount of exergy in the form of matter in an ordered form. This is what we do when enriching and refining a mineral deposit into pure material. We exchange, so to say, exergy in the form of energy for exergy in the form of matter.

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[2] Corrected from latter calculations

Table 2.2. The qualities of different materials i.e. forms of matter.

Form of matter	Quality index (Percentage of exergy)
Matter in an ordered form[1]	100
Matter as commercial goods[2]	almost 100
Mixtures of elements[3]	approximately 90
Rich mineral deposits[4]	50-80
Ore	approximately 50
Poor mineral deposits[5]	20-50
Mineral dissolved in seawater or soil	approximately 0

[1] e.g. carbon in the form of diamond
[2] e.g. iron, gold or lead
[3] e.g. steel, alloys or plastics
[4] e.g. bog iron (limonite) or sea nodules
[5] e.g. bauxite

From Table 2.2, we see that a qualitative index ranges from 100 for absolutely pure and atomically well-ordered materials such as diamonds, to almost 0 for materials evenly distributed in the soil or completely dissolved in seawater. The value of a qualitative index depends on in which environment the exergy is estimated. In Table 2.2, the estimate of the exergy content of the different materials was made with the earth's average combination of material as environment. This means that those materials which are common on earth are of a low exergy value. A comparison with energy forms in Table 2.1 can be made, where heat radiation from the earth is considered as worthless.

Exergy-rich systems, such as chemically concentrated materials, can, in practice, be utilized in chemical-electrical cells of concentration type. At a river mouth, the exergy-rich fresh water literally flows into the sea. If the fresh water is made to mix with the saltwater in a controlled process, work (exergy) could be extracted. An estimate proves that the outlet of Göta Älv[3] into Kattegatt is equivalent to a waterfall at a height of more than 100 meters. This might become an important energy source for the future. (The exergy content of fresh water is also illustrated by the fact that enormous energy quantities are needed to desalt seawater.) The exergy content in concentrated deposits of minerals will be further dealt with in connection with our discussion on resource accounting.

2.4. Global and local standard environments

As the exergy of a system is determined according to its environment, it is important to agree on suitable reference environments to be used. A global standard environment

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[3] Göta river flows into the Kattegatt sea

can be defined in terms of a standard atmosphere with a standard sea at sea level (for gravitational exergy, such as potential energy and tidal energy, the average sea level is a general standard), where the standard states are related to average geophysical conditions. For exergy analyses of traded goods, and for the use of exergy in the earth sciences, such a standard state is necessary.

Temperature conditions differ widely between different parts of the earth, as does the air pressure. Similarly, the chemical potentials of the water in lakes and rivers differ substantially from those of the sea. The structure of the ground and bed-rock varies much over the earth's surface as well as on the bottom of the sea. Thus it is necessary to introduce local standards of exergy also. The most obvious advantage of such local standards is in describing the use of energy (consumption of exergy) in space heating. By adapting the building technique to the prevailing climate, the consumption of energy for heating can be kept down. The relation between global and locally defined exergies of a system is given in Appendix A.

To what extent local standards should be averaged through time, or vary with seasonal or daily variations, is a question that needs to be studied. For the description of space heating seasonal variations are clearly essential. When local standards are used, the local exergy content of a system will consequently vary with the location. This variation may be related to the economic value of the system. A flow of energy and matter can e.g. change its exergy content when passing between different environments. The contrasts between e.g. an ice-block and its environment in Greenland or in tropical Africa are quite different. This variation may be related to the economic value of the system. An ice-block is worthless on Greenland, but it could be valuable in tropical Africa.

3. Exergy and resource accounting

3.1. Exergy, a concept in natural sciences

On the surface of the earth, at many different levels of size and time scale, systems operate involving many kinds of matter in a complex pattern. Energy and matter permanently flow through different systems on the earth's surface. Within many sciences, e.g. hydrology, climatology, oceanography and ecology, we are trying to describe and understand parts of these systems and flows. It may be a supernatural task to try to understand how all these systems and flows of energy and matter cooperate. We can easily split up all the systems of the earth's surface into 5 different spheres, see Fig. 3.1.

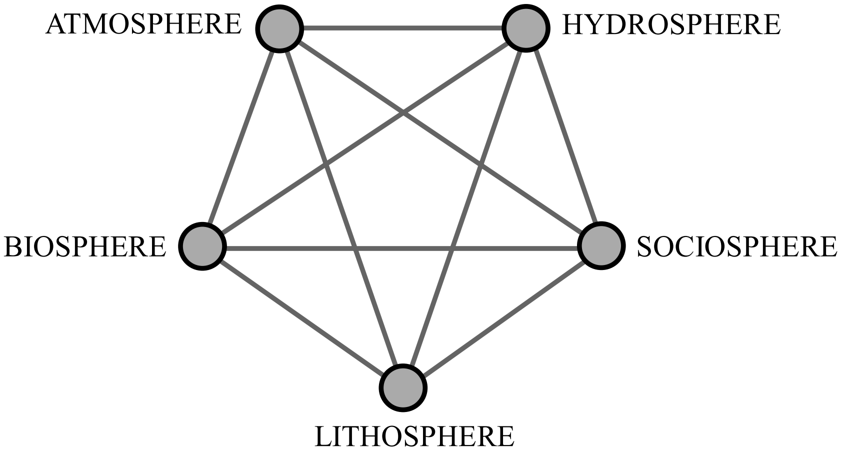

Fig. 3.1. Five spheres in mutual interaction.

The atmosphere is the air that surrounds the earth, principally consisting of nitrogen (about 80%) and oxygen (about 20%) plus a few percentages of other gases such as carbon dioxide, water vapor and ozone. The atmosphere is retained around the earth by gravitation that is determined by the mass of the earth. Water is the only matter on earth that can simultaneously exist in the three states of aggregation, solid, fluid and gas, because we can have ice, water and water vapor at the same temperature on earth. Furthermore, water is an enormous heat reservoir, thereby balancing local temperature variations on earth. The lithosphere is the solid bed-rock with all its minerals and salts. Through erosion, these matters are dissolved and are then important nutritive salts in the water. The biosphere consists of all living organisms on earth, and the sociosphere consists of all the systems ruled by man. Plants and animals consequently belong to the biosphere, and buildings and machines belong to the sociosphere. Only so-called primitive people and their tools belong to the biosphere. All these spheres influence each other. An example of this is the oxygen of the air, sediment, fossil energy deposits, and the DDT content in the biosphere. Figure 3.1 illustrates this influence as lines between the spheres. The communication between them is carried on by means of exergy. Exergy is consumed in the constant flows of energy and matter that go on within and in between these spheres. The driving source for the whole system is exergy that is pumped into it from outside. This process is illustrated by a schematic diagram in Fig. 3.2.

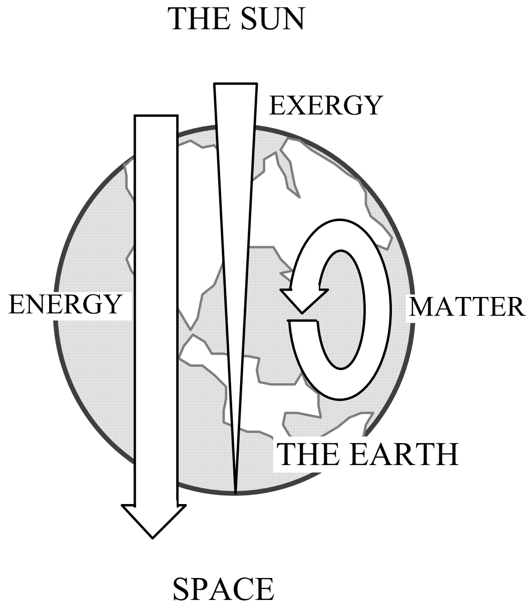

Figure 3.2. Flows of energy and matter on earth are driven by the contrast between the sun and space.

Exergy from the contrast between the sun and space drives flows of energy and matter through the spheres on the earth’s surface. We see in Fig. 3.2 that there is a balance between the inflow and the outflow of energy. The average temperature on the earth’s surface is determined by, among other things, the amount of energy that radiates towards the earth. Matter is transported via countless cycles through systems on earth. The circulation periods for these cycles of matter can vary from splits of seconds to billions of years. Examples of parts of such cycles can be nerve impulses in a cell and mining in a human society.

When exergy reaches the earth, it is gradually destroyed, but on the way it manages to drive, among other things, the water/wind system, and life on earth. Merely the water circulation in the hydrosphere takes about 7000 times the energy which is converted in the sociosphere by man {33}. Complex structures, rich in energy and capable of reproduction, are formed by photosynthesis in the biosphere. The green plants pick up exergy from sunlight by photosynthesis, and convert it into chemical exergy in materials, which then pass through different food-chains. At every link, exergy is consumed. The last link represents micro organisms, which decompose the materials. The exergy that cannot be utilized by these organisms forms peat instead, that gradually becomes stores of oil or coal. Stores in the form of living and dead organic matter on earth thus represent different forms of stored exergy.

The energy balance of the earth and the related exergy consumption can be illustrated by means of Fig. 3.3:

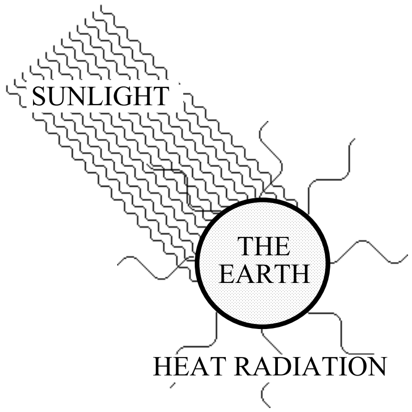

Figure 3.3. Short-wave sunlight inwards and long-wave heat radiation outwards.

Energy-rich sunlight reaches the earth. A lot of it is reflected directly, and therefore it does not join in the conversion processes on the earth's surface. In Fig. 3.3, this part of the process was omitted and the inflowing sunlight is thus the net flow of sunlight reaching the earth. The energy of this flow is converted on earth, and thereafter it leaves the earth as heat radiation. The exergy of the sunlight is, however, consumed on earth. Figure 3.3 illustrates this process as a change of the wave-length between the inflowing sunlight and the outgoing heat radiation. The inflowing solar radiation is relatively short-wave and therefore has a high quality. The out flowing heat radiation is, however, long-wave and consequently of low quality. The whole of the earth can thus be seen as an immense machine picking up exergy from the sun. Due to this, all flows of energy and matter are carried forward through systems on the earth's surface, and life can be created and maintained. The motive force is always the difference in quality between visible sunlight and outgoing invisible heat radiation.

In order to steer a process, e.g. a metabolic process in a living organism, along a definite direction, a thermodynamic **irreversibility** is needed. An increase in security can be obtained through an increase in irreversibility. This is obtained at the cost of an increased energy dissipation, i.e. an increased *exergy consumption*. The steering of a process in a definite direction must, therefore, use exergy. Processes of life and thermodynamics have been studied by Glansdorff and Prigogine {34} and Eigen {35}.

In H.T. Odum's diagramatic description of ecological systems {13}, energy plays a fundamental role, which would probably be better played by exergy.

Metabolic processes in living organisms and eco-systems have analogous counterparts in human societies. Experience in describing natural systems ought to be of great help in describing human societies {36}.

3.2. Exergy of natural resources

By using the exergy concept, we can describe various types of resources used in a society in terms of a common physical unit.

The so-called **energy resources** have exergy contents that are very close to the energy values often given. Either they are of a mechanical form (hydro-power, wind power) which, by definition, is 100 percent useful work, or they are of a high-grade chemical form, for which the commonly accounted enthalpy is rather close to the exergy value {30}. In conversion through heat, we lose a large fraction of the exergy, see Section 3.4. One way to overcome this difficulty is to develop fuel cells that can convert chemical exergy directly into electricity.

In ascribing a definite exergy value to nuclear fuels, several difficulties arise, such as neutrino radiation and the lack of a well-defined final state.

But there are also resources other than the energy resources that have exergy. A concentrated metal ore contrasts against the normal chemical composition of the background. The exergy due to this contrast is retained when the ore is mined. When the ore is enriched and reduced to metal, the exergy of the material is increased, the added exergy coming from fuels and reducing agents used in the process, see Appendix B. The exergy is not destroyed until the metal products made from the metal piece in question are rusting or being dispersed {38}.

Minerals that are very common in the earth’s crust or in seawater - such as sand, salt or water - have little exergy, and they are also generally less of a resource problem. In an arid zone, however, water can be a precious resource, but in that particular local reference environment it also carries a lot of exergy.

Biological materials have exergy in two forms - chemical and structural of which the chemical exergy dominates quantitatively. When a fuel is burnt, the chemical energy is transformed into heat, whereby, depending upon the flame temperature, more or less of the exergy is destroyed.

The structural exergy lies in the low entropy (“improbable”) shapes that living matter takes. We utilize these when using wood as a construction material, or wool as a fiber. When using biological matter as food, we use both the chemical exergy (as fuel for the metabolism) and the exergy of the micro-structure of amino acids and vitamins (for building the body and substituting worn-out cells). After a biological material has been used as structural material, almost all of the exergy is left and can be exploited as a chemical exergy source, e.g. fuel.

The interesting point of the above discussion is that all kinds of natural resources evidently can be accounted for in the common entity, exergy, which is an expression for both the ability to perform work and the structure of information in the system. What it measures is the **alternative physical work** that would be required if all inputs to the process instead - with total reversibility - were taken from the standard reference environment.

3.3. World trade and exergy flows

International trade can be seen as a resource flow, measurable in terms of exergy. Exergy analysis might throw some new light on international trade by providing information which is complementary to the monetary data mostly used.

An interesting point is that the exergy requirement for the production of a given product differs from place to place, depending on the differing reference environments. This is one of the reasons for trade. An analysis of this would help in finding to what extent trade is caused by differences in natural resources, in local reference environments or in the structure of production systems.

3.4. Difference between energy and exergy descriptions

The exergy concept is today primarily used within the steam power engineering, where energy forms of different qualities are dealt with. Many of the energy forms from Table 2.1 are represented. It is shown here that for hot steam, district heating and waste heat the quality index, i.e. the exergy in relation to the energy content, becomes lower and lower. This must be taken into account by those engineers who work with these different energy forms.

Let us make a closer study of how a power plant works. The upper part of Fig. 3.4 below is an outline of a power plant, in this case a condensing power plant, where the combustion of oil or coal takes place. It could also illustrate a nuclear power plant, where uranium is used instead for creating heat. The heat produced is used to boil water under high pressure in a large boiler, in principle a large pressure-cooker (steam production unit). The steam is lead to a turbine, where the steam pressure is converted into rotation of the turbine shaft. At the other end of the shaft, an electric generator is located, producing electricity. The electricity is then distributed to the consumer to be further converted.

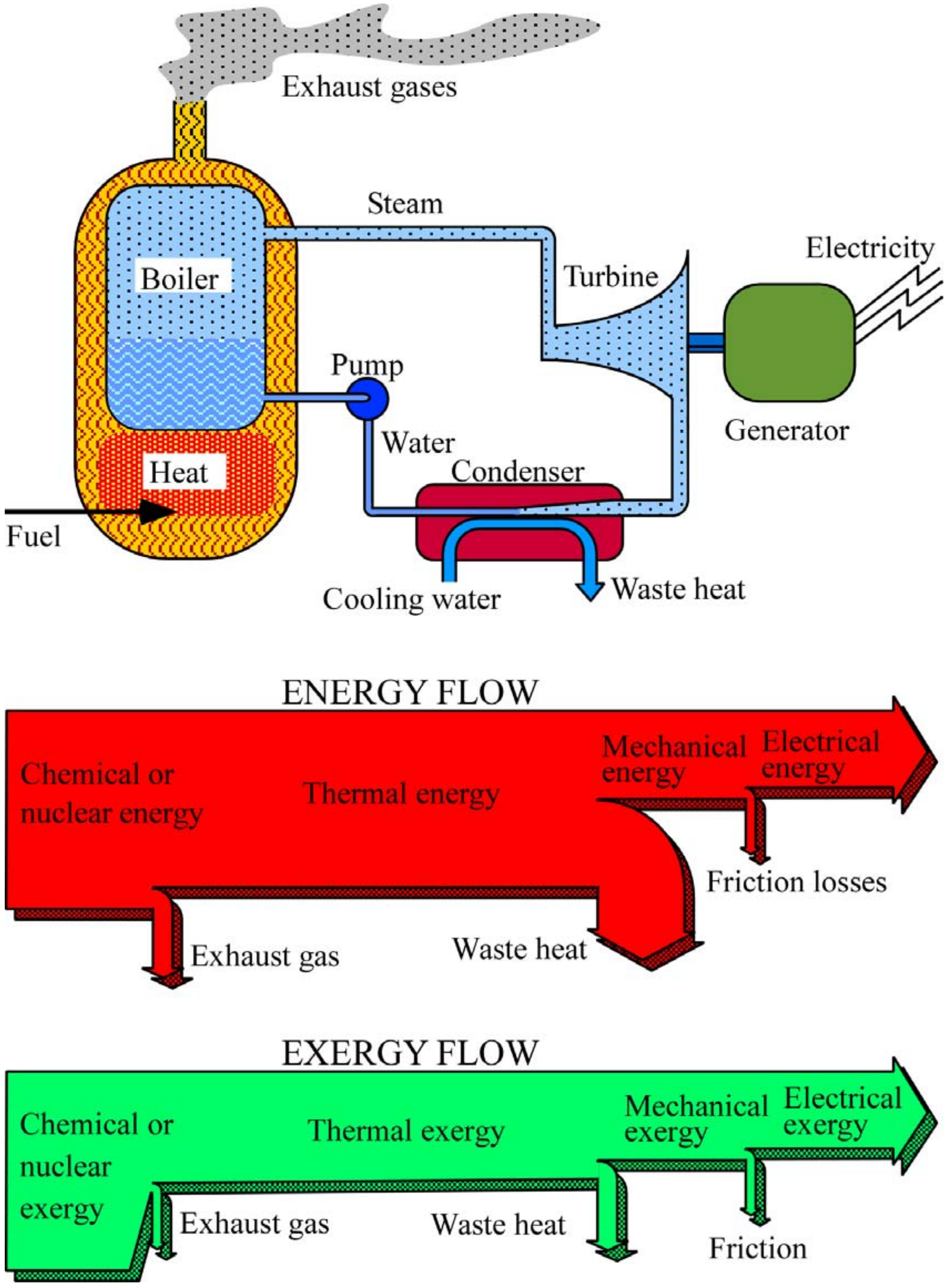

Fig. 3.4. The energy- and exergy flow through a condensing power plant.

When the steam passed through the turbine it transmitted exergy to the electric generator. After the turbine, the steam is chilled in a condenser to water, and brought back to the boiler. This cooling is necessary to optimize the power transmission in the turbine, since the turbine can work with maximal difference in pressure when the steam is condensed immediately after passing through it.

The chemical energy in oil and coal, or the nuclear energy in uranium, is thus transformed into electrical energy, but not without losses. The losses are great in an oil condensing power plant, no less than about 60%, and in a nuclear power plant they are no less than about 70%. Counting the total system, from the preparation of the energy raw material to the finishing treatment of the waste products, there are even greater losses. This is dealt with in exergy analysis in Section 3.9 below. Let us now see what happens to the losses in the power plant itself.

In the bottom part of Fig. 3.4 there are two diagrams of flows, so-called Sankey-diagrams. In the top diagram, the width of the flow is proportional to the energy content for the respective energy form, in the bottom diagram; the width is proportional to the exergy content. The first thing we notice is that the widths of the inflows and outflows in the two diagrams are almost equal. This is due to the fact that both the inflows and the outflows are very high quality energy forms. The quality indexes for the energy forms in question lie between 90% and 100%. For electrical energy the exergy content is as large as the energy content. The losses in the two diagrams are, however, quite different. At first we have losses in the furnace. The fuel is here converted into heat. In an oil or coal fueled power plant we get a flame temperature of about two thousand degrees (°C). In a nuclear power plant the temperature is instead a few hundred degrees (°C). The heat is then transmitted through heat exchangers to boiling water. The pressure is high, with the result that the water does not boil until it reaches a temperature of a few hundred degrees. Through the walls of the furnace, and through pipes, heat is transmitted to the environment, where it is lost. Heat is also led out with the exhaust gases, to keep the chimney of an oil and coal power plant free from condensed water. These furnace losses represent only a small percentage of the total energy conversion. We see, however, from the exergy diagram that something drastic happens. At this point, more than one third of the exergy is lost. We also see that it is lost in the process itself, i.e. only a very small part of the lost exergy leaves the power plant. The exergy flow just becomes narrower. Large quantities of entropy are created. This is due to the fact that the steam that leaves the boiler has a lower temperature and pressure than should be physically possible. The reason for this is limitations in the fatigue strength of the components included in the process, principally in the boiler and the turbine blades. In a nuclear power plant, more than half the exergy is lost at this stage of the process.

The width of the flows of thermal energy and thermal exergy as hot steam in Fig. 3.4, show the greatest difference between energy and exergy flow. This is also a completely different view of how the losses in the process arise. In a diagram of energy flows, the losses are heaviest in the condenser. A great deal of the energy is lost in the condenser through waste heat in the cooling water. Waste heat is, however, heat at a very low temperature and therefore energy of a very low quality. This is clearly shown in the exergy diagram. The exergy content of the waste heat is just a small percentage of the energy content. To make it clearer we can picture the following process. Let us suppose that we convert the thermal energy in the waste heat into mechanical energy by an ideal process. From the waste heat, we would then only be able to convert that part of the energy content that corresponds to mechanical work, i.e. the exergy content. At such a conversion process the loss would be waste heat at the same temperature as the environment, i.e. with the exergy content equal to zero. It is by no means possible to attain more mechanical or electrical energy out of the thermal energy than what is determined by the thermal exergy.

When changing from mechanical energy to electrical energy, both with an exergy content of 100%, small losses arise through friction. These losses are on the whole equally small in both diagrams. Part of the friction losses consists of mechanical fatigue, i.e. wearing out of shafts and bearings.

The conclusion we can draw from the diagrams will thus be that in the diagrams of energy flows, the heaviest losses appear in the condenser but from the exergy flow, the heaviest losses seem to happen already at the combustion in the boiler. We also see from the diagram of exergy flows that these losses in the boiler cannot be extracted. Thus, the exergy is used in the process itself. It is a inevitable “internal loss”, in the process and is dependent on the technical solutions available.

Let us now look at a larger system, the energy conversion in a whole society. For all of the governmental energy reports {2 - 4}, a lot of summaries of statistical data as to the extraction, distribution, and use of energy in Sweden were made. Parts of these were then illustrated by a diagram of flows {2}. Such a diagram is to be found on the front page on some of these reports. It describes the *energy flow* through Swedish society in 1971, see Fig. 3.5. The quality of the energy appears from the denotations of the different kinds of energy. Arrows turned downwards imply losses. Hydro-power is to be found in the top part of the diagram and fuel oil in the bottom part. The width of the flows is in proportion to the energy content in each respective energy form.

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

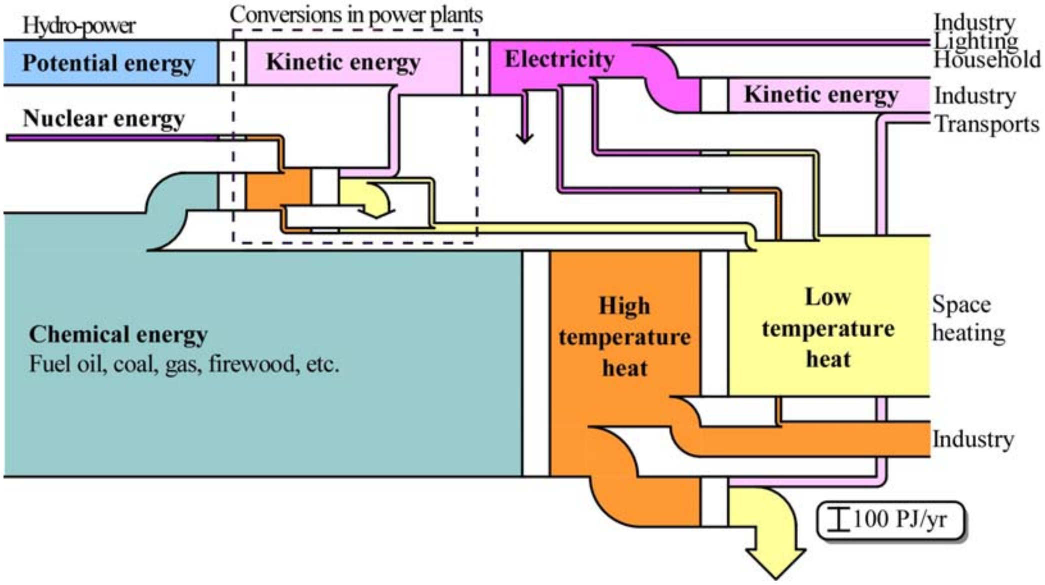

Figure 3.5. Energy conversion system in Swedish society 1971 in energy units.

The conversion of chemical energy into high temperature heat completely dominates the diagram. Oil, coal, gas, waste, and fire-wood are burnt in furnaces in order to produce heat. Most of the high temperature heat is then, via a heat exchanger, converted into low temperature heat that is used for space heating. The heating is further contributed to by district heating and electric heating. Part of the high temperature heat is used in industry, especially within the processing industry (the iron and steel works, and the pulp and paper industry). Within the iron industry, large quantities of coal are used, and within the pulp industry, large quantities of timber waste are used. The rest of the high temperature heat is used for transports. At the conversion of petrol and oil in a car engine, almost 100% of the chemical energy is converted into high temperature heat. About 20% of this heat is then further converted into mechanical energy in the car engine. Nearly half of this energy is then lost through friction in the transmission. This section is, however, not found in the diagram. The efficiency of the transports is represented through the efficiency of the car engine, and is found at the lowest conversion level in the diagram.

We see that the losses in the diagram are unimportant. Within the sector “Conversions in power plants”, we find the energy losses through waste heat from nuclear plants and oil condensing power plants. There are further losses of electrical energy through conductivity losses; about 10% of the transported energy is lost in this way. On the whole about 90 TWh is lost. At a total conversion of about 460 TWh, thus about 20% of the converted energy is lost.

We also see that at each conversion process we have a one to one relation, i.e. as much energy comes in as out of the conversion process. Energy is indestructible, so all energy must remain after a conversion.

We can make a diagram of *exergy flows* that illustrates the same energy system. Roughly it looks as shown in Fig. 3.6. The width of the flows here becomes proportional to the exergy content in each respective energy form. The units of the flows are, however, the same both for the energy and the exergy flow diagrams, i.e. TWh/yr. The difference now is that the width of the flows decreases radically at certain conversion processes, due to the decreasing energy quality and therefore also the decreasing exergy content. At the conversion of chemical exergy into high temperature heat, more than half of the exergy is lost. This is due to the fact that the exergy content of heat is much lower than the energy content.

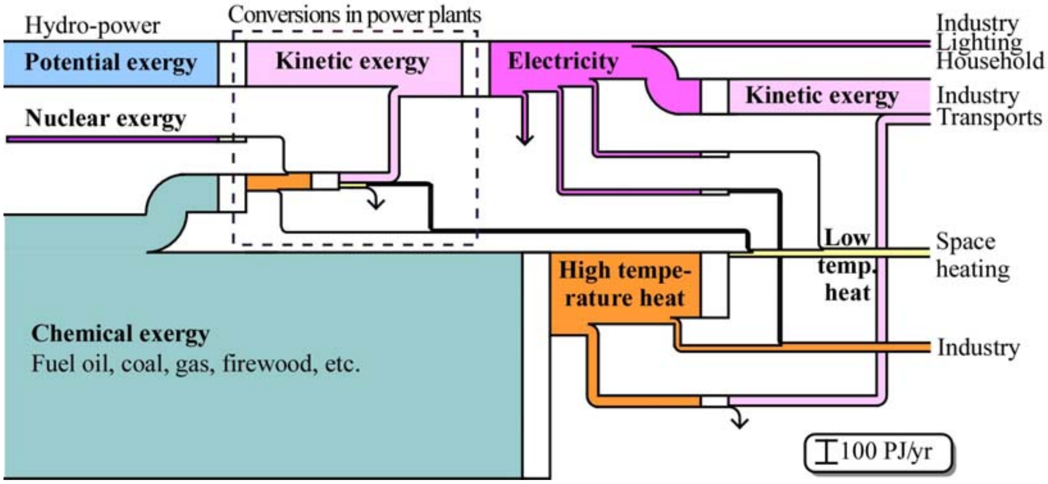

Figure 3.6. Energy conversion system in Swedish society 1971 in exergy units.

Further, there are heavy exergy losses at the conversion of high-temperature heat into low-temperature heat, and also at the conversion of electricity into high or low temperature heat. As the exergy content of the high temperature heat is not utilized at the conversion of high temperature heat into low temperature heat, heavy losses are suffered here too. Consequently, a heat exchanger can not utilize the exergy loss when heat is reduced. The temperature decline in an ordinary oil furnace is thus not utilized when a flame at a temperature of about 2000°C is used to heat water to a temperature of perhaps 80°C. Electrical heat means that 90% of the exergy is lost at the conversion of electrical energy into low temperature heat, i.e. the electrical heat has an exergy efficiency of 10%.

An efficient heat pump (“an inside-out refrigerator”) should be able to improve that efficiency to at least 30%.

It appears - not unexpectedly - that the largest losses of exergy occur in domestic heating. As we can see on the right hand side of Fig. 3.6, the exergy requirements in heating are quite small, and can be decreased even quite a lot further through improvements in insulation and in taking care of the ventilation heat. To decrease exergy losses within heating even further, we can either use a good exergy converter such as the heat pump, or spread-out exergy flows such as solar heating.

The total efficiency of the conversion process, from chemical exergy to mechanical exergy, is the same in both energy and exergy diagrams.

We can see that the losses in the exergy flow diagram are substantial. On the whole, there is a loss of about 320 TWh, i.e. 70% of the converted exergy is lost.

In the exergy diagram, inflows and outflows in exergy conversions do not need to have a one to one relationship. Exergy is not indestructible and it can be consumed.

By using diagrams such as Fig. 3.6 to describe the exergy flows in an energy system, we obtain a clearer idea of where measures should be taken to take care of the energy and exergy better.

3.5. Exergy and other resource measures

Resources are the known and retrievable parts of natural resources, i.e. those substances in ground, water and air which can be utilized. When a resource is used in society, it is often called raw material. By resource measures I mean those measures which are traditionally used to quantify these flows of resources and raw materials.

Resources are traditionally divided into energy resources and other resources. The exergy content of the energy resources is determined by multiplying the energy content with the quality index for the form of energy in question, see Table 2.1. Energy resources are measured in energy units, i.e. the same units as exergy. Other resources are usually measured in units such as weight units, volume units, or just number of units. So, within forestry we speak of m3 of timber, and in agriculture of metric tons of crops or number of animals. These measures are often chosen for purely practical or traditional reasons.

Let us call a resource used in society a commodity. Statistics on commodities are based on the quantity of each commodity. According to international norms, commodities are then divided into commodity groups, commodity subgroups, etc. The statistics are then shown in tables or diagrams in accordance with these commodity norms.

In statistics there is no common physical factor between different commodities, therefore the statistics cannot be shown in integrated form such as a flow diagram of different energy commodities, see Fig. 3.5. The only common measures used today are economic measures such as SEK (Swedish kronor). The disadvantage with such measures is that the economic value of a commodity is determined by costs for production, and supply and demand. The economic value can also be affected by subsidies and taxes on certain commodities. This means, in this case, that the value of a commodity can change even though the commodity itself has not changed in physical respect. To avoid such problems, the value of a commodity must be determined purely by the physical properties of that commodity.

It is natural to choose the exergy concept as a measure of the physical value of a commodity. Exergy is, by definition, a measure of the "physical value" of a system, in relation to its environment. In practice, the exergy content of a commodity can be calculated through multiplying the amount of the commodity by a so called quality factor, which is determined partly by the quality of the commodity, partly by the environment of the commodity. The unit for such a quality factor will then be, for example, kWh per ton, or kWh per m2. The exergy content for the Swedish iron ore conversion in 1975 is calculated in Appendix B. You will find the results of this calculation in Fig. 3.9. The unit of all the flows is TWh per year, i.e. the same unit as in the energy and exergy diagrams in Figs. 3.5 and 3.6. We also see that the losses are great. Approximately 47 TWh of energy, electricity and ore is needed to produce the amount of iron and ore in question, about 7 TWh. The efficiency is thus about 15%. There will be more about this in Section 3.8, which concerns efficiency concepts.

Thus a change to quantifying flows of material by exergy only means determining the conversion factors for each material. This can constitute the first part of an expanded resource budgeting, as well as a link in an integration with the traditional energy budgeting, which I mentioned in the second part of the preceding section. One advantage with a change to measuring resources and raw materials in exergy units is that energy resources and energy raw materials will have the same units as other resources and raw materials. A division into energy resources and other resources and raw materials can often be very approximate. We can, for example, regard oil as an energy raw material and wood as another material, but the distinction is not very meaningful, since oil can also be used for production of materials just as wood can be used as fuel. Therefore, these resources ought to be considered together, in which case the concept of exergy would be a useful resource measure. This is illustrated in the diagram of the Swedish exergy conversion in Fig. 3.9.

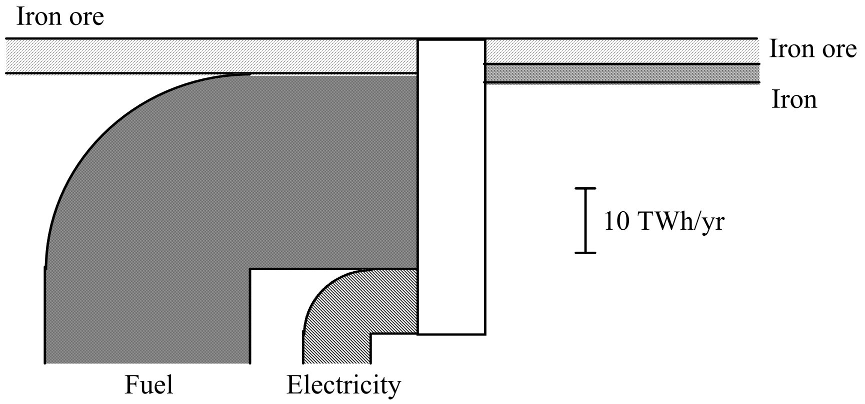

Figure 3.7. The Swedish iron ore conversion in exergy units in 1975

The concept of exergy can only show the physical quality of a commodity. The properties which are interesting in this context are then concentration, chemical composition and amount of the commodity. However, the exergy content says nothing of the physical or biological properties of a commodity, e.g. electric conductivity, nutritive value, toxicity or such properties. Commodities are only considered as carriers of exergy. However, let us assume that we are studying a specific property, for example the electric conductivity, of different materials. Then the efficiency of the exergy conversion can be a measure of the quality of the material. A material with poor electric conductivity will have greater exergy losses than a material with good electric conductivity when used as a conductor of electricity. In Chapter 4, I will discuss the efficiency of the transfer of information between different systems in terms of exergy per information unit.

3.6. Flows, deposits and funds

Energy and material resources occur partly as flows, partly as stocks. We interpret the continuously flowing solar energy and flows of water such as rivers as **flows**. A flow has a limited capacity, but is unlimited in time. An ecosystem, such as a forest, is a valuable stock. It is constructed out of flows of sunlight, water, carbon dioxide and minerals. This gives rise to a flow of newly formed biological matter, and a part of this can be taken out of the system without causing the destruction of the stock. Other stocks, e.g. an oil deposit, have completely different properties. These can give rise to a flow only while they are successively drained and emptied.

As to stocks, we therefore differ between *dead stocks*, or **deposits**, and *live stocks*, or **funds**. A deposit is a stock which is emptied as it is used, e.g. an oil find or a mineral ore. A fund or a live stock is *a stock which, without being used up, converts one resource flow into another in a desirable manner* {10}. I.e. a fund is an exergy converting system. For a hunting and gathering culture, the forest is a fund which uses small part of the incoming flow of sunlight to return flows of edible or in other ways useful plants, and animals which can be caught or hunted. For a farming culture, the cultivated land represents a similar fund, which gives a substantially greater return, but, contrary to the forest, needs to be continuously re-cultivated. The global system, created by the earth's atmosphere and hydrosphere, is a fund which catches and transfers solar exergy. This live stock distributes the temperature more evenly over the earth. It also distributes the water, and it has a protecting and purifying ability. Thereby it provides the basis for another fund, the biosphere, to convert the flow of sunlight into exergy rich biological matter.

Some live stocks can give a continuous return, e.g. a hydro-electric power plant. Others periodically, e.g. yearly, build up deposits which can be harvested, e.g. a field. For some funds this period of build-up can be quite long, e.g. a forest.

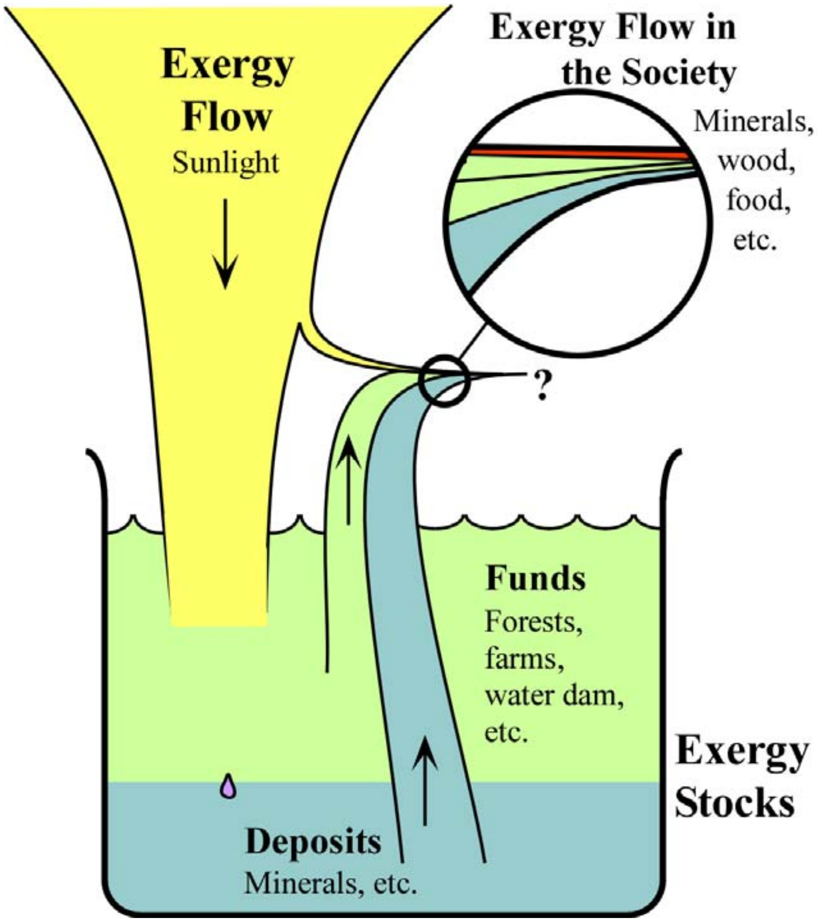

Figure 3.8. The exergy flow from the sun and the exergy stocks on earth create the resource base for human societies on earth.

The deposits of oil and coal are added to so slowly that this is hardly of any practical interest. Peat bogs also grow very slowly, but still fast enough for the ground to be considered of interest as a fund for taking care of solar exergy. Metal ores are created by geological processes. Lake and bog iron, however, are deposited at such a rate so that the same lake can sometimes be "harvested" again in less than a century.

In Fig. 3.8, we see how the exergy flow through human society is maintained. 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, for solar heating. In society there is thus, on the whole, a continuous exergy loss. Some exergy flows, such as flows of ores, increase their exergy content when passing through society. However, other flows decrease their exergy content all the more. Let us have a closer look at the exergy conversion in the Swedish society.

3.7. Exergy conversion in Swedish society

A diagram of exergy flows can be constructed over the total conversion of energy and material which takes place in the Swedish society during one year. This will look like the diagram in Fig. 3.9.

We recognize the lower part of this diagram as the one on exergy flows in Fig. 3.6. Here we find the "inflows" of chemical exergy, nuclear exergy and hydro-electric power. Now we see the conversion of these flows in society much clearer than before.

The new flows in the diagram derive from exergy that we traditionally consider as pure materials (except solar heat) separate from the energy conversion in society. One of these is harvested forest, i.e. the amount of forest that we cut down in one year. Harvested crops are the amount of plant material produced on our cultivated land during one year. We mine ores from the ground as material. This is because the ores contain iron, a metal which is important to us. Another addition is solar heat, i.e. that part of the solar exergy which we use for domestic heating during the heating season.

We have obtained the figures for this diagram in the statistics available principally from The Central Bureau of Statistics (SCB) {39}. In addition to this, there are some approximations and evaluations since there are seldom enough figures on the quality of energy and material forms. Due to this, the inaccuracy in some flows can be up to 5 TWh/yr. This concerns in particular the flows of crops and heat.

Let us now have a closer look at the flows in Fig. 3.9. At the top we have an inflow of sunlight. This flow is estimated as 3 TWh/yr on the basis of figures on how much of domestic heating is covered by so-called passive solar heat. A south window admits about 2 kWh/m^2 per day during the heating season in Stockholm. (A south window can be made to act as a small heating element by suitable control of the window shutters. {40}.) An active use of solar heat could in the future cover heating requirements completely. The main problem today is how the heat could be stored. The sun shines least when we need it the most, and vice versa. The inflow of solar heat in the Swedish exergy conversion is the only inflow which comes directly from the exergy flow of sunlight towards the earth, see Fig. 3.8. Sunlight is naturally the basis for all inflows, except for the inflow of ores and nuclear fuels. This is because all these inflows consist of solar exergy which has been stored from hundreds of millions of years as oil and coal to a few months as crops and hydro-electric power.

The topmost actual conversion in the diagram concerns the forest industry. The stock of forest, a fund, is harvested each year and the timber is used either as timber raw material or converted into paper pulp and paper. At the conversion of timber into pulp, large amounts of heat are used to boil wood chips in the processing of paper pulp. This heat is produced by burning effluence (liquors) and fuel oil. (In principle, the conversion of timber into paper pulp could be done together with an exchange of heat {41}). Approximately 70 TWh of effluence and fuel oil is converted into less than 15 TWh of heat. Together with 53 TWh of timber and 15 TWh of electricity this makes about 50 TWh of wood, pulp and small amount of paper. The efficiency of the conversion for the whole of the forest industry is then about 36%.

The next conversion process in the diagram shows agriculture and the food industry. Harvested crops are converted into food with the aid of fuels and electricity. The food consists partly of vegetable products such as vegetables and bread, partly of animal products such as milk and meat. The exergy flow of food is based on how much food Swedes eat in one year (2 700 Kcal per person and day makes about 9 TWh/year). This means that the food which is thrown away is not included in the food flow, but is represented as a loss in food processing. Some estimations imply that 25 - 30% of the food that leaves the shops is thrown away. Large parts of the losses in agriculture are also inevitable since the some crops are not edible to humans, such as straw. Regrettably the use of straw in animal production has decreased considerably the last few years. This depends to a large part on the shift in the consumption of animal products from milk and butter to pork and poultry. Due to this, the efficiency of the conversion process within food production is quite low, only about 9%. Also, the exergy content of the agricultural produce is lower than the exergy content of the inputs such as fertilizers, machine wear, and fuels {43}. About a third of the inputs of fuel and electricity in food production is used in the food processing industry.

Hydro-electric power is the next conversion process in the diagram. The losses at the conversion into electricity are relatively small. This is because the potential energy stored in the water reservoir and the electrical energy produced is both energy forms of high quality and are easy to convert into each other. There are some losses of electricity due to conductivity losses during transport. This is shown in the diagram as a narrowing of the exergy flow of electricity. I discussed the use of electricity in connection with Fig. 3.6.

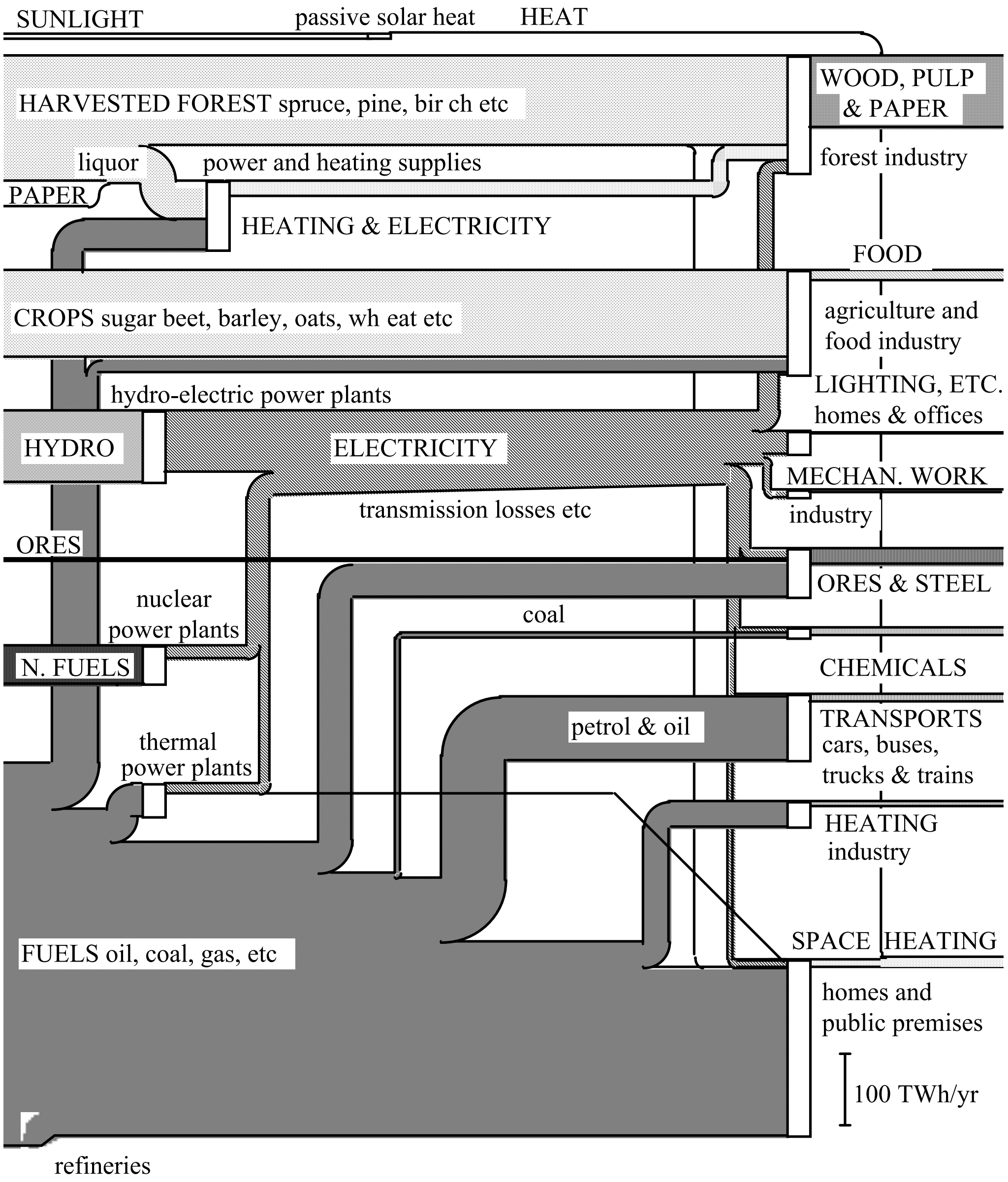

Figure 3.9. Conversion of energy and matter in Swedish society in 1975 in exergy units. (Total exergy conversion 662 TWh)

In Section 3.5 and Appendix B, I made a summary of the Swedish iron ore conversion process. We see this conversion process in its context in the diagram in Fig. 3.9.

As we see in the diagram, the chemical industry converts fuels and electricity. Two thirds of the converted “fuels” can be found in the end products such as rubber, plastics and fertilizers. The chemical industry is hereby a direct example of how a traditional energy raw material such as oil can be used as a material. The “used” material can then be used as energy raw material. This is of course true about some other materials as well, such as wood and paper, though we should first of all strive to re-use material as material, not as energy raw material.

The transport sector has here been given an efficiency of conversion of about 10%, i.e. the approximate efficiency of a car, bus or truck. The transport work thus consists of exergy to overcome the air resistance and to give the vehicle an accelerative force.

The conversion of fuels into heat is divided between industrial and other premises, such as residential premises, shops premises and public premises.

Other natural exergy flows support society through more indirect means. They purify water, air and earth, and store, for example, heavy metals and sulphides. The natural ability to purify air and water could, roughly estimated, mean 0.5 TWh per year in Sweden in terms of exergy, which is too little to be represented in the diagram in Fig. 3.9. However, the same purification would, with industrial methods, cost many times more, both in terms of exergy and economically.

By using diagrams such as Fig. 3.9 to describe resource flows, we obtain a clearer idea of where to put in efforts to make better use of the resources. This should be done at all levels of the resource system.

Another advantage with the diagram in Fig. 3.9 is the division of all inflows into direct flows, flows from funds, and flows from deposits. Thus the inflow of sunlight is a direct flow of exergy from the sun. Then follow the inflows of harvested forest and crops, and hydro-power. All these flows derive from terrestrial funds of exergy. The remaining inflows of ores, nuclear fuel and fuels, come from non-renewable stocks, deposits, on earth.

To maintain a society with respect to the exergy conversion for longer periods of time, that society's exergy requirements must be almost completely covered by the solar flow and from the flows of terrestrial funds. As we can see in the diagram on the exergy conversion in the Swedish society in 1975, this is not at all the case. Thus the situation in which we find ourselves now cannot last in the long term.

3.8. Concepts of efficiency

Analogous to the two concepts *energy* and *exergy*, we can define two concepts of efficiency in an energy (and exergy) conversion process,

i) the energy in the desired end product divided by the inputs of energy. This quantity is called the “first law efficiency” in the APS-report {22}. Here it is called **energy efficiency**, and is denoted by η_{en}.

ii) the exergy of the desired end product divided by the inputs of exergy. This quantity is called the “second law efficiency” in the APS-report {22}. Here it is called **exergy efficiency**, and is denoted by η_{ex}.

At conversions of energy between different forms, there are generally some losses of energy. Because the physical environment at energy conversions is often ignored, the energy efficiency can become greater than 1 (i.e. 100%). An example of such a conversion process is the heat pump, which can be found in Fig. 3.10. The heat pump has oceans of “free” energy (with a quality index of 0) to scoop out of its environment. We then speak of a coefficient of performance (COP) instead of efficiency. The exergy efficiency always has to be smaller than one. This is due to the fact that exergy cannot be created; it can only be destroyed or consumed.

The diagrams in Fig. 3.10 illustrate the differences between energy and exergy flows, and thereby efficiency, for 4 conversion systems: an oil furnace, electric heater, an electric heat pump and a combined power and heat plant.

At the top we see the conversion of fuel into heat in an ordinary oil furnace. The energy efficiency is limited to about 85%, principally through losses of smoke. The low value of the exergy efficiency, about 4%, is, however, due to the fact that the fall in temperature when a thousand degree flame heats water to 60°C is not utilized.

As we can see, electric heating has an energy efficiency of 100%. In the diagram for the electric heat pump we see that this is not any top limit of energy efficiency at the conversion of electricity into heat. A heat pump can, of course, also be run with fuels by connecting it to a combustion engine. The heat pump can also in this way take the place of an ordinary furnace for space heating. If the environment is ignored, the conversion of electrical energy or fuels into heat can be well over 100%. We see that in looking at exergy the picture becomes quite different. The exergy efficiency for electric heat is about 5% and for the heat pump 15%.

In Fig. 3.4, the energy and exergy flows through a condensing power plant were compared. Here we saw that the efficiency is the same from both energy and exergy point of view. This is because the inflow of fuels and the outflow of electricity both have a high quality, i.e. a high exergy value. In the diagram of a combined power and heat plant in Fig. 3.10, we see that the exergy efficiency is about the same for a condensing power plant as for a combined power and heat plant. We can understand this better when we see how the exergy losses are distributed in a condensing power plant. The greatest exergy loss occurred at the conversion of fuels into heat in the boiler. Since the conversion is the same in both condensing power plant and combined power and heat plant, the total exergy efficiency will be the same, about 40%. When looking at energy, circumstances are quite different. When the energy efficiency of a heat plant is stated, it is seldom shown that the theoretical maximum energy efficiency is perhaps 300%, not just 100% {4, 5}.

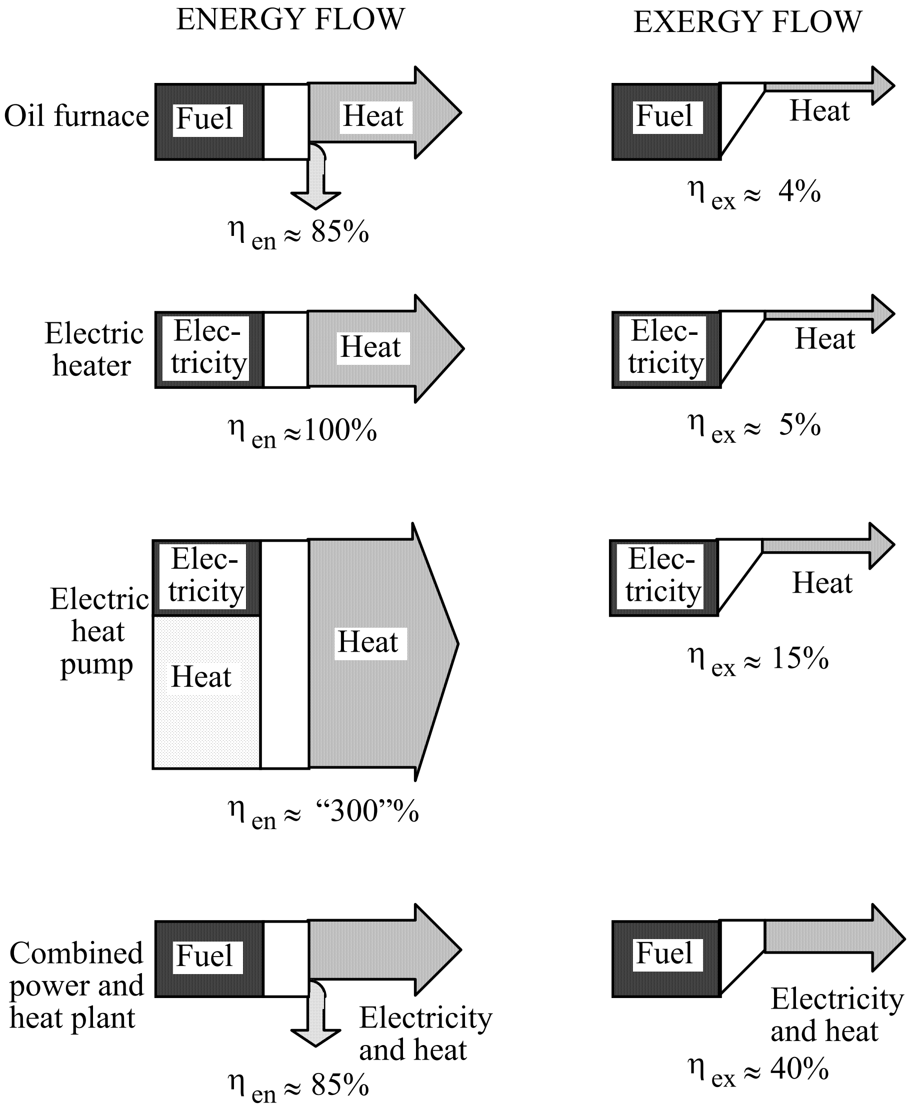

Figure 3.10. Energy and exergy efficiency for an oil furnace, an electric heater, an electric heat pump and a combined power and heat plant.

There are no general efficiency concepts today for material conversions. The natural cause for this is that there is no general resource measure. At analyses of energy in agriculture, efficiency is often given as energy input divided by energy output, i.e. energy efficiency, even though we at first see agricultural products as materials (biological matter). Within forestry, this type of efficiency concept is lacking. Efficiency concepts which are similar to exergy efficiency are used more and more in iron and steel production {45}. The measures most often used are Gibbs or Helmholtz free energy, see Appendix A. Together with information of the standard states of the participant substances, this gives information of the exergy efficiency of the process in question.

In Section 3.5 and in Appendix B, the conversion of Swedish iron ore was discussed very shortly. The total exergy efficiency for the iron and ore conversion was in Section 3.5 stated as 15%. For the iron conversion itself the exergy efficiency is about 6%, see Appendix B.

The concept of exergy efficiency is clearly directly related to the practical use of energy. But, according to the second law of thermodynamics, an exergy efficiency of 100% can only be accomplished at reversible processes which in principal take infinite time. A conversion process which takes place at a rate (exergy per time unit) close to zero must have a gradient other than zero.

The production of entropy and the exergy losses associated with this are discussed in Appendix D. A **maximal exergy efficiency**, $\eta_{\text{max}}(\nu)$, is defined. This depends on the rate (ν) of the conversion process. The nature of this dependency at simple assumptions is shown in Appendix D.

It could also be useful to introduce a **relative exergy efficiency**, η_{rel}, which brings together η_{ex} and $\eta_{\text{max}}(\nu)$ according to (C.7),

$$\eta_{\text{ex}} = \eta_{\text{rel}} \cdot \eta_{\text{max}}(\nu) \tag{9}$$

3.9. Exergy analysis

The exergy content in an end product does not correspond to the exergy which is used in the production. To draw up an exergy budget, it is necessary to take all different inflows of exergy in the process into account {38}. In 1974, a conference {46} was held by the International Federation of Institutes for Advanced Studies (IFIAS) at which this type of budgeting was denoted **energy analysis**, and Gibbs free energy was chosen as a unit of measure. In a progress report from the project group “Energy and Society”, supported by the Secretariat of Futurological Studies, there is an interesting description of energy analysis {47}.

The energy analysis has been criticized from many directions {24}. In energy analysis we often only measure one resource, energy, without taking into consideration other resources which are needed in the conversion process. This is due to the natural limits of the energy concept. By instead choosing exergy as a measure, we partly bypass these problems. However, some general standards must be introduced. This type of budgeting should be called **exergy analysis**.

When we apply exergy analysis to production processes and services, we should not limit the analysis to one specific part of the process, but analyze the process as a whole as well. Exergy analysis should also be applied to various functions in society, such as transports. Exergy analysis should also be useful at an analysis of the whole metabolism of society, as described in Section 3.7. This was partly done when we analyzed chains of resources.

4. Exergy and information

Exergy is a measure of how much a system deviates from its equilibrium with the environment, see Eq. (5). The more a system deviates from equilibrium the more information is needed to describe it and the greater is its capacity for carrying **information** {53}. There is therefore a close connection between exergy and information (or information capacity). This connection is of fundamental importance. It is discussed further in Appendix C. The relation between exergy, E in Joule (J) and information, I in binary units (bits) is

$$E = \mathrm{k}' T_0 I \tag{10}$$

where T_0 is the temperature of the environment measured in Kelvin (K) and where

$$\mathrm{k}' = \mathrm{k}\ln 2 \approx 1.0 \cdot 10^{-23}\ \mathrm{J/K} \qquad (\mathrm{k} = \text{Boltzmann's constant}) \tag{11}$$

is the fundamental constant {21}.

For example, the net flow of information capacity to the earth from the sun is about {21}, see Appendix E, Eq. (E.7),

$$1.2\times10^{17}(1/290 - 1/5800)\ \mathrm{J/Ks} \approx 4.0\times10^{37}\ \mathrm{bits/s} \tag{12}$$

Man only uses a fraction of this, about 5×10^{13} bits/s. Thus the relation between used and available information capacity is about 10^{-24}. The same relation for energy conversion is about 3×10^{-5}. Thus, the unused information flow from the sun is enormous. Some of the explanations for this follow below.

Information has to be stored and transported with the help of methods that are as safe as possible. To attain this, redundant codes are used, and at copying processes dissipation of extra energy is allowed, so as to render the process irreversible (one-way). The quality of the transfer increases with the loss of some of the information capacity.

At everyday communication of information, the energy consumption is quite high. This makes the *exergy per bit* relation high, which means that only a small part of the available information capacity is used. Therefore only a small part of the inflow of information capacity towards the earth is used as mentioned earlier, see Eq. (12). However, if we consider the conversion of solar exergy into the ordered structures of plants, we realize that even though only a small part of the primary inflow of information is captured, parts of percent, this amount is still quite enormous in itself.

It is of interest to compare the efficiency of information transfer between different systems. A measure of efficiency is the amount of exergy converted per bit of information. The dimension of this is temperature. The lower this temperature is, the more efficient is the information transfer. If this temperature is too low, however, thermal fluctuations in the environment can destroy the information, see Table 4.1.

Table 4.1. Efficiency in information transfer expressed in exergy per bit of information and in characteristic temperature

	Exergy per bit [J/bit]	$T_{transfer}$ [K]
Electric typewriter[a]	1	10^{23}
Radio receiver[a]	5×10^{-4}	5×10^{19}
Television[a]	2×10^{-5}	2×10^{18}
Computer memory	10^{-12}	10^{11}
Human speech	10^{-16}	10^{7}
Human ear	10^{-17}	10^{6}
Human eye	5×10^{-18}	5×10^{5}
Protein biosynthesis in a cell[b]	4.6×10^{-21}	460

[a] Data from {21}
[b] Data from {48}

The sensitivity of the retina is such that the human eye functions near the quantum mechanical limit. It is in fact enough with only a few quanta to cause a reaction in the eye. Storage of information in a computer memory has a characteristic temperature of about 10^5 times the temperature for sight. But on the other hand the time resolution, and thus the rate, is about 10^5 times higher than for the eye. The conclusion is that living creatures and computers are each efficient in their use of exergy to receive and transfer information. The biosynthesis in a cell is after all many times more efficient.

Electronic circuits, man’s ear and eye, and protein biosynthesis are drawn in a logarithmic information rate (frequency) - power diagram in Fig. 4.1. The minimum power requirement of integrated circuits has been calculated by many {49-52}. Brillouin {53} has shown that an elementary process in a circuit, such as a measurement, a storage or a logic operation, requires an energy conversion which is large in relation to $kT \approx 4\times10^{-21}$ J (at room temperature). This is necessary to avoid thermal fluctuations which are the cause of noise in electronic circuits, Brownian movement, etc. The room temperature is marked with a straight line. A process must ordinarily be far above this line to avoid serious disruption from thermal fluctuations. The protein biosynthesis {54} is surprisingly close to this critical line. The transfer from messenger RNA to proteins, which uses half of the power requirements, is actually below this line. This is possible because all of 4.3 bits of information are transferred at each transformation. The ear and the eye occupy strikingly large areas in the diagram, covering many orders of magnitude. Electronics is probably the best technology we know today, from an exergy efficient viewpoint. But, as Fig. 4.1 shows, life itself is far more efficient in its use of exergy to construct biological matter.

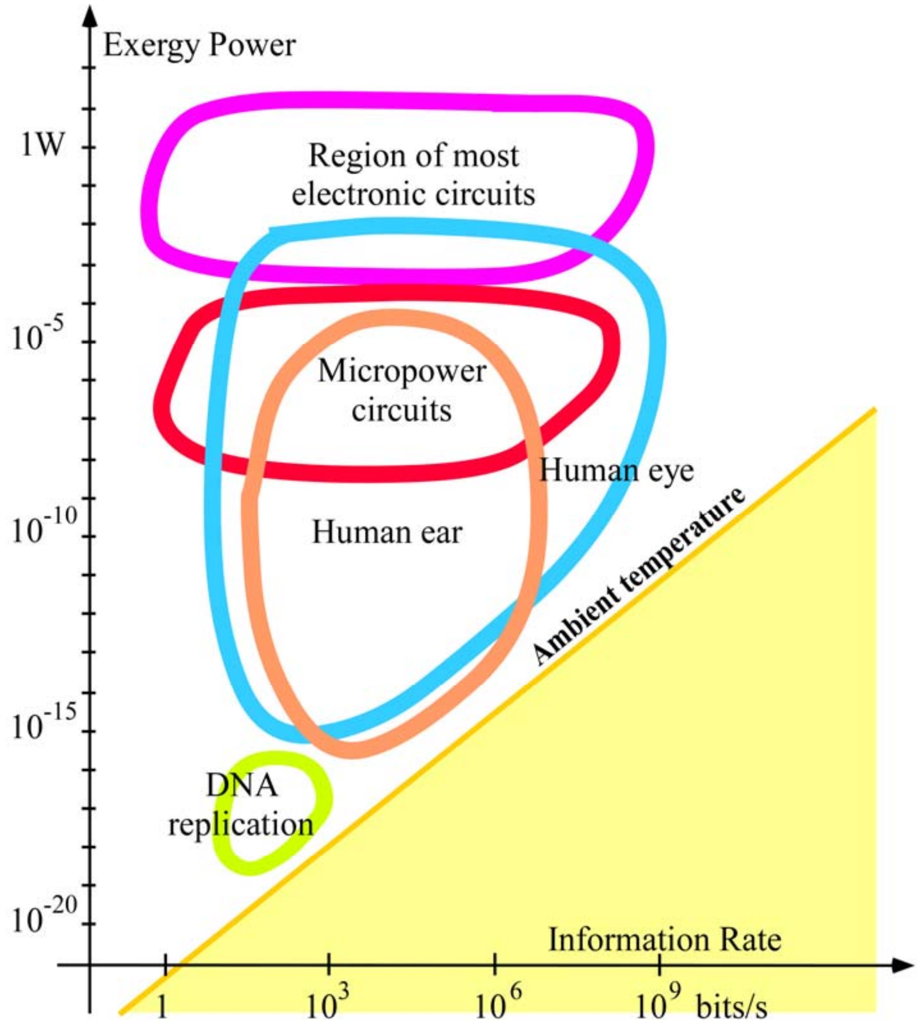

Figure 4.1. Information rate - power diagram of information transfer

Biological structures live by transforming energy from one form to another. The solar exergy is used to build up complicated organic matter. This information is transferred from generation to generation. The information which is stored in the genetic matter (DNA molecule) directs the construction of matter. When biological material, e.g. wood or cellulose, is used as construction material, it is these structures and this information that we benefit from.

Both exergy and information are measures of the deviation from a **reference environment**. The exergy is the maximal amount of work that can be derived from such a deviation, but the work is also needed to maintain and transfer information. The relationship between exergy and information is therefore a very close one.

5. Concluding remarks

All living systems are part of a flow of energy and matter. They receive energy and matter at a low entropy and emit it at a high entropy. Thereby a net inflow of negentropy or exergy is maintained, which keeps the system alive. In living organisms exergy is used to drive metabolic processes and to maintain and develop structures from molecular level and upwards. It is therefore important to understand how exergy is converted. The exergy concept should thus be useful to the geophysical and biological sciences, as well as the technological sciences.

The metabolic processes in society are usually described within economics, but also within other sociological sciences. Even these processes are driven by exergy. It would therefore be natural to relate sociological and economical analyses of a society on an analysis of the exergy conversion in this society.

Exergy is only a physical concept which can be used to describe the reality in which we live. Unclear definitions of concepts and measures can slow down or obstruct a rational tackling of important resource problems. The measure of energy has different meanings in different situations, not least depending on where or by whom it is done. The exergy concept does not provide a solution of the energy and resource problems. The exergy concept is a useful tool in describing the energy and material conversion in society. From technological sources it is often said that the exergy concept is a useless measure since it depends on the environment. In my view, this is on the contrary the value of the exergy concept. The human society must live in harmony with nature; human activity must be adapted to the environment. All utilization of resources and disposal of waste products affect nature. This effect is strongly related to the amount of exergy in the utilized resource or the disposed waste.

Appendix A: Derivation of the exergy concept

Consider a system A in a surrounding system A_0, assumed to be homogeneous and to be large in comparison to A, fig. A.1. The “environment” A_0 can be characterized by its intensive parameters T_0, p_0 and μ_{i0} (temperature, pressure, and chemical potentials). The corresponding parameters for A are T, p and μ_i. (For the moment A is also assumed to be homogeneous.) The extensive parameters for A are U, V, S and n_i ([internal] energy, volume, entropy, and the number of moles of different chemical elements). The extensive parameters for A_0 are accordingly U_0, V_0, S_0 and n_{i0} and are assumed to be large in comparison to the corresponding quantities for A,

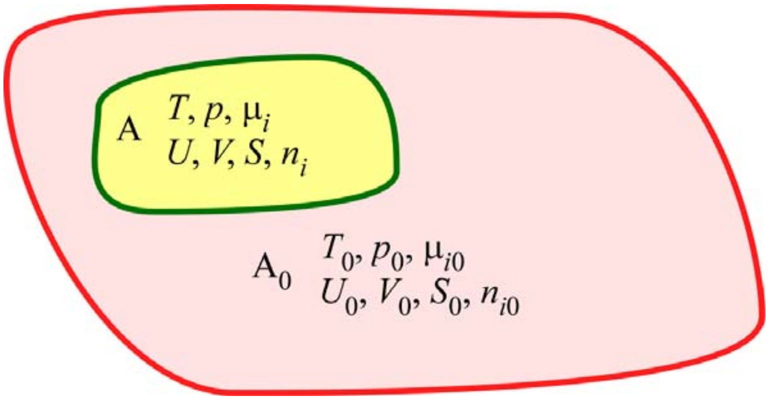

Figure A.1. A system A in an environment A_0.

$$\begin{cases} U << U_0 \\ V << V_0 \\ n_i << n_{i0} \end{cases} \tag{A.1}$$

The combined system $A + A_0$ is assumed to be isolated (no exchange of matter or energy with the surroundings) apart from work W extracted from A,

$$\begin{cases} \mathrm{d}U + \mathrm{d}U_0 + \mathrm{d}W = 0 \\ \mathrm{d}V + \mathrm{d}V_0 = 0 \\ \mathrm{d}n_i + \mathrm{d}n_{i0} = 0 \end{cases} \tag{A.2}$$

Interaction between A and A_0 can take place in a controlled way through the interface of A. Since A is small, Eq. (A.1), this does not change the intensive parameters of A_0,

$$\begin{cases} dT_0 = 0 \\ dp_0 = 0 \\ d\tilde{\mu}_{i0} = 0 \end{cases} \tag{A.3}$$

The entropy differential of the environment A_0 is

$$dS_0 = \frac{1}{T_0}(dU_0 + p_0 dV_0 - \sum_i \mu_{i0} dn_{i0})$$

$$= -\frac{1}{T_0}\left(dU + p_0 dV - \sum_i \mu_{i0} dn_i \right) - \frac{dW}{T_0} \qquad \text{(A.4)}$$

where we have used (A.2). The total entropy differential system *and* environment is

$$dS^{\text{tot}} = dS + dS_0 = -\frac{1}{T_0}\left(dU + p_0 dV - T_0 dS - \sum_i \mu_{i0} dn_i \right) - \frac{dW}{T_0} \qquad \text{(A.5)}$$

This may be written as

$$dS^{\text{tot}} = -\frac{1}{T_0}(dE + dW) \qquad \text{(A.6)}$$

where we have introduced the **exergy** E,

$$E = U + p_0 V - T_0 S - \sum_i \mu_{i0} n_i \qquad \text{(A.7)}$$

If we use the relation

$$U = TS - pV + \sum_i \mu_i n_i \qquad \text{(A.8)}$$

in (A.7) we get

$$E = S(T - T_0) - V(p - p_0) + \sum_i n_i (\mu_i - \mu_{i0}) \qquad \text{(A.9)}$$

which shows that E vanishes at equilibrium (T=T_0, p=p_0, μ_i=μ_{i0}).

Assume now that A evolves towards equilibrium with its environment A_0 without doing any work (dW = 0). The exergy is then changed from E to 0 and the total entropy is changed from S^{tot} to $S^{\text{tot}}_{\text{eq}}$ (eq stands for equilibrium). By integrating (A.6) we then get

$$S_{eq}^{tot} - S^{tot} = -(-E)/T_0$$

and thus

$$E = T_0\left(S_{eq}^{tot} - S^{tot}\right) \tag{A.10}$$

Now defining *negentropy* Σ as

$$\Sigma = S_{eq}^{tot} - S^{tot} \tag{A.11}$$

we then have

$$E = T_0\Sigma \geq 0 \tag{A.12}$$

The exergy of A thus is T_0 multiplied by the *negentropy* for *A and* its environment A_0. We note that in the definition of exergy (A.7) only the intensive parameters of A_0 appear.

During the process through which equilibrium is attained the exergy thus changes by -*E* (from *E* to 0). Let the total entropy increase be ΔS^{tot} and let the total work extracted be *W*. Then the integrated version of (A.6) is

$$\Delta S^{tot} = -\frac{1}{T_0}\left(-E + W\right) \tag{A.13}$$

or

$$W = E - T_0\Delta S^{tot} \tag{A.14}$$

Since

$$\Delta S^{tot} \geq 0 \tag{A.15}$$

with equality only for a reversible process $\Delta S^{tot} = 0$, we have

$$W \leq E \tag{A.16}$$

i.e. *the exergy E is the maximum amount of work that may be extracted from A* in its process of reaching equilibrium with its environment, A_0.

We may subtract from (A.7) the corresponding equation at equilibrium. Since *E* vanishes at equilibrium we then find

$$E = U - U_{\mathrm{eq}} + p_0\left(V - V_{\mathrm{eq}}\right) - T_0\left(S - S_{\mathrm{eq}}\right) - \sum_i \mu_{i0}\left(n_i - n_{i,\mathrm{eq}}\right) \tag{A.17}$$

which is a useful equation for practical determinations of exergy.

In special cases exergy differences are related to differences of other, better known, thermodynamic potentials, as described in Table A.1.

Table A.1.
Relations between differences in exergy and in other thermodynamic potentials.

Case	$\Delta E=\Delta X$	Definition of X	Usually named
$\Delta n_i=0$	$\Delta E=\Delta G_0$	$G_0=U+p_0V-T_0S$	
$\Delta n_i=0,\ \Delta V=0$	$\Delta E=\Delta F_0$	$F_0=U-T_0S$	
$\Delta n_i=0,\ \Delta S=0$	$\Delta E=\Delta H_0$	$H_0=U+p_0V$	
$\Delta n_i=0,\ p=p_0,\ T=T_0$	$\Delta E=\Delta G$	$G=U+pV-TS$	Gibbs free energy
$\Delta n_i=0,\ \Delta V=0,\ T=T_0$	$\Delta E=\Delta F$	$F=U-TS$	Helmholz free energy
$\Delta n_i=0,\ \Delta S=0,\ p=p_0$	$\Delta E=\Delta H$	$H = U+pV$	Enthalpy

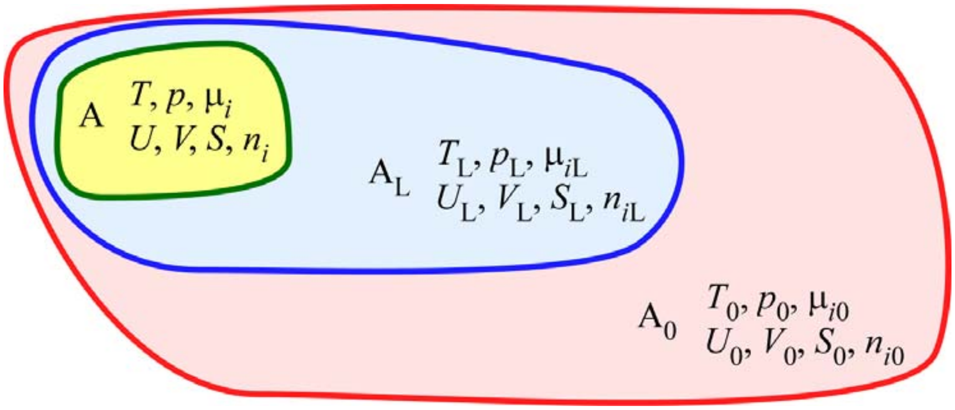

Figure A.2. System A in a local environment A_L in an environment A_0.

It may be of interest to consider the case of a system A in a local environment A_L which in its turn is included in a global environment A_0 (Fig. A.2). We may then define a *"local" exergy*.

$$E_{\mathrm{L}} = U + p_{\mathrm{L}}V - T_{\mathrm{L}}S - \sum_i \mu_{i\mathrm{L}} n_i \tag{A.18}$$

which is related to the *"global" exergy*

$$E = U + p_0V - T_0S - \sum_i \mu_{i0} n_i \tag{A.19}$$

through

$$E = E_{\mathrm{L}0} + E_{\mathrm{L}} \tag{A.20}$$

where $E_{\mathrm{L}0}$ gives the contribution of exergy due to the deviation of the local environment from the global one,

$$E_{\mathrm{L}0} = S(T_{\mathrm{L}} - T_0) - V(p_{\mathrm{L}} - p_0) + \sum_i n_i(\mu_{i\mathrm{L}} - \mu_{i0}) \tag{A.21}$$

which is the exergy expression (A.9) for A with the intensive parameters of A_{L} replacing those of A. However $E_{\mathrm{L}0}$ is not an exergy function. For instance it is clearly not positive definite.

The exergy or negentropy may be said to be a measure of the *contrast* of a system against an average “gray” background, see Eqs. (A.9) and (A.12). It is therefore natural that these concepts are closely tied to information theory, see Appendix C.

Appendix B: Exergy content of materials

Assume that the temperature T and the pressure p are constant i.e. $T=T_0$ and $p=p_0$, then according to Eq. (A.9) we have

$$E = \sum_i n_i(\mu_i - \mu_{i0}) \tag{B.1}$$

From chemistry we have that the chemical potential μ_i for an element i may be written as

$$\mu_i = \mu_i^0 + \mathrm{R}T_0 \ln a_i \tag{B.2}$$

where a_i is the activity for the element i and μ_i^0, is the chemical potential for the element relative to its *reference state*.

Further we have

$$a_i \propto c_i \tag{B.3}$$

where c_i is the concentration of the element i. From (B.2) and (B.3) we may write (B.1) as

$$E = \sum_i n_i(\mu_i^0 - \mu_{i0}^0) + \mathrm{R}T_0 \sum_i n_i \ln \frac{c_i}{c_{i0}} \tag{B.4}$$

The exergy of a material may thus be calculated from its chemical potential and from its concentration in its actual state and in its reference state. This is illustrated in an example from the Swedish iron production in 1975. This illustration is to be regarded as a simple example of the use of the exergy concept within resource accounting.

If we only consider one element we may instead write Eq. (B.4) as

$$E = n\left[\mu^0 - \mu_0^0 + \mathrm{R}T_0 \ln \frac{c}{c_0}\right] \tag{B.5}$$

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. We then have c=60%.

Now suppose that the bed-rock represents a standard environment and that its iron atoms are in their (energetically) lowest ionization state, i.e. Fe^{2+}- ions, then we have c_0=5% and the difference in chemical potential becomes 50 kJ/mole {56}.

With T_0=15°C, the exergy content of magnetite iron ore with 60% iron becomes 56 kJ/mole ore 170 kWh/ton.

In an analogous way we find that the exergy content of pure iron becomes 92 kJ/mole or 460 kWh/ton.

The Swedish production of iron ore was in 1975 approximately 36 Mtons. (Estimated on the basis the production in 1974.) 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 6.1 TWh.

The production of iron was in 1975 roughly 6 Mtons, representing an approximate quantity of 2.7 TWh. To produce this iron about 10 Mtons of ore was needed, corresponding to 1.7 TWh together with 10 TWh of electrical exergy and 30 TWh of coal, coke and other fuels. The exergy efficiency in the iron production process then becomes η_{ex}=6%. Figure 3.7 illustrates the situation.

Appendix C: Efficiency concepts at conversions of exergy

A conversion process taking place at a non-zero rate v (exergy per unit of time) must be driven by a non-zero gradient g. For many applications it is probably sufficient to assume *linearity*, as in Eq. (E.2),

$$v = \varepsilon g \tag{C.1}$$

where ε is a constant independent of g.

The *entropy production per unit of time* connected with such a conversion process is quadratic with respect to v (compare Eq. (E.4))

$$\frac{\mathrm{d}S}{\mathrm{d}T} = \chi v^2 \tag{C.2}$$

where χ does not depend on v. If several ways are possible for the conversion process to occur from the initial to the final form of energy then let χ_0 assign the lowest possible value of χ for the conversion process being studied. Then we have a *minimum entropy production per unit time*

$$\left(\frac{\mathrm{d}S}{\mathrm{d}T}\right)_{\min}(v) = \chi_0 v^2 \tag{C.3}$$

and hence a *minimum exergy destruction per unit time* $T_0\left(\mathrm{d}S/\mathrm{d}t\right)_{\min}(v)$ where T_0 is the environmental temperature. Thus, the maximum amount that can go into desired outputs (exergy per unit time) is

$$v - T_0 \chi_0 v^2 \tag{C.4}$$

we are thus led to define

iii) *the maximal exergy efficiency related to the conversion rate v* as

$$\eta_{\max}(v) = 1 - \left(v/v_0\right) \tag{C.5}$$

where

$$v_0 = 1/\left(T_0 \chi_0\right) \tag{C.6}$$

is the *characteristic power* connected to the conversion process.

iv) We can also connect (ii) and (iii) and define a *relative exergy efficiency* η_{rel} for a non-zero rate conversion process

$$\eta_{\text{ex}} = \eta_{\text{rel}}\ \eta_{\max}(v) \tag{C.7}$$

Appendix D: Exergy and information

Thermodynamics deals with the physical laws of systems containing many particles. From a *macroscopic* point of view the systems are small (approximately 10^{-21} m^3), but from a *microscopic* point of view they are large (10^{-21} m^3 contains approximately 10^9 atoms). Thus, it is impossible to have a detailed knowledge of the motion of individual particles. In *statistical mechanics*, which provides the theoretical basis for the understanding of thermodynamics, we take advantage of the large number of particles and use statistical methods to describe macroscopic properties as average properties resulting from the motion and interaction of many particles.

Information theory deals with a system of incomplete information {57}. The general problem of how to take into account, in an unambiguous way, the available (incomplete) information was successfully tackled by Jaynes {58}. As Jaynes showed, statistical mechanics is a special instance of information theory. Conversely, powerful concepts and methods developed in statistical mechanics may be extended to other fields through information theory.

Let the system being described consist of *N* particles. The number of possible states **Ω** depends exponentially on *N*. Let the **probability** for the *j*th state be realized by P_j,

$$\sum_{j=1}^{\Omega} P_j = 1 \tag{D.1}$$

The **entropy** is then defined in statistical mechanics as,

$$S = -\mathrm{k}\sum_{j=1}^{\Omega} P_j \ln P_j \tag{D.2}$$

where k is Boltzmann's constant.

The probabilities at equilibrium P_j^0 are those that maximize entropy *S* under whatever constraints on the system that may be given

$$S_{\mathrm{eq}} = S_{\max} = -\mathrm{k}\sum_{j=1}^{\Omega} P_j^0 \ln P_j^0 \tag{D.3}$$

The (excess) **negentropy** of the system described by the probabilities P_j then is

$$S_{eq} - S = \mathrm{k}\left(\sum_{j=1}^{\Omega} P_j \ln P_j - \sum_{j=1}^{\Omega} P_j^0 \ln P_j^0\right) \tag{D.4}$$

The **information** content is, according to information theory {59}, in binary units (bits)

$$I = \frac{1}{\ln 2}\left(\sum_{j=1}^{\Omega} P_j \ln P_j - \sum_{j=1}^{\Omega} P_j^0 \ln P_j^0\right) \tag{D.5}$$

As an example, if the system contains N different particles with 2 possible states each, then $\Omega = 2^N$. If there are no constraints, all P_j^0 are equal 2^{-N}. Complete information about the system (one P_j equal to unity, the others vanishing) then gives $I = N$. For each particle there is then information equivalent to one yes or one no answer to a specific question. Each such answer amounts to one binary unit (bit) of information. From Eqs. D.4 and D.5 we see that negentropy and information are very simply related

$$S_{\text{eq}} - S = \text{k}'I \tag{D.6}$$

where

$$\text{k}' = \text{k} \ln 2 \approx 1.0\times10^{-23} \text{ J/K} \tag{D.7}$$

plays the rule of fundamental constant. Thus one bit is equivalent to 1.0×10^{-23} J/K of negentropy.

The relation in Eq. A.10 between exergy and entropy,

$$E = T_0(S_{\text{eq}}^{\text{tot}} - S^{\text{tot}}) \tag{D.8}$$

("tot" stands for the total system, which is here only called the system) combined with Eq. D.6 gives us the following relation between exergy and information

$$E = \text{k}'T_0 I \tag{D.9}$$

Thus $\text{k}'T_0 \approx 2.9\times10^{-21}$ J is the amount of exergy connected to one bit of information at room temperature.

It should be noted that "**information**" is a measure not necessarily of actual meaningful information but rather of **information capacity**. It can also be thought of as a measure of **order** or **structure**.

Appendix E: Exergy and some idealized thermodynamic systems

1. Equilibrium

An isolated system A at equilibrium has maximum entropy, $S = S_{eq}$. Let the system be described by the intensive variables $X_i(\mathbf{x},t)$ depending on position $\mathbf{x}$ within A, and time t. The values of the variables X_i are determined through the condition of maximum S,

$$\frac{\delta S}{\delta X_i} = 0 \qquad \text{(E.1)}$$

The entropy may decrease only temporarily through fluctuations, as indicated in Fig. E.1.

At equilibrium, parameters such as temperature and entropy are well-defined.

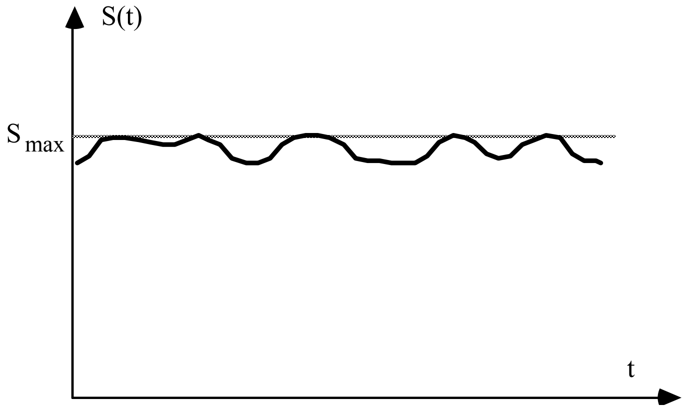

Figure E.1. Entropy as function of time for a system in equilibrium

2. A system not deviating too far from equilibrium

Consider a small volume ΔV around the point $\mathbf{x}$ of the system A, see Fig. E.2. If ΔV is macroscopically small but still large enough to contain a large number of particles it may be considered at a specific time to constitute a system which has reached equilibrium in ΔV. (The relaxation time for reaching internal equilibrium in ΔV is assumed to be small compared to a typical period of time describing interaction with the surroundings.) Thus, temperature, pressure, entropy density and so on may be defined as functions of the point $\underline{x}$ and time t.

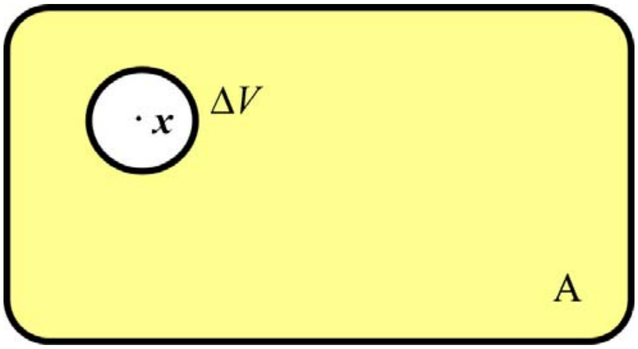

Figure E.2. A small volume ΔV surrounding the point $\boldsymbol{x}$ in a system A

Flows $\mathbf{J}_i(\boldsymbol{x},t)$ are driven by gradients of the intensive variables X_i. A linear relationship can be assumed

$$\mathbf{J}_i\left(\boldsymbol{x},t\right)=\sum_j \mathrm{L}_{ij}\nabla X_j\left(\boldsymbol{x},t\right)) \qquad \text{(E.2)}$$

where the coefficients L_{ij} satisfy the Onsager relations

$$\mathrm{L}_{ij} = \mathrm{L}_{ji} \qquad \text{(E.3)}$$

When the system evolves the entropy increases. Let the entropy production per unit volume and time be $\sigma(\boldsymbol{x},t)$. Then {59}

$$\frac{\mathrm{d}S}{\mathrm{d}t}=\int_{\mathrm{A}}\mathrm{d}^3 x\sigma\left(\boldsymbol{x},t\right) \qquad \text{(E.4)}$$

where

$$\sigma\left(\boldsymbol{x},t\right)=\sum_{i,j}\mathrm{L}_{ij}(\nabla X_i)(\nabla X_j)\geq 0 \qquad \text{(E.5)}$$

We see from Eqs. (E.4) and (E.5) that for systems which are not isolated, $\mathrm{L}_{ij} \neq 0$, there is an entropy production whenever there is a gradient. The entropy production has its minimal value for a source-free gradient,

$$\nabla(\nabla X_i)\,) = 0 \qquad \text{(E.6)}$$

III. Systems far from equilibrium. Living systems.

A system may be maintained away from equilibrium if it lies in an energy flow and receives energy from one system and passes it to away to another. For such a system A, see Fig. E.3, the inflow of energy (temperature T_1) carries low entropy and the outflow (temperature $T_2<T_1$) carries high entropy. If the power is P and the average temperature of A is T_0 ($T_1>T_2>T_0$), then the *net exergy gain per unit time*, W is

$$W = T_0 P\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{E.7}$$

This exergy flow can be used to construct and maintain structures far away from equilibrium.

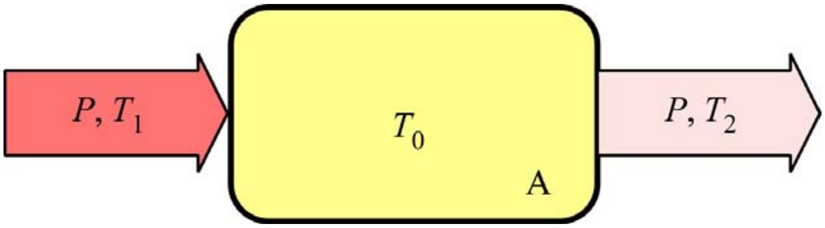

Figure E.3. A system A of average temperature T_0 in an energy flow P.

For living organisms equilibrium means death. Human beings, as well as animals in general, stay away from equilibrium (i.e. stay alive) by extracting chemical energy in the processing of food into waste. This energy is then passed on to the environment as heat. The whole biosphere lives by converting high frequency (heat) radiation emitted to space, see Fig. 3.3. The fundamental process here is the photosynthesis in the plant. Physically, of course, living systems are extremely complicated. A much simpler example of Fig. E.3 is a metal rod conducting heat from a hot reservoir to a cold reservoir.

If the deviation from equilibrium is not too great, a system in a position between a *steady energy giver* and a *steady energy receiver* evolves into a *stationary state*. This is for instance true for the metal rod in the example just mentioned.

A stationary state not far from equilibrium is characterized by minimal entropy production,

$$\frac{\delta}{\delta X_i}\left(\frac{\mathrm{d}S}{\mathrm{d}t}\right) = 0 \tag{E.8}$$

and the boundary conditions imposed by the energy giver and the energy receiver. Thus, in the evolution towards a stationary state, the entropy production decreases steadily until it reaches the minimum value determined by Eq. (E.8).

If a system is in a *negentropy (or exergy) flow*, Ref. {26} and if *self catalytic processes* are possible, then fluctuations may be used as *starting points for producing structure and order* out of a more chaotic state, Refs. {34} and {35}. This is the way life once began on earth, Ref. {34}. The description of such phenomena, however, is outside the scope of this report.

A simple way of helping a system which involves self catalytic processes is to enclose it within a shell of some sort. A living cell is an obvious example of this.

IV. The exergy of an ideal monoatomic gas

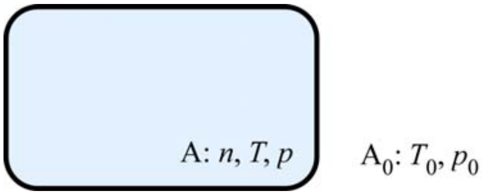

Figure E.4. A gas in a container in an environment of the same gas.

Consider an ideal monoatomic gas enclosed in a container in an environment of the same gas, see Fig. E.4. If T or p deviate from T_0 or p_0, work may be extracted from A. To determine the exergy we use Eq. (A.16). Assuming that the gas is thin enough to be considered as an ideal gas, we have for the volume V, energy U, and entropy S of A

$$\begin{aligned} V &= \frac{n\mathrm{R}T}{p} \\ U &= \frac{3n\mathrm{R}T}{2} \\ S &= S_{\mathrm{eq}} + n\mathrm{R}\left[\frac{3}{2}\ln\left(\frac{T}{T_0}\right) + \ln\left(\frac{V}{V_0}\right)\right] \end{aligned} \tag{E.9}$$

where n is the total number of moles, and

$$\begin{aligned} V_{\mathrm{eq}} &= \frac{n\mathrm{R}T_0}{p_0} \\ U_{\mathrm{eq}} &= \frac{3n\mathrm{R}T_0}{2} \end{aligned} \tag{E.10}$$

We vary volume and temperature and keep n constant, $n = n_{\mathrm{eq}}$, we then get

$$E = n\mathrm{R}T_0\left\{\frac{3}{2}\left[\frac{T}{T_0} - 1 - \ln\left(\frac{T}{T_0}\right)\right] + \frac{V}{V_{\mathrm{eq}}} - 1 - \ln\left(\frac{V}{V_{\mathrm{eq}}}\right)\right\} \tag{E.11}$$

Expressed in terms of relative deviations from equilibrium

$$t = \frac{T - T_0}{T_0}$$
$$v = \frac{V - V_{\text{eq}}}{V_{\text{eq}}} = \frac{T p_0}{T_0 p} - 1 \qquad \text{(E.12)}$$

the exergy is

$$E = n\mathrm{R}T_0\left[\frac{3}{2}g(t) + g(v)\right] \qquad \text{(E.13)}$$

where $g(x)$ is the function, also see Fig. E.5

$$g(x) = x - \ln(1 + x) \qquad \text{(E.14)}$$

We see that $g(x)$ increases rapidly with increasing negative value of x. For the temperature part in Eq. (E.13) this means that if the gas is much colder than the environment it carries a large amount of exergy.

The divergence at $x = -1$ is connected to the use of Stirling's formula (E.15) in the derivation of Eq. (E.9). For a large n we have

$$\ln n! \approx n(\ln n - 1) \qquad \text{(E.15)}$$

When $x \to -1$ Stirling's formula is no longer valid since n becomes small (see the comment of this in Chapter 2 in Ref. {22}), the gas is no longer to be regarded as an ideal gas.

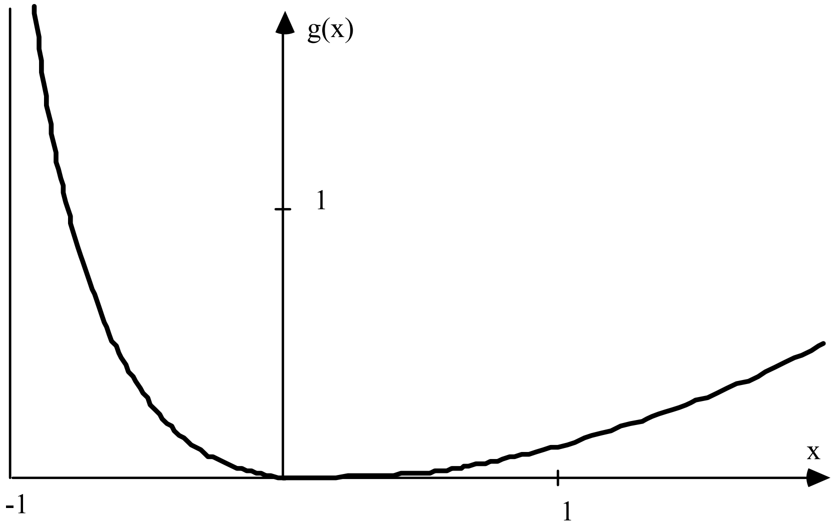

Figure E.5. The function $g(x) = x - \ln(1+x)$.

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EXERGY CONVERSION IN THE SWEDISH SOCIETY

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The exergy concept is reviewed as a tool for resource accounting. Conversions of energy and material resources in the Swedish society are described in terms of exergy. The 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.

1. A classification of resources

Natural resources, such as energy and material resources, appear partly as *flows* and partly as *stocks*, Fig. 1. 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.

Among stocks we therefore differentiate *dead stocks* or *deposits* from *living stocks* or *funds* [Georgescu-Roegen (1971 and 1975)]. This is 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.

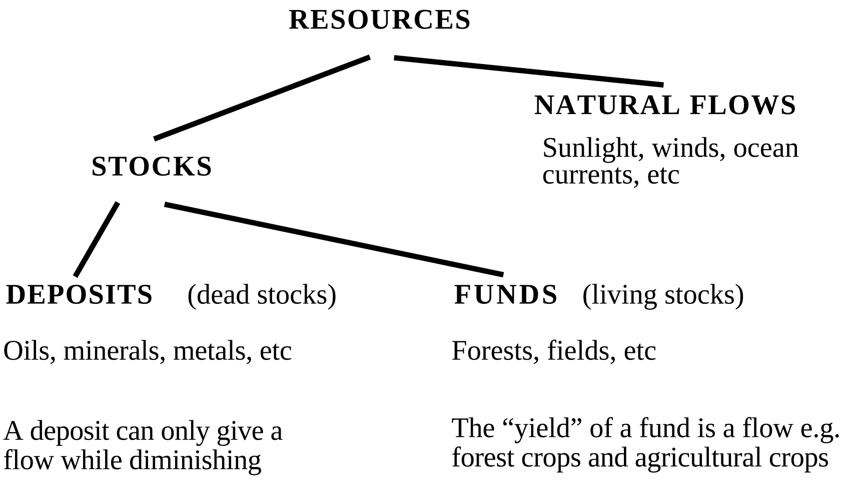

Fig. 1. A classification of resources.

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2. Energy and exergy

Energy cannot be created or destroyed. Energy appears in many forms and different qualities and the quality of energy can increase locally or be destroyed. In Table 1 some energy forms are listed in decreasing order of quality. (We shall return to the quality factor used in the table.) It must be noted that this factor is only approximate. When using energy we utilise the energy conversions along its way towards heat at environmental temperature.

The necessity to determine the available part of the energy, or – which is the same – the amount of mechanical work that could be extracted from it, has long been recognised [Carnot (1824), Gibbs (1873), Darrieus (1930), Keenan (1932 and 1941)].

In 1953 Z. Rant (1956) suggested that the term *exergy* should be used to denote ‘technische Arbeitsfähigkeit’. A clear, and completely general, definition was given by H. D. Baehr (1965):

> ‘Die Exergie ist der unbeschränkt, d.h. in jede andere Energieform umwandelbare Teil der Energie.’ (Exergy is the totally convertible part of the energy i.e. that part which may be converted into any other energy form.)

R. B. Evans (1969) has shown that exergy (which he prefers to call ‘essergy’) in itself incorporates the concepts of *free energy* used by Helmholtz and by Gibbs and ‘availability’ introduced by Keenan (1932). Another – quite adequate – name for the same thing ‘available work’ was used by a working group within the American Physical Society (APS) in 1975 [Berman et al. (1975)]. T. S. Sørensen (1976) has shown that exergy is a useful concept in Brønstedian Energetics. A comparison of different heating systems based on the theory of exergy has been made by L. Borel (1975). The exergy concept is also being used in groups working with systems analysis [Thoma (1977), Voigt (1978)]. A workshop on *Second Law Analysis of Energy Devices and Processes* was held in august 1979 [Cambel et al. eds. (1980)].

Exergy is a measure of how far a certain system deviates from equilibrium with its environment. The exergy E for a system in a large environment is [Wall (1977)]

$$E = T_0\,(S_{\mathrm{eq}}^{\mathrm{tot}} - S^{\mathrm{tot}}) \tag{1}$$

where T_0 is the temperature of the environment and $S_{\mathrm{eq}}^{\mathrm{tot}} - S^{\mathrm{tot}}$ is the deviation from equilibrium of the *negentropy* (=minus the entropy) of the system *and* its environment, i.e., the total system. (‘eq’ denotes equilibrium with the environment.)

Another expression for the exergy is

$$E = U + p_0 V - T_0 S - \sum_i \mu_{i0} n_i \tag{2}$$

where U, V, S, and n_i denote extensive parameters of the system (energy, volume, entropy, and the number of moles of different chemical components) and p_0, T_0, and μ_{i0} are intensive parameters of the environment (pressure, temperature, and chemical potential which also may include gravitational and electromagnetic potentials etc.).

A very useful formula for determining the exergy was given by the APS-group [Berman et al. (1975)],

$$E = U - U_{\mathrm{eq}} + p_0(V - V_{\mathrm{eq}}) - T_0(S - S_{\mathrm{eq}}) - \sum_i \mu_{i0}(n_i - n_{i\,\mathrm{eq}}) \qquad (3)$$

where on the right side easily determined quantities appear. It is thus an easy task to determine the exergy content of a given system in a given environment.

For a substance which has an exergy content deriving only from its concentration the following relation holds

$$E = \mathrm{R}T_0 n \ln(c/c_0) \qquad (4)$$

where

n = number of moles of the substance,
R = gas constant,
T_0 = temperature of the environment,
c = concentration of the substance in the material in question, and
c_0 = concentration of the substance in the environment.

For materials like inert gases or other not chemically active materials this concept of exergy is applicable. Materials which react chemically get an additional exergy contribution from the change in the chemical potential.

The exergy content in a material can thus be summarised in the formula

$$E = n\,(\mu - \mu_0 + \mathrm{R}T_0 \ln(c/c_0)) \qquad (5)$$

where

μ_0 = chemical potential for the material in its reference state, i.e. in equilibrium with the environment.

The chemical potential for most materials is to be found in a tabular form [Handbook of Chemistry and Physics].

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.
2. A system carries more exergy the more it deviates from the environment. Hot water has a higher content of exergy during the winter than it has on a hot summer day. A block of ice carries hardly any exergy in winter while it does in summer.

3. When the energy loses its quality this means that exergy is destroyed. The exergy is the part of the energy 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, rich in exergy, reaches the earth. A lot of it is reflected but the energy absorbed 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. The green plants absorb exergy from the sunlight 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.
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 utilised 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 is decreased (point 3).
6. An obvious difficulty in the definition of exergy 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).

3. 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 has mostly been used within heat and power technology, where one works with heat of varying qualities. 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 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, Table 1. 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 it's 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.

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[a]
Nuclear energy	0.95
Sunlight	0.9
Hot steam (600°C)	0.6
District heat (90°C)	0.2- 0.3[b]
Heat at room temperature (20°C)	0-0.2[b]
Thermal radiation from earth	0

[a] may even exceed 1, due to definition of system boundaries and final states
[b] strongly depending 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.

4. Resource conversions in the Swedish society

The main conversions of energy and materials in the Swedish society in 1980 is shown in Fig. 2. 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/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 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 exergy flows exceeding 5 PJ/year are included. The inflows are ordered according to their origins. Sunlight is thus a renewable natural flow. Harvested forests, agricultural crops, and hydropower are renewable exergy flows deriving from funds. Iron ore, nuclear fuels, and fossil fuels are non-renewable exergy flows from deposits. Exergy conversions are represented by the unfilled boxes. The resources actually demanded in society appear as outflows on the right side of the diagram. The total inflow of resources during 1980 accounts to 2539 PJ or 305 GJ/capita and the net output becomes 500 PJ or 60 GJ/capita.

4.1. 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 in Section 4.8. 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.

4.2. Forestry and industry based on forests

In the Statistical yearbook of forestry (1980) 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 [Wall (1983)]. 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 fibres. The structural exergy is well utilised when wood is used as building material or as raw material for the production of paper. By burning useful wood this part is utilised very badly. We optimise 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.

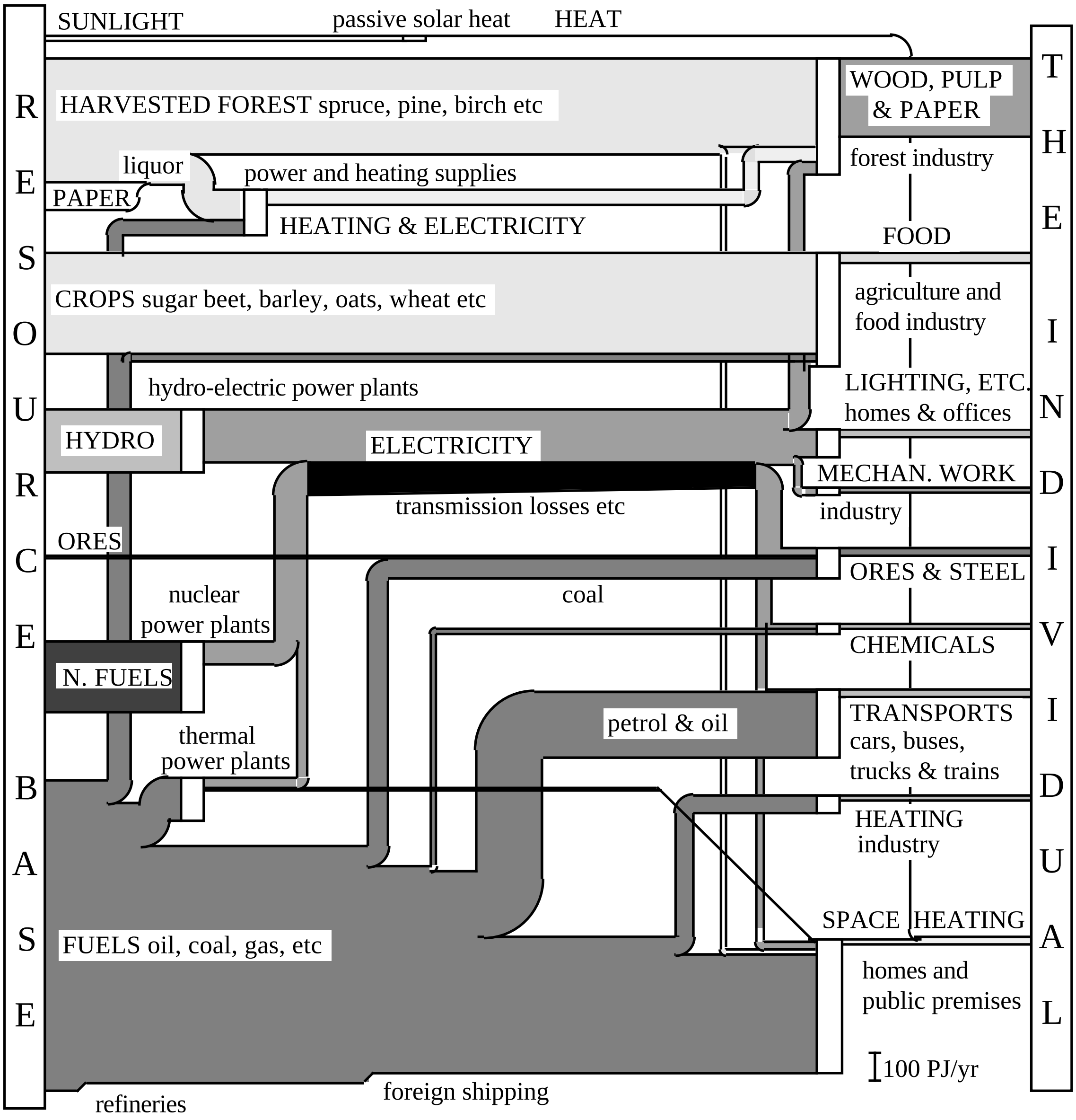

Fig. 2. The exergy conversion system in the Swedish society in 1980.

In 1980, the forest crops were used according to Table 2. Swedish timber-cutting was 49.2 Mm^3 or 394 PJ. (The annual growth of forests is about 60 Mm^3 or 480 PJ.) The change of storage adds 23 PJ. 178 PJ of the forest products was used by the saw mill industry. Their production consisted mainly of timber, 114 PJ. Parings and chips to the pulp industry amounted to 74 PJ, and 15 PJ from edgings were used for producing wallboard, particle board, and plywood. 266 PJ were used by the pulp and paper industry.

The paper industry also used 14 PJ of waste paper. The production was: 43 PJ from mechanical, chemical and dissolving wood pulp, 16 from sulphite pulp, and 96 PJ from sulphate pulp. Of this production, 64 PJ were market pulp and the rest were used in the paper production. The main products were Kraft paper, 54 PJ, and newsprint paper, 29 PJ. Writing paper and board amounted to 31 PJ.

The export of products from the forest industry was 194 PJ, mainly paper, pulp, and planed boards. The total imports were 73 PJ, mainly paper wood, 20 PJ, and sawed timber, 29 PJ.

From private forests 19 PJ was used as firewood. Chips and bark from saw mills were also used as fuels, 8 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. 120 PJ of the forest crops (lignin) together with 63 PJ of other fuels (see Section 4.7) gave less than 60 PJ of heat (see Section 4.8). Within the wood and pulp industry, 57 PJ of electricity was also consumed. The exergy content of the outputs, consisting of timber, pulp, and paper, was 331 PJ.

Table 2
The conversion of forest products within Swedish forestry
and industry based on forests in 1980, measured in PJ.

Timber-cutting	394
Timber from stores	23
Waste paper	14
Imports	73
Total consumption	504
Input to the saw mill industry	178
Input to the pulp and paper industry	266
Use of wood based fuels (lignin)	120
Production of timber ware	133
Production of market pulp	64
Production of paper	114
Firewood	19
Total production	330

4.3. 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 fertilisers, 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 substances.

The agricultural land of Sweden covers at present about 3 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 3, the exergy contents [Wall (1983)] of the most common Swedish crops are to be found [The Statistical yearbook of agriculture (1980)].

Table 3
Vegetable and animal yield in Sweden 1980.

	MJ/kilogram	kton	PJ
Vegetable yield			
For humans:			
Bread cereal	15.5	1416	22
Sugar beets, potatoes etc.	4.2[a]	3186	13
Total			35
For animals:			
Coarse grain	15.8	3896	61.6
Oliferous plants	19.1	323	6.2
Legumnious plants	16.7	24	0.4
Hay	15.3	4132	63
Pasture			23
Total			approx. 155
Residues:			
Straw	15.7	6720	106
Harvesting loss etc.			32
Total			138
Total vegetable yield			328
Animal yield			
Meat, eggs		575	12
Milk		3338	11
Wool, blood, skin etc.			1
Total animal yield			24

[a] There is a large uncertainty in the precise composition of the materials, especially concerning the water content.

The total exergy content of the vegetation products was 190 PJ. In addition to this there were residues such as straw and harvesting losses, 138 PJ. The amount of residues that was brought back into cultivation was estimated to 31 PJ. The exergy from fossil fuels, mainly diesel fuel and fuel oil, and electricity used in agriculture and in greenhouses, was 25 PJ. Another 24 PJ was used 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 fertilisers, amounted to about 24 PJ. This is not included here. The output from this sector is food.

The food consumption in Sweden for 1980, with approximately 8.3 million inhabitants, can be estimated in different ways. According to the recommended daily intake, the people in Sweden should consume 29 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 36 PJ for the Swedish consumption. If the statistics of the total consumption of food, distributed from stores, can be trusted, the Swedes consumed 42 PJ in 1980. The waste could consist of non-digestible food like peels and bones. About 70% is eaten, which corresponds to other estimates of 30% waste [Eriksson (1978)].

4.4. Electricity from hydropower and thermal power

Electricity was used within the forest industry, 57 PJ, and in the food production, 19 PJ. Furthermore, electricity was used for lighting, electrical domestic appliances etc., 114 PJ. Within the manufacturing industry much of the electricity, 27 PJ, was used for driving machines i.e. mechanical work. The rest of the electricity went mainly into the mining industry and the iron and steel industry, 34 PJ, the chemical industry, 20 PJ, transports, 8 PJ, and electric heating, 33 PJ.

In 1980, production of electricity from hydropower 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 gross exergy supply becomes 248 PJ, as hydropower.

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, 10 PJ, goes into the outflow of heating for housing and other premises.

The production of electricity was 91 PJ and 38 PJ respectively from nuclear and fossil fuels. The total production of electricity was then 340 PJ, of which 2 PJ was net imported electricity. Of this production 307 PJ was used. The rest, 33 PJ, was lost along its way to the consumer due to electric resistance and imperfect adaptation between production and consumption.

4.5. 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:

$$\mu(\mathrm{Fe}_{\mathrm{magnetite}}) \approx \frac{1}{3}\,(-1014.2 + 2\times3.84)\ \mathrm{kJ/mole} \approx -335.5\ \mathrm{kJ/mole}$$
$$\mu_0(\mathrm{Fe}_{\mathrm{hematite}}) \approx \frac{1}{2}\,(-741.0 + 1.5\times3.84)\ \mathrm{kJ/mole} \approx -367.6\ \mathrm{kJ/mole}$$

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:

$$e_{\mathrm{iron\ ore}} \approx 10.7\left[\{-335.5-(-367.6)\}\times10^{3} + 8.31\times288\times\ln\left(\frac{0.83^{\dagger}\times0.43}{2\times2.7\times10^{-4}}\right)\right] = \approx 0.51\ \mathrm{MJ/kilogram}$$

$$e_{\mathrm{iron}} \approx 17.9\left[\{0-(-367.6)\}\times10^{3} + 8.31\times288\times\ln\left(\frac{1}{2\times2.7\times10^{-4}}\right)\right] = 6.90\ \mathrm{MJ/kilogram}$$

since 1 kilogram of Fe is equivalent to 17.9 moles.

These figures correspond well with commonly used values of iron [McGannon (1971), Gyftopoulos et al. (1974)].

The Swedish production of iron ore in 1980 was approximately 26.9 Mtons. 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 14 PJ.

The production of iron was about 3.5 Mtons, representing an approximate quantity of 24 PJ. To produce this iron about 5.7 Mtons of ore was needed, corresponding to 3 PJ together with 34 PJ of electrical exergy and 77 PJ of coal, coke and other fuels.

4.6. 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 284 PJ.

[†] 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.

4.7. 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 1980 equal to 1140 PJ.

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. 18 PJ of oil and 20 PJ of electricity were converted into 30 PJ of rubber, plastics, fertilisers 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 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, 237 PJ. Petrol and oil are converted into transport work in cars, buses, trucks etc. About 10% of the exergy content of the fuel is used to run a vehicle.

33 PJ was used in the oil refineries, 36 PJ for bunkering for foreign shipping, 419 PJ for direct conversion into heat for housing and other premises, 167 PJ for the production of electricity and heat in combined power and heating plants and in oil-based condensing power plants, and 60 PJ for heat production within the industry.

4.8. Exergy losses at the conversions into heat

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

The exergy content of heat is

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

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. 3, we can see how the exergy content depends on the temperature. Exergy becomes almost equivalent to energy at very large values of temperature. In Fig. 3, some different forms of heat are marked. The temperature of the environment is 15°C.

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 dependant 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. 4.

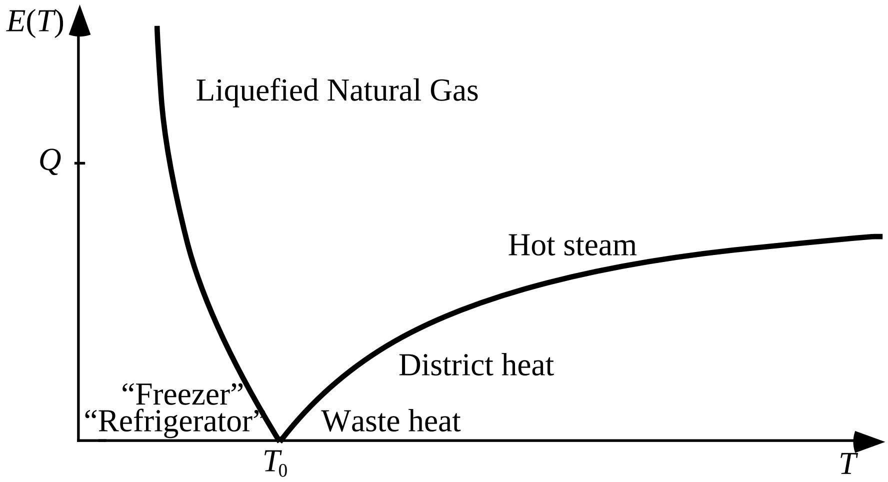

Fig. 3. Exergy as a function of temperature.

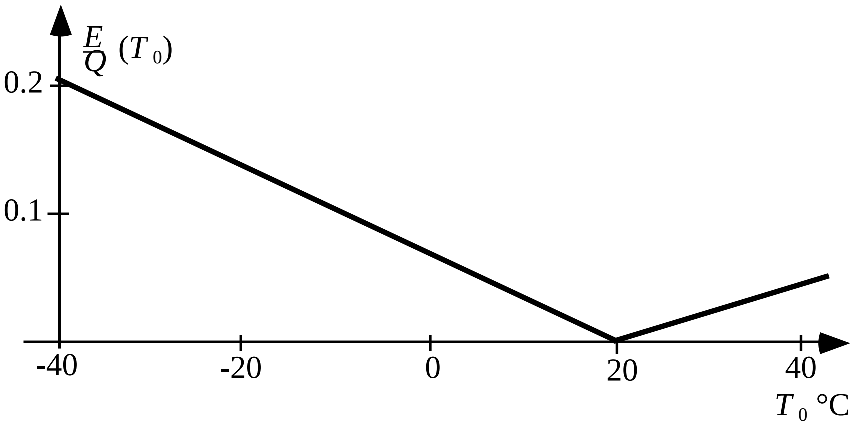

Fig. 4. The exergy content of the indoor heat as a function of the outdoor temperature.

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 content is

$$\frac{E}{Q}=\frac{\left(a^2+\frac{b^2}{2}+\frac{c^2}{2}\right)d+\frac{b}{\omega}\left[\frac{b}{2}\sin(\omega d)-4(a-c)\sin\left(\frac{\omega d}{2}\right)\right]}{T\left[ad-\frac{2b}{\omega}\sin\left(\frac{\omega d}{2}\right)\right]} \tag{7}$$

where

E = exergy,

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),

$\omega = \frac{2\pi}{365}$ per day.

In Table 4, meteorological data, relative population X, exergy value E/Q, and relative exergy value XE/Q for different areas in Sweden are shown. Sweden is here divided into seven different areas. The meteorological data for an area is defined by the meteorological data for a representative town in that area. The diurnal temperature variations are set to 4°C for all areas during the heating season [Sundell (1980)].

Table 4
The average temperature T_0, the minimum five-day mean temperature T_{min}, number of heating days d, exergy value E/Q, relative population X and relative exergy value XE/Q in 1975.

Representative town[a]	T_0°C	T_{min}°C	d days	E/Q%[b]	X%	XE/Q%
Umeå	4.0	–11.0	277[c]	6.72	9.4	0.632
Östersund	4.2	–9.2	283	6.27	8.5	0.533
Karlstad	7.7	–4.4	235	5.00	9.9	0.495
Stockholm	8.4	–3.2	230	4.84	24.0	1.160
Jönköping	7.9	–3.6	237	4.82	17.3	0.834
Göteborg	9.3	0.3	226	4.00	16.6	0.664
Malmö	9.1	–1.6	225	4.54	14.3	0.649
				Total	100.0%	4.97%

[a] The country is divided into areas according to: (the letters represent counties) Umeå: BD, AC, Y, Östersund: X, Z, W, Karlstad: S, T, U, Stockholm: A, B, C, D, Jönköping: E, F, G, H, I, R, Göteborg: N, O, P, Malmö: K, L, M.

[b] Calculated with an indoor temperature of 20°C and a diurnal temperature variation of 4°C.

[c] The value is estimated for Luleå.

The exergy value E/Q, decreases when we move towards the south from Umeå to Malmö. This is also reflected in the decreasing heating needs. By summing up relative exergy values of the areas, we get the total amount of exergy in space heating for the whole country. The result can be stated: 5.0% of the supplied heating energy represents exergy. (In addition to this there are of course furnace losses etc.) This estimate 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.

Table 5
The annual mean temperature T_0, exergy value E/Q and relative exergy value XE/Q in 1975.

Representative town[a]	T_0°C	E/Q%[b]	XE/Q%
Luleå	3.1	8.29	0.780
Östersund	4.2	7.23	0.615
Karlstad	7.7	6.18	0.612
Stockholm	8.4	6.02	1.445
Norrköping	7.9	6.22	1.076
Göteborg	9.3	5.59	0.928
Malmö	9.1	5.83	0.834
		Total	6.29%

[a] The country is divided into areas according to: (the letters represent counties) Luleå: BD, AC, Y, Östersund: X, Z, W, Karlstad: S, T, U, Stockholm: A, B, C, D, Norrköping: E, F, G, H, I, R, Göteborg: N, O, P, Malmö: K, L, M

[b] Calculated with an indoor temperature of 20°C.

An estimate of the exergy content in heat for space heating is also 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%, Table 5. 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, 1 PJ from fire wood, 2 PJ of district heat, 2 PJ of electric heat, and 15 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 21 PJ. The total exergy supply is, however, more than 500 PJ.

4.9. Chains of resource conversions

Let us now look at the following chain of resources: nuclear fuel to electricity to heat in the diagram of Fig. 2. In the conversion of nuclear fuel to electricity, 32% of the exergy in the nuclear fuel is utilised. Then, if we follow the electricity flow down to the electric heating, only 5% of the electricity is converted into heat. The total conversion into heat thus only utilises 1.6% of the exergy in the nuclear fuel. In today’s light water reactors (LWR), only a minor part of the nuclear exergy in the fuel is utilised. A breeder reactor is more efficient. If we also include this imperfection the overall efficiency of the conversion of nuclear exergy (LWR) to space heating becomes extremely low. In the future this misuse of resources must be avoided. The conversion of fossil fuel (oil) via electricity to heat is somewhat better, 2.0%. Instead of resistance heating (short-circuiting device) we should use heat pumps, and in the near future improve the conversion of electricity to heat to over 30%. Today there exist, for this purpose, commercially available heat pump systems with an exergy efficiency of 20%. There are many other chains of conversions in the diagram that could be discussed but this is one with an especially small overall efficiency. (Still, it is becoming increasingly common. In 1975, the use of electricity for this purpose was 22 PJ.)

Of the total inflow of energy and material resources into the Swedish society of about 2500 PJ in 1980, only 20% or 500 PJ reached final use. Heavy losses could be considerably reduced by an active resource budgeting and economising 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 even somewhat worse, namely about 14%.

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 in 1980, 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.

Appendix

Let us suppose we want to maintain a constant temperature T in a house in an environment at a lower temperature T_0(t) depending on time, t. To do this we must add a certain power $\dot{Q}$(see Fig. A:1) because of the heat losses of the house.

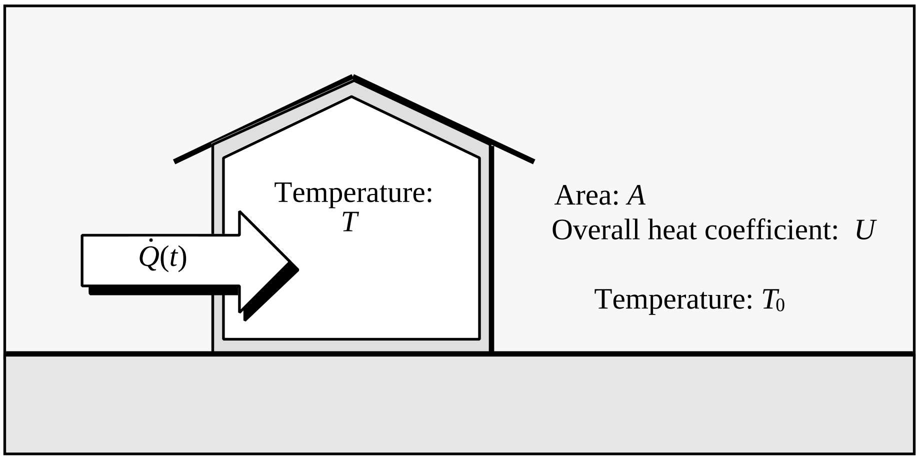

Fig. A:1. The heat balance of a house.

The necessary power $\dot{Q}(t)$ depends on the overall heat coefficient U of the system, its limited area A, and the difference between the temperature inside and outside the house according to

$$\dot{Q}(t) = UA(T - T_0(t)). \qquad \text{(A:1)}$$

The total amount of heat required during a year is

$$Q = \int_0^d \dot{Q}(t)\mathrm{d}t \qquad \text{(A:2)}$$

where d is the number of days of the heating season.

The exergy flow $\dot{E}(t)$ corresponding to the heat flow $\dot{Q}(t)$ is

$$\dot{E}(t) = \frac{T - T_0}{T}\dot{Q}(t). \qquad \text{(A:3)}$$

We assume that the temperature of the environment varies harmonically during the year according to

$$T_0(t) = T_0 + \left(T_0 - T_{\min}\right) \times \cos\left(\frac{2\pi t}{365}\right) + \frac{T_{\mathrm{day}} - T_{\mathrm{night}}}{2\cos(2\pi t)} \qquad \text{(A:4)}$$

From (A:1), (A:2), (A:3) and (A:4) we then get the total exergy needed

$$E = \int_0^d \dot{E}(t)\,\mathrm{d}t = Q\,\frac{\left(a^2 + \frac{b^2}{2} + \frac{c^2}{2}\right)d + \frac{b}{\omega}\left[\frac{b}{2}\sin(\omega d) - 4(a-c)\sin\left(\frac{\omega d}{2}\right)\right]}{T\left[ad - \frac{2b}{\omega}\sin\left(\frac{\omega d}{2}\right)\right]} \qquad \text{(A:5)}$$

where

$a \;=\; T - T_0$

$b \;=\; T_0 - T_{\mathrm{min}}$

$c \;=\; \dfrac{T_{\mathrm{day}} - T_{\mathrm{night}}}{2}$

$\omega \;=\; \dfrac{2\pi}{365} \approx 0.0172$

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EXERGY FLOWS IN INDUSTRIAL PROCESSES

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Abstract

The concept of exergy is defined and applied to industrial processes. The study discusses the meaning of the choice of definition of efficiency, system limitations and problem definition. The exergy flows for a pulp and paper mill and a steel plant are presented. The study establishes the energy flows in processes and draws up the exergy losses. For the purpose of comparison, the Swedish space heating system is described using the exergy concept. The energy and exergy prices of several common energy forms are compared.

The aim of this report is to show the simplicity and the value of using the concept of exergy when analyzing industrial processes and to develop conventions and standards within the field. The large losses which are revealed in an exergy treatment of a process should be seen as a challenge to achieve technical improvements, not as an insurmountable obstacle.

The author welcomes opinions, comments and critical reviews of this study.

Göteborg, July 1986
Göran Wall

Content

1. SUMMARY

The report begins by defining concepts that are important for exergy studies. Exergy is defined as the work that can be extracted when a system is brought into equilibrium with its surroundings without incurring any losses (Wall 1977). The efficiency of a process is here defined as the used exergy outflow divided by the used exergy inflow.

Our ability to find new solutions is often limited by the existing technology. We often overestimate current technology in relation to past technology and to future alternatives. Thus, today’s most sophisticated computers are mere “steam engines” when compared to the simplest biological cell or to future computers as is also illustrated by the rapid developments in the computer field. This paper emphasizes therefore the importance of defining the problem in scientific terms, that is, unhindered by the limitations of current technology. Such a description must, of course, be based on clearly defined scientific concepts. Unfortunately, this is not always the case with the result that our picture of reality is false and may consequently constitute an obstacle to important technological advances.

This study presents in more detail the energy and exergy flows of two typical Swedish industries, a pulp and paper mill and a steel plant. These are also described in relation to Sweden’s space heating system. The pulp and paper industry described is SCA-Nordliner in Munksund which produces unbleached kraft liner, see Fig. 5.1. After the wood is cleaned, debarked and chipped, the wood chips are processed in a continuous digester to a sulphate pulp. The separated bark is combusted together with fuel oil to produce steam and electricity both of which are used in the process. The chemicals and the stripping (or draw-off) liquor leave the digester after processing. A major part of the chemicals is recovered in the flash and heat exchangers, evaporators, soda recovery unit and lime sludge reburning kiln, while the liquor is used to produce steam. The washed sulphate pulp is then transported to the paper mill where it is formed, dewatered, pressed, dried, reeled and cut for delivery. Approximately 36% of the energy losses are incurred in the soda recovery unit, approx. 17% in the steam production unit (or steam production unit), and approx. 34% in the paper mill. In terms of exergy losses, approx. 40% are incurred in the soda recovery unit, approx. 31% in the steam production unit and approx. 16% in the paper mill, see Table 5.1 and Fig. 5.2. The sum of the energy and the sum of the exergy losses in these three sub processes is the same, but the relative proportions in the two treatments vary considerably. Furthermore, seen from an energy point of view, the unutilized outflows (or waste flows) amount to 57% of the total losses as compared to an exergy loss of only 7%. It can be seen that these flows constitute a considerably smaller resource than an energy treatment leads us to believe, and it may thus be concluded that an energy treatment paints an incorrect picture of the process.

The steel plant is represented by Halmstads Järnverk which produces reinforcing steel from scrap iron, see Fig. 6.1. The scrap iron is melted in two electric steel furnaces and

then undergoes continuous casting. The steel is subsequently cut into blanks which are then reheated in a pusher type furnace and then rolled to circular crossections with diameters from 6 to 32 mm. The major part of the energy losses is incurred in the electric steel furnaces and during continuous casting, and amounts to approx. 44% of the total losses. The picture of the losses is more or less the same when we look at the exergy losses, see Table 6.1 and Fig. 6.2. Nearly half of the exergy losses are incurred in these two sub processes. The difference between the energy and the exergy treatments increases when we look at the unutilized flows in the process such as exhaust gases and heat. These account for approx. 65% of the energy losses but only for about 28% of the exergy losses. What appears as a substantial unutilized resource flow in terms of energy is thus shown to be considerably less in terms of exergy, which is mainly due to the temperature of the flows. Thus, only a minor improvement in efficiency can be achieved by utilizing the existing unutilized flows. It is only by introducing new more efficient processes that major improvements can be achieved.

As a comparison to the industrial processes, the study also describes the Swedish space heating system. This comparison reveals many interesting differences. The Swedish space heating system represents the largest single exergy saving potential in the country. The efficiency of conversion to heat is estimated to be about 5% for Sweden as a whole. Two observations can be made - one, that new technology offers enormous potential for improving Sweden’s space heating system, and two, that current-day systems are highly inefficient. Modern nuclear energy technology, which utilizes only a small fraction of the exergy content of nuclear fuel yields an extremely low efficiency in space heating.

Finally, the study provides a short description of the price of several of the most common energy forms in relation to energy and exergy content. This is relevant since the design of the energy system mostly depends on the price of different energy forms. The approximate energy price of electricity in SEK/GJ is about 70, gasoline about 110, fuel oil about 50, wood about 20, and district heat about 60. The high price of gasoline can be justified by its special area of use, the low price of wood can be explained by the fact that efficient energy production from wood is expensive. In terms of exergy, we obtain instead the following prices (SEK/GJ): electricity about 70, gasoline about 120, fuel oil about 50, wood about 20, and district heat about 340. The very high exergy price of district heat is difficult to justify but can be explained by today’s rather inefficient heat production technology. This means that it will hardly be possible to maintain the price of district heat as heat pump technology develops further. In the future, when heat pumps will have a coefficient of performance (COP) of about 5, the relative price of district heat will be about 5 times too high.

The method presented in this report is also valuable for long-term planning of, for example, research efforts on more efficient allocation of resources since it reveals the real losses.

2. INTRODUCTION

The concept of exergy is coming into increased international use. Many books published over the recent years have been based on the concept of exergy (Ahern 1980, Baehr 1978, Chapman 1983, Edgerton 1982, Moran 1982), many conference reports (Reis 1985, Gaggioli 1980, 1983, Wolfe 1975, Penner 1980) as well as a good many articles within a number of sub fields (Eriksson 1984, Marín 1986, Siemons 1986, Stecco 1986). Nonetheless, the concept of exergy is uncommon in describing industrial processes. This is unfortunate, particularly as I am absolutely convinced that the concept of exergy will become standard for all process analysis in the near future. This concept is both readily understood and easy to apply. The present report is based on an earlier work (Wall 1983) and has been adapted for a wider audience. Hopefully it will contribute towards a deeper understanding of the concept of exergy and increase the area of its use. The report is primarily intended for persons directly connected with energy and materials processing within business and industry. However, it is written in such a way that persons with a different background can without difficulty partake in the study and its conclusions. Detailed information such as tables and computer programs are presented in the appendixes. The objective is not to describe the calculation methods in exhaustive detail, but to more concisely point out the value of this method and provide new insights and conclusions.

The main objective is to show the applicability of the exergy for studies of industrial processes. The concept of exergy provides an estimate of the minimum theoretical resource requirement (requirement for energy and material) of a process. This in turn provides information on the maximum savings that can be achieved by making use of new technology and new processes. New technology and new processes do not come about by themselves. By giving a deeper insight into processes, the exergy concept provides a better foundation for improvement and for calculating expected savings. As a complement to the present materials and energy balances, exergy calculations can provide increased and deeper insight into the process, as well as new unforeseen ideas for improvements.

Another important goal is to establish standards as soon as possible in order to facilitate application in industry and in other planning processes such as energy planning.

3. DEFINING THE CONCEPT

Energy is often defined as work or the ability to perform work. This is wrong. 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 can be defined as that which is indestructible or that which is always conserved during every closed process. Energy is thus most often an all too hazy concept.

S. Carnot described the relationship between work and heat (energy) as early as 1824:

$$W = Q\,(T - T_o)/T \tag{1}$$

where W is work that can be extracted when heat Q flows from a heat reservoir with an absolute temperature T to a reservoir with an absolute temperature T_o. (Note that the reservoirs' temperatures are not affected by the heat flow between them.)

During 1873-1878 J. W. Gibbs published three works from which it could be read that the work that can be extracted from a body in its surroundings is:

$$W = U + p_oV - T_oS - \sum \mu_{io} n_i \tag{2}$$

where U, V, S, and n_i are the body's internal energy, volume, entropy and the number of moles of substance "i", and p_o, T_o and μ_{io} are the ambient pressure, temperature, and the chemical potential of substance "i", respectively. This fundamental expression is the basis for all subsequent work. The only thing that needs to be added is that for a flow we obtain the expression:

$$W = H - T_oS - \sum \mu_{io} n_i \tag{3}$$

where H=U+pV is enthalpy and where chemical potential can be generalized to include other potentials such as electrical, magnetic and mechanical potential.

The term *exergy* (Ger. *exergie*) was proposed by Z. Rant as late as 1953 in order to describe work in this context. A complete definition was given by H. D. Baehr in 1965:
Die Exergie ist der unbeschränkt, d.h. in jede andere Energieform umwandelbare Teil der Energie. (Exergy is the totally convertible part of the energy, i.e. that part which may be converted into any other energy form.)
Thus, exergy is work extracted when a system is brought into equilibrium without incurring any losses.

Unfortunately, the concept of exergy has been attributed with many unnecessary names. Technische Arbeitsfähigkeit (technical ability to perform work), available work, availability, available energy and essergy - the essence of energy, are all names for generally the same thing, namely, exergy. In everyday language it is even often the case that one means exergy when one speaks about energy, for example, energy consumption.

The concepts of energy and exergy are related to the first two laws of thermodynamics: **1st law**: *Energy is constant in a closed system* (compare with: that which is constant in a closed system is called energy which is a more accurate/correct formulation). **2nd law**: *Heat can only move spontaneously from a higher to a lower temperature*, which yields work determined by exergy for heat in relation to transition. To analyze the process in terms of the 2nd law of thermodynamics is thus analogous to using the concept of exergy. (From the point of view of electrical science, we can treat energy as a kind of standard potential and exergy as voltage in relation to our chosen surroundings.)

The exergy of a system may also be written as (Wall 1977):

$$E = S(T - T_o) - V(p - p_o) + \sum n_i(\mu_i - \mu_{io}) \tag{4}$$

where we clearly see that exergy approaches zero as the system approaches equilibrium with the environment. We also see that exergy here is expressed as the sum of terms for differences in temperature, pressure and chemical potential. As I mentioned above, the effects of electricity, magnetism, gravity, radiation, etc. can also be added to this expression.

Analogously, the exergy of a flow can be written as:

$$E = H - H_o - T_o(S - S_o) - \sum \mu_{io}(n_i - n_{io}) \tag{5}$$

with the result that the exergy of a steam flow, for example, can simply be calculated from conventional steam tables. A computer program in BASIC has been developed in order to calculate steam data with table accuracy on a microcomputer (PC), see Appendix 3. This has previously only been possible on large computers (Keenan et al. 1978, Reynolds 1979).

For mixtures of substances, the calculation of exergy content is somewhat more complicated. The enthalpy can be calculated as the sum of the enthalphies of its substances. The entropy of a mixture, on the other hand, is determined by its nature. An ideal mixture is one where the elements are completely intermixed, i.e. two mixed gases or a drop of ink dissolved in water. The entropy of such mixtures is:

$$S = \sum x_i s_i - R \sum x_i \ln x_i \tag{6}$$

where x_i is the molar ratio of substance i, and R the gas constant.

There is no general theory or unequivocal concept for non-ideal mixtures. (This may be noted as serious in terms of the significance of these mixtures). Examples of non- ideal mixtures are alloys, suspensions and emulsions. It has been assumed here that the entropy of such mixtures is the sum of the entropies of the mixed substances, i.e., the last term which gives the entropy of the actual mixing process in Eq. (6) is excluded.

Data on thermal capacities is only available for pure elements and for certain chemical compounds such as oxides (Weast 1983 and U S Atomic Energy Report). That is why the thermal capacity of a mixture has been assumed to be the sum of the values of the substances in relation to their proportion. However, the result is that the mixtures where new phases appear are attributed incorrect values for thermal capacity. However, the size of this error is considered negligible in relation to errors in other data such as quantities and temperatures. The method of calculation is shown in Appendix 4, which is the BASIC program for calculating the thermal and chemical energy and exergy of an arbitrary mixture of certain substances under constant pressure.

Efficiency is a very valuable concept for describing the workings of a process. Usually we use the value 1 or 100% as the maximum efficiency. Unfortunately, this does not always apply when using the concept of energy. A maximum efficiency of hundreds of percent is not unusual, see Chapter 7. When calculating efficiency, it is also very important to clearly define system boundaries. Efficiency is here defined as useful energy/exergy output divided by the energy/exergy utilized in the process, that is the incoming quantity of energy/exergy minus the outgoing quantity that is not used. As a result, the efficiency of processes with large waste flows may be high. Efficiency may also be defined as the utilized outflow divided by the direct inflow indispensable for the process or as the minimum theoretical exergy requirement divided by the actual exergy requirement. One problem that applies to both of the former definitions is that processes where the energy/exergy flow passes through the process more or less unaffected yield an ostensibly high efficiency, that is, nearly 100%, for example, this may apply to a high temperature heat flow passing through a process where the temperature is raised only one or two degrees with relatively large losses. For the latter definition, it is true that an exact calculation of the minimum theoretical exergy requirement is difficult to make. Thus, each choice of definition entails both advantages and disadvantages. The efficiencies of certain processes in the study are also calculated, these are given in Appendixes 1 and 2. However, efficiency is an altogether overly simple measure for a good description of a process and can never replace a more detailed analysis.

The study does not include indirect “resource costs”, such as the energy and materials necessary for manufacturing fixed capital, i. e. machines. The term energy/exergy *analysis* should be reserved for such studies (Wall 1977).

4. DEFINING THE PROBLEM

The following two examples illustrate the importance of a clear problem definition (Andersson 1981).

(1) When Gustav III (1746-1792) of Sweden wished to send a message, it was natural for him to think of a messenger on horseback. Taking this train of thought a little further, a research program for improving communication methods would consequently have entailed a commitment towards improving horse-breeding methods. An energy analysis of the function of sending a message from Stockholm to Göteborg, for instance, would have resulted in a study of horse eating habits. However, with time, it was realized that neither horses nor couriers were necessary in order to transfer a message. Neither were letters in themselves, that is, paper and ink, necessary. Experiments with optical telegraph chains came under way and, with time, messages could be sent by cable, and today even via satellite.

(2) Today, when we set about to estimate the energy requirement for cutting a log of lumber into boards, we start out by assuming that the lumber will be sawn. When the price of fuel goes up, we begin by examining whether the process can be improved by selecting a more efficient motor to drive the saw-blade. We conclude that electric motors are usually 90% efficient and that it is thus not possible to achieve more than a 10% improvement. But in scientific terms, cutting results in two surfaces of a section which are separated so that the forces of attraction are negligible, i.e. a distance of several atom diameters. If one considers that wood has an ultimate strength of 10^4 N/cm^2 and that the distance required to separate the surfaces is $3 \cdot 10^{-9}$ m (10 times the diameter of a water molecule), it takes less than 0.3 J to cut a log 5 m long and 20 cm in diameter. Thus 1 kWh should suffice to cut 10 millions logs. However, a saw not only creates two new surfaces, but also the surface around each sawdust. Consequently, in the best of cases, a saw with a 1 kW motor can cut 300 logs of lumber per hour, i.e. 30 logs per kWh. Hence, it is not true that we can reduce the energy requirement by a maximum of 10%. We can reduce the requirement by more than 10^5 if we find better methods than cutting.

The seemingly high efficiency of today’s computers fades in the light of comparison with the simplest biological cell. Reproducing a DNA molecule in a cell is at least 10^9 more efficient (Wall 1977). In this perspective, biotechnology appears to have enormous technical potential for development well worth a commitment.

These examples are not selected to diminish existing technology, but to put it in a scientific perspective. This is the only way we can perceive the enormous potential of existing technology. We must learn to view the shortcomings of current-day technology as a challenge for improvement, not as an insurmountable obstacle.

The following description is a proposal for an adequate study and description of technological processes (Edgerton 1982, Wall 1985):

- Briefly describe the system to be studied
- Define the system, system boundaries, components, and various subsystems, etc. (A flow diagram is often the best way to define the system, sometimes it is also necessary to draw a schematic picture of the system.)
- Define those physical properties of the immediate surroundings that are important for the system, such as temperature and pressure. These are the reference conditions to which all resource flows are related.
- Give the conditions and approximations as well as sources for an analytical description of the process.
- Calculate the material balance used in the process by giving the necessary thermodynamic qualities of each flow.
- Calculate the energy balance
- If possible, describe the thermodynamic relationships of each component
- Calculate the exergy of all of the flows in the process and the exergy losses of each component. If possible, state the reason for the exergy losses.
- Suggest possible improvements

This method of working is, of course, obvious for the most part and standard practice. The most important difference, however, is the taking into account of the immediate surroundings and its effects on the system. That in itself allows us to introduce and apply the exergy concept and thus calculate the real losses in the process. As an example of the application of this method, I have selected a pulp and paper mill, a steel plant, and the Swedish space heating system.

5. A PULP AND PAPER MILL

The following two chapters describe a number of subprocesses in the steel and pulp and paper industry. In those cases where the descriptions are based on earlier energy studies which at times lacked sufficient data for making exergy calculations, estimates have been made. Certain data have been changed when they were shown to be obviously wrong during the exergy calculations. In order to simplify the description, the minor flows were neglected. Efficiency, defined as utilized outflow divided by utilized flows, is also given. Other efficiencies are also given for certain processes such as heating of steel.

The data used in this chapter is based on an energy study by Jan Fors and Börje Nord in 1980 of a pulp and paper industry - SCA-Nordliner i Munksund and contacts with chief of operations at the mill, Bo Häger, as well as on litterature (Ejderby 1976, Libby 1962, MacDonald 1969, Sittig 1977, Marín 1986). The mill annually produces 265 000 tonnes of unbleached kraft liner from 210 000 tonnes of unbleached sulphate pulp and 55 000 tonnes of recycled waste paper which is used mostly as raw material for corrugated fiberboard. The plant, which consists of the sulphate pulp factory and of the paper mill, is schematically illustrated in Fig. 5.1. The process may be briefly described as follows:

- The wood is separated from the bark. The bark is combusted in a steam production unit and the wood chipped.
- The chips are cooked with white liquor at high pressure in the continuous digester.
- The pulp and liquor are removed from the bottom of the digester by a blower mixer, to be screened, washed and refined.
- The pulp is then dried in the paper mill by dewatering, pressing and through evaporation.

The material flows of every subprocess given in tonne per tonne of produced paper (tonne/tp), and the energy and exergy flows in MJ/tp are presented in Appendix 1. Note that the paper mill supplies fiber via waste paper which accounts for the fact that the real production of pulp in a pulp factory is equivalent to a production of approx. 0.78 tonnes of paper. (In order to obtain values in tonne per tonne of pulp, this should be multiplied by a factor of 1.22.) The yield of the process, given as quantity of dry wood (fiber) in the paper, is 57%.

Table 5.1 gives the assumed chemical composition of the flows in the process. Figure 5.2 shows the exergy flows in the entire process. (It is interesting to compare this diagram to the energy flow (Fors and Nord 1980)). The most exergy-intensive processes are readily distinguishable. It is also interesting that large quantities of exergy in the form of liquor and black liquor (or concentrated waste liquor) circulate through the process. The circuit of the processing chemicals in the stripping liquor, mixed (or semi thickened) liquor, black liquor, green liquor and white liquor can also be readily discerned. A description of each subprocess is given below.

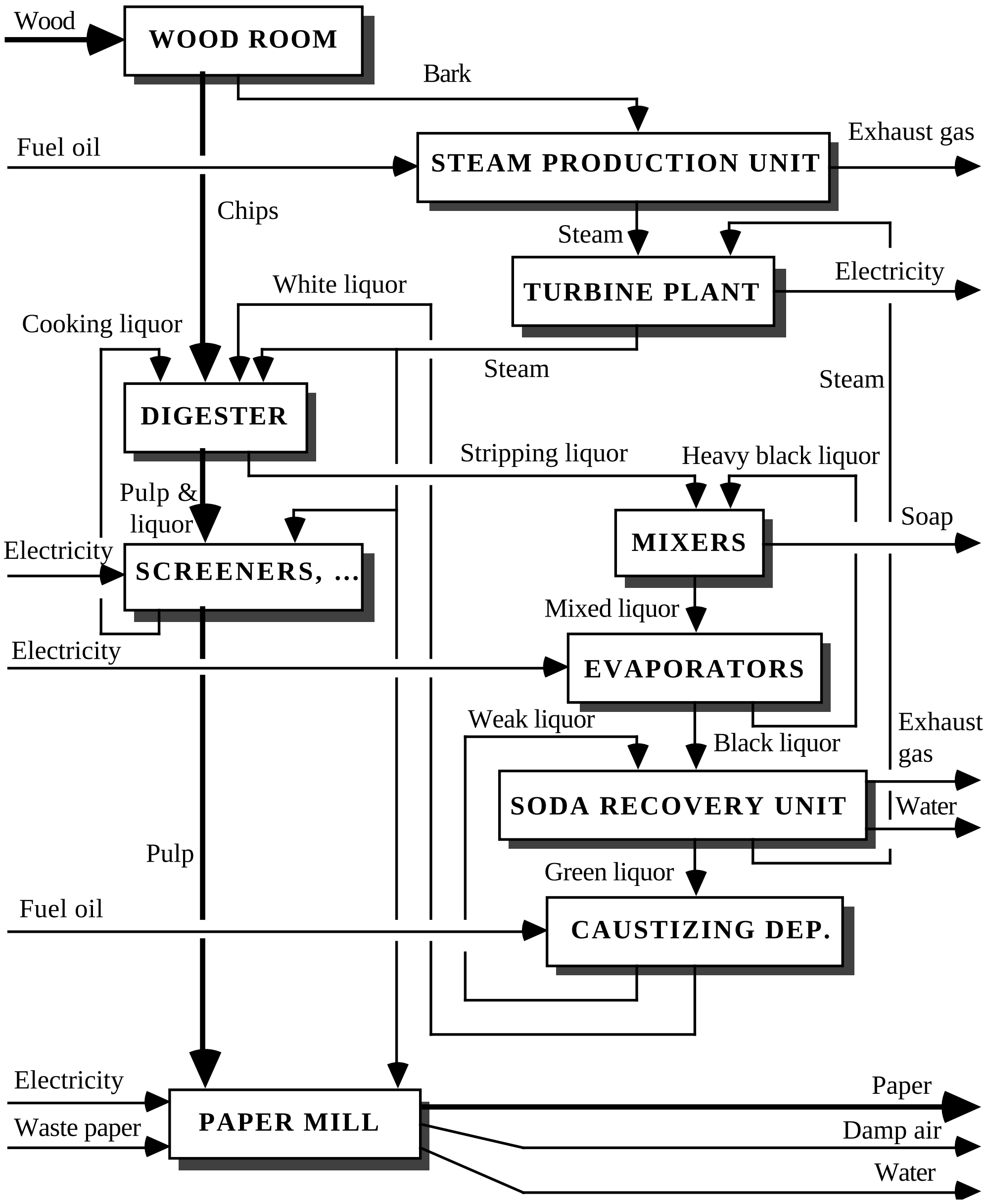
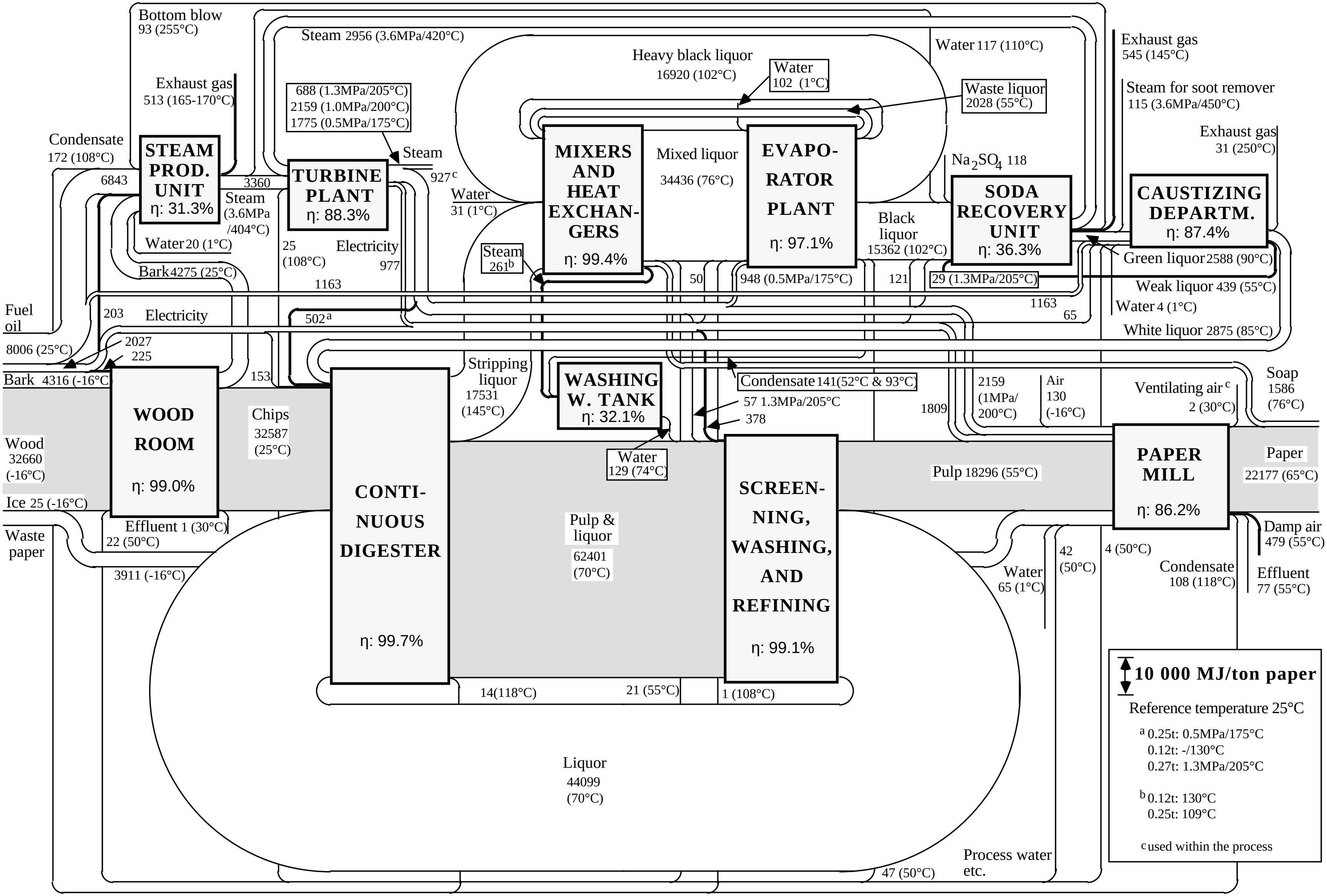


Fig. 5.1. A pulp and paper mill

Fig. 5.2. Exergy flow trough a pulp and paper mill



THE EXERGY FLOW IN A SWEDISH KRAFT LINER MILL (SCA-MUNKSUND) DURING JANUARY 1979

Table 5.1. Assumed chemical composition of substances in the pulp and paper mill

Substance	H	H_2O	C	O	Na_2CO_3	NaOH	Na_2S
Stripping liquor	0.6	85.8	4.7	3.9	0.9	2.5	1.6
Bark[a]	2.4	60.0	20.0	17.2			
Mixed liquor	0.9	76.2	7.4	6.4	1.7	4.5	2.8
Green liquor		80.8			14.0		5.2
Liquor	0.7	88.7	6.9	3.3	0.1	0.2	0.1
Pulp	0.8	87.1	6.3	5.8			
Pulp & liquor	1.4	78.0	12.4	7.6	0.1	0.3	0.2
Paper/kraft liner	5.8	7.6	45.0	41.6			
Waste paper	4.6	26.4	35.9	33.1			
Waste liquor	0.9	77.2	7.5	6.2	1.5	4.1	2.6
Weak liquor		95.9			3.0		1.1
Soap	4.7	27.6	46.9	20.9			
Black liquor	3.3	39.6	18.8	16.3	4.2	11.5	7.2
Wood/chips	3.1	50.0	25.0	21.9			
White liquor		83.2			3.1	8.4	5.3

[a]0.4% N

Wood room

The incoming wood is separated from ice and snow with hot water prior to debarking in the barking drum (bark quantity 0.44 tonnes/tp). The ice (0.70 tonnes/tp) is melted and heated with hot water to 30°C. The bark is pressed in order to reduce its water content from 65-70% to below 60% and thus upgrade its fuel value. The bark is then transported in a blowoff pipe to the steam production unit where it is combusted. The debarked logs are heated with hot water to 25°C and chipped (2.67 tonnes/tp). This increases the wood's energy value. The exergy of the wood, however, is reduced, since -16°C represents a contrast in temperature which disappears when the wood is assumed to be heated to 25°C, which is the given reference temperature. (This temperature agrees with the general standard (Weast 1983).) Electricity is used for debarking, chipping and dewatering of the bark in a bark press. A large quantity of effluent (6.13 tonnes/tp) builds up at a low temperature (30°C). The energy and exergy losses are, as we see, minor, see Appendix 1, which results in high efficiency values, 99.8% and 99.0%.

Continuous digester

The digester is continuous and of the KAMYR type. The wood chips and white liquor are continuously fed into the upper part of the digester while the pulp is removed from the lower part (of the digester) using liquor (pulp and liquor: 10.64 tonnes/tp). The processing chemicals, which are removed with the stripping liquor, are recovered by means of the white liquor. The chips are not fed directly into the digester. First, they pass through a steaming vessel which maintains a pressure of approx. 0.25 MPa. The chips are subsequently fed into a high pressure feeder with several rotating bins. This way, the chips can be fed from a bin to the top of the digester while another bin is being filled with chips and liquor. The digester is filled at all times and maintains a overpressure of 1 MPa. As we can see, the losses are once more minor and the efficiencies high.

Screening, washing and refining

The pulp is pulverized, refined and separated from the liquor. Knots and fiber bundles are broken up in the primary refiner. The cleansing liquid is brought in at the top in a continuous diffuser and pressed through the pulp. The liquor, which is heavier than water, is thus pushed out through the perforated bottom. Impurities larger than the pulp fibers are separated through screening. That pulp which passes through the screen is called accept and is used as the upper layer in the production of kraft liner. The pulp which does not pass through the screen is called reject pulp and is used for the bottom layer of the kraft liner. Both the accept and the reject pulp is subsequently washed in a washing filter consisting of rotating cylinders which are densely perforated and covered with a metal gauze. The remaining liquor is sucked out by the low pressure on the cylinder’s inner side. The pulp is rinsed with water above the water level of the tray in order to improve its washing effect. Finally, the pulp is refined once more prior to being pumped via storage tanks to the paper mill. Whenever large quantities of hot water with a low exergy content are used, the energy losses are higher than the exergy losses. Consequently, the exergy efficiency (99.1%) is higher than the energy efficiency (98.4%).

Mixers and heat exchangers

The liquor leaving the digester is thickened by being mixed with the black liquor to enable it to be processed in the evaporator. Mixing of the concentrated liquor prevents foaming in the evaporator and reduces the evaporator’s energy consumption. Mixing takes place in stages which, at the same time, yields valuable steam. Subsequent to the first inmixing, the concentrated waste liqour is brought into a mixing tank which maintains a pressure of 0.27 MPa. A part of the water content of the liquor is evaporated when the pressure is lowered. The steam released in this way is utilized in the digester’s steaming vessel. In the other mixing tank with a pressure of 0.14 MPa, the steam is flashed to a column where it is condensed and the built-up liquor vapor condensate is pumped to wash-water tanks.

The liquor is then exchanged with cold water which is heated to 55°C in order to be used in other processes. The waste liquor and the heavy black liquor are mixed while the soap is skimmed off from the readymade liquor surface as a by-product before the mixed liquor is pumped to the evaporation plant. The soap, which has been dissolved in the water, sharply reduces its solubility when the liquor is thickened, forms a coating on top of the liquor, and can be thus easily skimmed off. The soap is boiled to resin oil (liquid resin or tall oil) in a resin boiling plant and sold. Production amounts to 45 kg of resin oil per tonne of pulp.

We can note from Fig. 5.2 that the exergy content of the incoming cold water, at 24°C below the reference temperature, is 31 MJ/tp, i.e. higher than for the same quantity of outgoing hot water at 55°C, 21 MJ/tp, i.e. 30°C higher than the reference temperature.

Evaporator plant

The mixed liquor is evaporated to about 60% of dry content (black liquor) by being steamed in order to be more efficiently combusted later in the soda recovery unit. In order to keep steam consumption to a minimum, this process takes place in several steps at successively lower temperatures and pressures. The liquor is brought in through the bottom part of the unit in tubes which are heated with steam on the outside. The upper part of the evaporator has a separator which separates the liquor from the steam, whereby the liquor leaves through the bottom part of the separator while the steam leaves through the top. In order to keep fresh steam consumption to an absolute minimum, the evaporators are connected in series so that the subsequent steps are accomplished at a lower pressure and thus lower temperature and heated with the steam used in the previous step. The connection is in five steps, which are also termed effects. This way, fresh steam needs to be supplied only in step 1. A four-step system thus consumes only 30% of the heat as compared with an evaporator plant which makes use of only one step. A five and six-step system yield a consumption of 25% and 20%, respectively. In step 3 the mixed liquor is brought in and subsequently passes steps 4 and 5. Following step 5, the dry content of the liquor is over 35% and is termed semi-concentrated (or thickened) black liquor. The latter is heated in two tubular preheaters and six coil type preheaters before it is evaporated to the desired dry content in steps 1 and 2. Part of the concentrated liquor obtained is combusted in the soda recovery unit and the rest is used to raise the concentration of the stripping liquor. The utilized waste liquor is also mixed in the stripping liquor. The major part of the liquor vapor condensate is pumped to a wash-water tank, a minor part, however, is used in a column. The heat given off when the liquor vapor in step 5 condenses is used for hot water production by being heat exchanged with cold water that is heated to 50°C. The efficiency of the evaporation is lower than that of the previously described processes since this processes requires large quantities of steam for heating purposes.

Soda recovery unit

The organic substances in the black liquor released from the wood in the continuous digester are combusted in the soda recovery unit. Small quantities of chemicals such as sodium sulphate (about 30kg/tp) are added to the black liquor to replace the chemicals that were lost in the pulping process, before the liquor is sprayed into the soda unit through nozzles. The non-combusted substances in the concentrated liquor, are recovered in the melt at the bottom of the unit. Chemicals carried over with the gas exhaust (primarily sodium sulphate) are recovered in the electrostatic filter to be brought back to the black liquor. The heat generated during combustion is utilized to produce steam at a pressure of 3.6 MPa and a temperature of 430°C. The hot exhaust gases are utilized partly in order to reheat the combustion air and to heat the incoming feedwater from 110°C to 190°C. The recovered melt is cracked with steam before it falls into the melt mixer. Here, the melt is dissolved in the weak liquor from the causticizing department and this solution, in accordance with its color, is called green liquor. The green liquor is subsequently transported to the causticizing department where it is converted to the white liquor. The soda recovery unit is essentially a chemical reactor for recovering the processing chemicals present in the concentrated liquor. Energy efficiency is considered only once the safety and environmental requirements have been fulfilled. This explains the unit’s low exergy efficiency, which is a mere 36.3%.

Steam production unit

The production of steam from the combustion of the black liquor in the soda recovery unit does not suffice to meet the steam requirement of the mill, which is why a special steam production unit is installed. The bark and fuel oil are combusted and converted to steam at a very low exergy efficiency, for further comments see the total process below. As can be seen in Fig. 5.2, a bark equivalent of about 4.3 GJ/tonne paper was combusted in January 1979. The steam production unit consists of two steam boilers both of which can be oil fired and one which can be bark fired thanks to a special (Axon) furnace. As in the case of the soda recovery unit, the difference between energy and exergy efficiency is large, 88.4% as compared to 31.3%, respectively. This can be explained partly by the significantly lower exergy value (as opposed to the energy value) of the utilized outflows.

Turbine

The steam produced in the soda recovery unit and the steam production unit has considerably higher pressure and temperature than is necessary for the process. The steam can therefore by utilized in a back pressure turbine to generate electricity. The generated electricity constitutes approximately 30% of the mill’s electricity requirement. There are also pressure relief valves to make it possible to lower the pressure even while the turbine is not operating. A steam storage tank is used to level out the variations in production and consumption of steam. As a result of the large portion of steam that is being throttled (about 25%), the exergy efficiency is only 88%. In this case, more efficient regulation is recommended (compare cyclical regulation to throttling of fans and pumps).

Lime sludge reburning kiln and causticizing

In the causticizing department, the green liquor, which contains soda and sodium sulphide, is converted, causticized, to the white liquor. Sodium sulphide is used for pulp processing while the soda must be converted to sodium hydroxide before it can work effectively. This is done by adding lime to the green liquor.

$Na_2CO_3 + CaO + H_2O \rightarrow 2NaOH + CaCO_3$
(soda + lime + water → sodium hydroxide + calcium carbonate)

The lime and the green liquor are mixed in a so-called lime-slaker. The mixture then passes three causticizing vessels where the causticizing reaction takes place during mixing and at a temperature of 100°C. The so-called lime sludge (calcium carbonate sludge) is separated from the liquor in a white liquor clarifier and washed from the remaining chemicals in a lime-sludge washer and rotary vacuum filter before it is combusted in the lime sludge reburning kiln. A weak liquor builds up in the filter during the washing which is then used as the washing liquid in the lime-sludge washer. As it leaves the filter the lime sludge has a dry content of about 60%. Chemically the lime sludge is equivalent to limestone and is therefore converted to lime in the reburning kiln to be reused in the process. In this way, only the lime which is lost in the process has to be replaced. As the hot lime leaves the kiln at a temperature of about 1100°C, it is cooled to 200°C, at the same time preheating the combustion air. The exergy turnover in this process is, as we can see, relatively small. Because the reburning kiln is one of the few units to use oil (about 1200 MJ/tp), it attracts special interest from the point of view of efficiency.

Paper mill

The paper mill manufactures kraft liner which is built up of two layers. The bottom layer i made up of relatively roughly ground pulp, so-called base pulp (base stock), while the upper layer, which is thinner, is called top stock. The paper mill consists of the following units: stock preparation (also called beater section, crushing or grindning mill), wire part, press section and drying section, each of which fulfills the following functions:

Stock preparation. Between the sulphate factory and the paper mill is a pulp storage unit to which the (white) pulp water (the water from the drying of pulp to paper) is pumped in order to reduce fiber concentration. This mixture (4% pulp) is subsequently transported to the stock preparation department. Here, the fibers are ground, suitable chemicals added and the pulp diluted with the pulp water to form a mixture called stock with a fiber concentration of about 2.7%. Before the stock is pumped out to the wire part, it is diluted to a fiber concentration of 0.5% by briefly circulating the pulp water through the paper machine. The stock preparation department also processes waste paper fibers which are mixed into the base pulp.

Wire part consists of rollers, head boxes, suction boxes, etc. to construct the sheets and dewater the stock.

Press section consists of three rollers to press out the water under high pressure. This also improves fiber contact.

Drying section has the task of drying out the remaining water from the web by means of 96 steam-heated cylinders.

The paper machine is finished off with a calendering section and a reel-up, where the paper is reeled on a so-called reeling drum. The paper on the reeling drum is subsequently cut into suitable sizes in a slitter-rewinder and is then ready for delivery.

Nearly 100% of the supplied steam is used to dry the pulp to paper. The moist air thus obtained as a by-product is utilized to a minor extent to preheat the ventilation air. The supplied waste paper represents a fiber addition of about 0.2 tonnes/tp.

In a final product that contains about 0.93 tonnes of fiber, the extra fiber from the waste paper constitutes about 22%. If this extra fiber is removed from the process, the supplied raw material must correspondingly increase, that is, be multiplied by a factor of 1.28 to reach the same quantity of produced paper, i.e. 1 tonne.

The total process

Table 5.2 is a compilation of every subprocess and gives the quantitative and percentual energy and exergy losses relative to the entire mill. The total losses also include the unutilized outflows. Of the direct energy losses of the mill, the predominant losses are incurred in the soda recovery unit which accounts for more than half of the energy losses (column 1 and 2). Considerable losses are also incurred during screening, steam production and in the paper mill. If we also include the unutilized process flows (columns 3 and 4), the losses incurred in the soda recovery unit appear to be somewhat less. The steam production unit and the paper mill, which yielded considerable energy losses in the form of moist air and hot water now also play an important role.

Table 5.2. Energy and exergy losses in the pulp and paper mill

	Energy losses				Exergy losses			
Process:	Direct	%	Total	%	Direct	%	Total	%
Wood room	65	0.8	194	1.0	385	1.6	386	1.5
Continuous digester	169	2.0	169	0.8	270	1.1	270	1.0
Screening, etc.	1087	12.7	1087	5.4	570	2.3	570	2.1
Mixers, etc.	42	0.5	42	0.2	206	0.8	206	0.8
Evaporation	840	9.8	840	4.2	1039	4.2	1039	3.9
Soda recovery unit	4485	52.5	7228	36.2	9889	39.9	10549	39.8
Steam production unit	1271	14.9	3405	17.0	7616	30.8	8129	30.6
Turbine plant	3	0.0	3	0.0	742	3.0	742	2.8
Caustizing department	16	0.2	132	0.7	479	1.9	510	1.9
Paper mill	560	6.6	6875	34.4	3569	14.4	4125	15.6
Total	8538	100	19975	100	24765	100	25526	100

From the direct exergy losses (column 5 and 6) we also conclude that the soda recovery unit, the steam production unit, and the paper mill are the least efficient conversion processes. However, we see that the steam production unit now appears as a considerably larger source of loss than previously. This picture holds even when we compare the values in the last two columns which include the exergy losses in the unutilized process flows. From the column showing the direct exergy losses, we also see that exergy losses are almost equally distributed among the other processes. This is probably due to the fact that the mill is pretty well optimized in this regard. We also see a dramatic difference between the sum of the direct and total energy and exergy losses. In the case of energy, the unutilized outflows, i.e. the difference between the total and the direct losses, constitute 57% of the total losses but in the case of exergy, only 7%. The unutilized outflows are, essentially, a much smaller resource than energy calculation reveals. This constitutes the largest difference between an energy and an exergy treatment.

The losses in the paper mill can be partly justified by the considerable demands of the readymade product. This is also the final subprocess, which indicates that the all to large direct demands on the limiting of energy and exergy losses may result in an increased number of rejects which may result in even higher total losses for the entire factory. The immediate efforts to increase exergy efficiency should therefore be directed at the soda recovery unit and the steam production unit. Before we examine these in more detail, let us see how the losses in the unutilized process flows are distributed in terms of energy and exergy.

In Table 5.3 we see that the exergy losses are predominantly exhaust gases and damp air which, of course, are strongly linked to the soda recovery unit and steam plants. The temperature of the exhaust gases varies between 145°C and 170°C. This makes the exhaust gases interesting from the point of view of electricity production (Horio 1982). However, of immediate interest is the preheating of air and fuel. The temperatures of the damp air and water are so low that they can only be applicable for space heating purposes or possibly as a heat source in a heat pump system.

Table 5.3. Unutilized outflows

Unutilized outflows:	Energy	%	Exergy	%
Damp air	4680	40.9	479	27.2
Flue gas and soot blowing	4993	43.7	1204	68.4
Water (30-55°C)	1764	15.4	78	4.4
Total	11437	100	1761	100

Thus, an exergy calculation for the mill unequivocally reveals that the soda recovery unit and steam production unit ought to be made more efficient. That this should be possible to accomplish can also be seen by looking at the combustion efficiencies of these two, which are a mere 27% and 31%, respectively. The disparity between the exergy price and capital costs, however, indicates that the calculation method ought to be taken further, for example, using thermoeconomic methods (Wall 1985). Thus, altering the steam production unit, for example, to replace oil-firing with bark-firing, can be cost-effective in spite of the higher energy and exergy losses.

Let us now treat the entire factory as a process of conversion where investments like wood yield paper and liquid resin, Fig. 5.2 (the ice is negligible). We see that about 47% of the incoming exergy remains in the final product. Of the exergy content of the incoming wood, about 56% remains in the manufactured paper. This value can be compared with the yield, 57%, measured as dry substance. For the process as a whole, the result can be a nearly double exergy yield from the wood. At present, it is impossible to say how this can be accomplished. Perhaps in the future, bacteria and fungi will be able to decompose the wood to a pulp more efficiently than current-day processes. A first step towards more exergy-efficient processes would be to channel efforts to improve the mill in accordance with the exergy losses. However, in the short run, research efforts ought to be directed primarily to improve the soda recovery unit. This study is concerned with exergy and does not deal with other aspects such as practical and economic which are also relevant. Other studies are needed to provide additional justification to the proposed measures.

6. A STEEL PLANT

The data for this study is based on a 1978 study by Jan Fors and Rune Hardell of energy use in three steel plants, interviews with chief of operations at the Halmstad steel mill, Roland Myrgård, and current litterature in the field (Flinn 1963, Hiwatashi 1981, Nishikawa 1980, Fett 1982, Sharp 1967 and Sims 1962). The energy calculations in this study differ from those of Fors and Hardell in terms of the chemical energy in the material that has not been combusted. Moreover, different methods have been used for calculating the heat content which yields values for the exhaust heat, for instance.

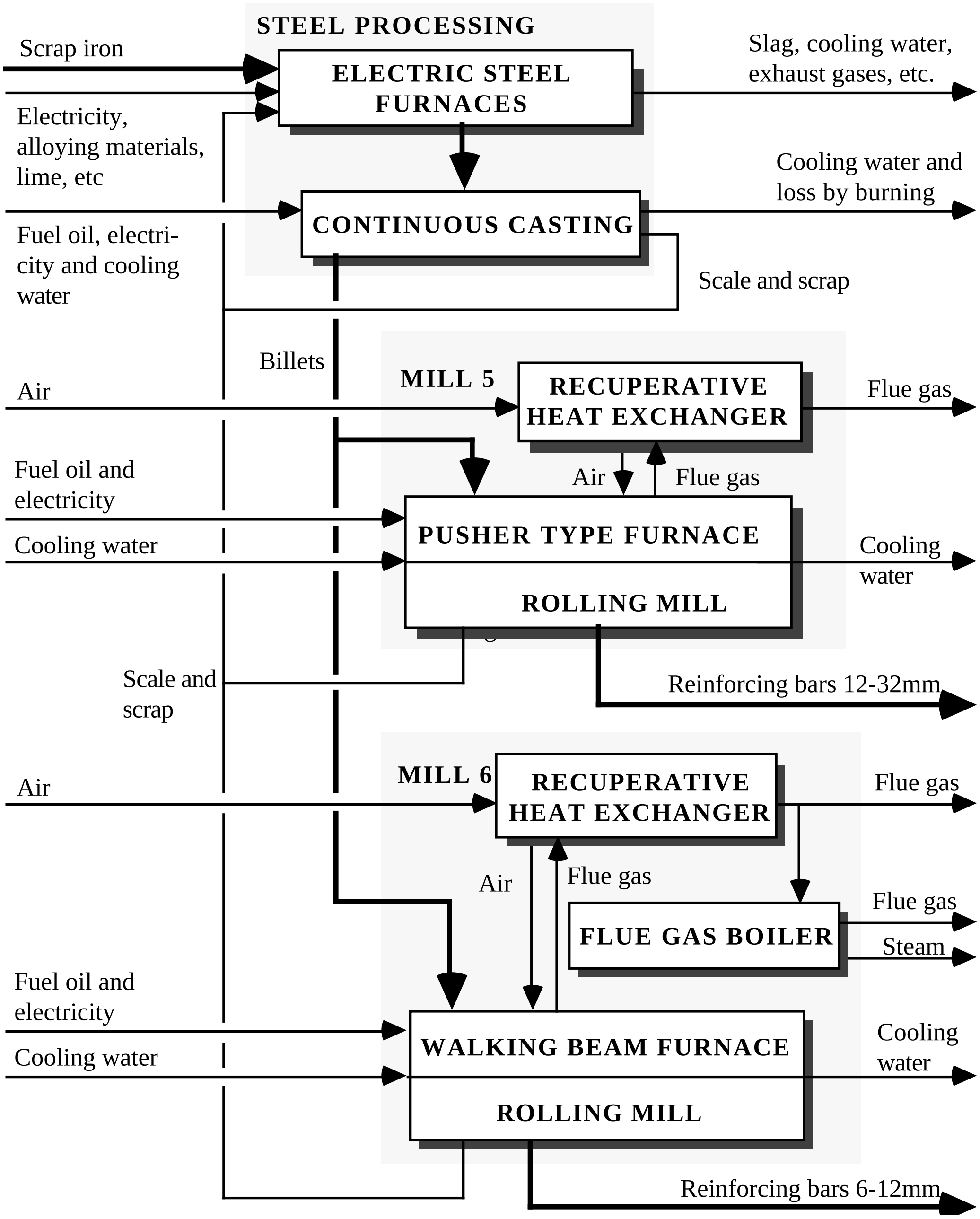
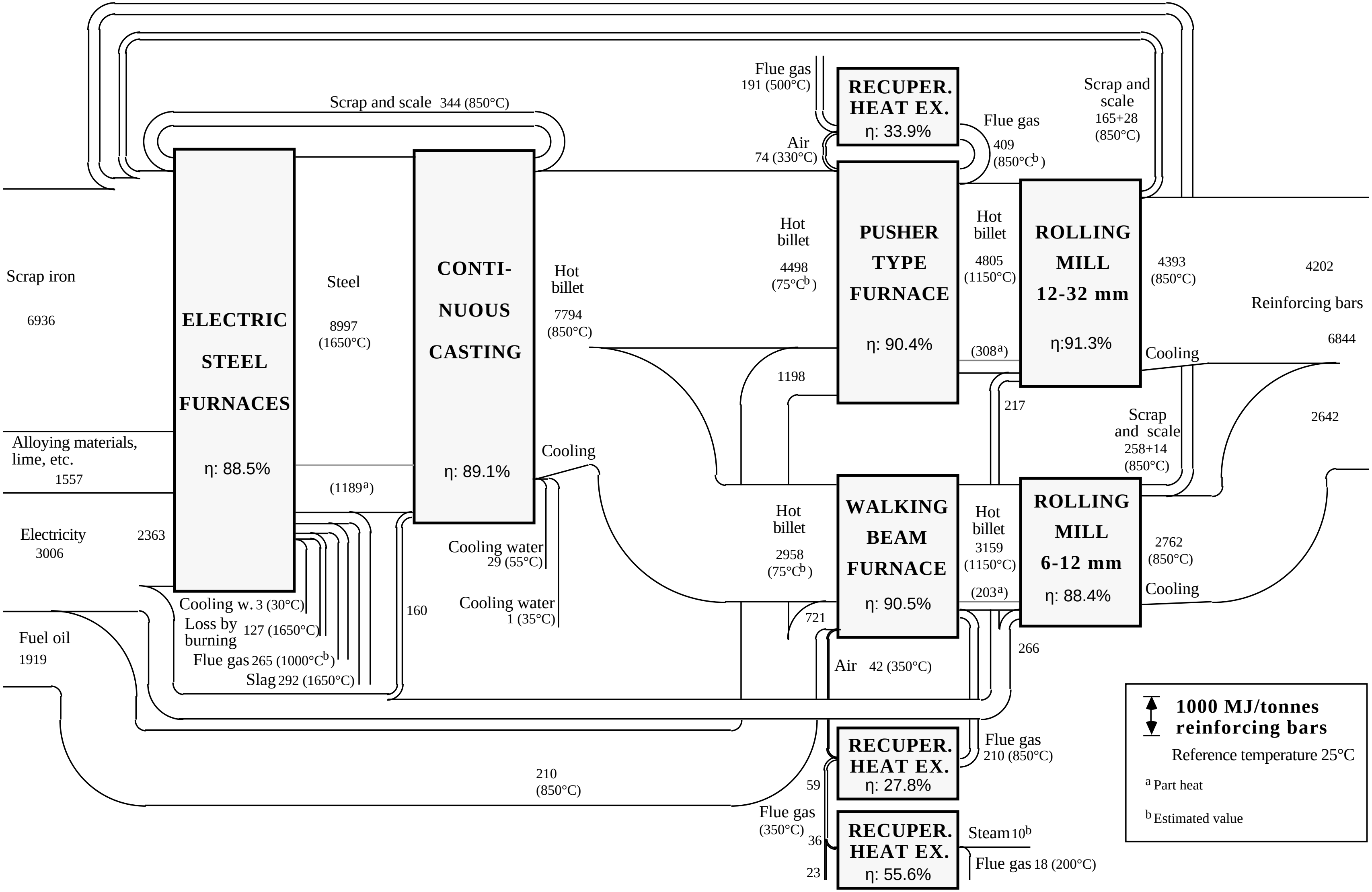


Fig. 6.1. A steel plant

Fig. 6.2. Exergy flow in a steel plant



THE EXERGY FLOW IN A SWEDISH STEEL PLANT (HALMSTADS JÄRNVERK) DURING MARCH 1976

The Halmstad steel plant has an annual production capacity of approximately 280 000 tonnes of reinforcing steel (this is valid for the actual year under study (Fors 1978)). The present study deals with the steel mill and with the rolling mill. The raw material is melted in two electric steel furnaces with a 50 tonnes capacity each and is then cast in two continuous casting machines with three continuous runs each. The billets are rolled in two rolling mills (mill 5 and 6) to bars and wires of circular crossections of 5 to 32 mm. (The data is based on monthly production in March 1976). Figure 6.1 gives a schematic illustration of the process. The material flow in kg/tonne of produced reinforcing steel (kg/tr) and the energy and exergy flows in MJ/tr of the mill are given in tables in Appendix 2 for every subprocess. Note that the exergy value given for the steel only represents the so-called “physical quality” of the steel in relation to the reference conditions selected. That is, the work that could be theoretically extracted if we could operate a machine in which steel is converted to the metal oxides and other reference condition substances. The exergy value does not include other properties that are a measure of quality such as ductility and corrosion restistance. The exergy value is more linked to the manufacturing of the product at hand than with its properties. The exergy value can be said to give the minimum theoretical resource requirement for manufacturing the product at the assumed reference conditions. By comparing in terms of exergy two different methods of manufacturing the same end-product, we can establish which method is thermodynamically most efficient.

Figure 2 illustrates the exergy flow in the steel plant. The widths of the illustrated flows are proportional to the exergy content. Total inflow is approximately 12 700 MJ/tr and the total outflow of reinforcing steel is approx. 6 800 MJ/tr. The unutilized outflows are equivalent to approx. 1 000 MJ/tr which yields an exergy efficiency of 54%. This diagram also provides a good overall picture of the mill’s resource flows of electricity, fuel oil, heat and steel.

Electric steel furnaces

Scrap iron is melted and, in order to obtain the right chemical composition, alloying materials are added. Lime and fire-resistant material as well as graphite from electrodes are consumed in the process. Large quantities of cooling water are used to maintain the furnace at a low and stable temperature. Scrap iron and electricity represent the largest exergy flows. The cooling water accounts for the largest material flow, about 17m^3/tr. The readymade steel constitutes the predominant outflow, and through its high temperature of about 1 650°C it also contains a large quantity of thermal energy. By comparing the inflows and outflows, we can calculate the energy and exergy efficiencies, see Appendix 2. The exergy efficiency is lower than the energy efficiency, 88.5% as compared to 97.7% which is due to the fact that the heat in the readymade steel has a lower exergy than energy value, 1 662 MJ/tr energy as compared to 1 189 MJ/tr exergy, which is also shown in Fig. 6.2.

The chemical energy content of the steel is 7.55 MJ/kg. The chemical exergy value of the scrap iron has gone up from 6.45 to 6.84 MJ/kg in the readymade steel, which represents a small change in exergy but a very important change in quality.

Slag (292 MJ/tr) and exhaust gases (265 MJ/tr) from the molten iron represent the largest unutilized (waste) flows. The temperature of the exhaust gases varies between 500°C and 1 500°C. The cooling water represents a substantial energy flow, 356 MJ/tr, but because of its low temperature, 30°C, is of very little interest in terms of exergy, 3 MJ/tr. The thermal exergy content is less than 1% of the thermal energy content since the temperature is only 5°C higher than ambient temperature. The readymade steel is tapped on a ladle and tranported to be cast.

Continuous casting

The solidifying steel is cooled with water as it is cast and subsequently cut into suitable lengths to billets. As the steel is cooled, the thermal energy and exergy in the hot billets is lost. The hot billets are placed on a cooling bed, where the temperature drops from about 850°C to about 450°C. Because in the later stages of processing, the steel is handled with magnets, the temperature must be lowered to well below Curie temperature, which is about 770°C. During the cold season of the year, this heat is used for space heating. From the cooling bed the billets are placed on wagons outside awaiting transport to the rolling mill. As a rule, the temperature drops to somewhere between 100°C and the prevailing outdoor temperature before the billets are transported to the rolling mill. This process is illustrated in Fig. 6.2 as a decrease in the outflow from the continuous casting.

Pusher type furnace (mill 5)

The rolling mill consists of two mills. The heavier steel is rolled in mill 5 into bars between 12 and 32 mm in diameter and in mill 6 to bars and wires between 6 and 12 mm in diameter. Large quantities of cooling water are used in the rolling mill, too, about 2 900 kg/tr. No measurements have been made of how this water is being used in the rolling mill, which is why I have chosen to illustrate this separately.

The rise in temperature is about 15°C and the change in energy and exergy (content) is about 183 MJ/tr and 5 MJ/tr, respectively. About two thirds of the billets are rolled in mill 5. The billets are heated to about 1 150°C prior to rolling.

Heating takes place in such a way that the billets are successively pushed against the hotter part of the furnace. The composition, by weight, of the exhaust gases is 73% nitrogen, 10% oxygen, 12% carbon dioxide and 5% steam. The losses consist of heat given off to the surroundings and in the exergy calculation also as losses when the chemical exergy in the fuel oil is converted to heat. The efficiency of the furnace, defined as heated steel divided by utilized fuel (oil and air) is about 74% for energy and about 35% for exergy. This leaves plenty of room for technical improvement as shown by the low values of exergy efficiency.

Recuperative heat exchanger (mill 5)

Part of the exhaust heat from the pusher type furnace is used to preheat the combustion air from outdoor temperature to about 330°C. (Note that the direction of the current for this process is reversed in Fig. 6.2, i.e. from right to left). It is assumed that the temperature of the flue gas entering the recuperative heat exchanger is 850°C, and that leaving the heat exchanger 500°C, respectively, since exact data is not available. The efficiency, defined as absorbed heat divided by heat given off is 73% and 34%, respectively. The exergy efficiency is very low despite the high energy efficiency.

Rolling mill (mill 5)

The hot billets are now rolled to reinforcing bars 12-32 mm in diameter. Scrap and scale is returned to the electric steel furnaces. The temperature of the readymade steel is assumed to be 850°C. The losses are primarily heat lost to the surroundings as a result of the cooling and the internal friction losses when the billets are rolled. The heat of the finished reinforcing steel, 191 MJ/tr, is lost to the surroundings through cooling.

Walking beam furnace (mill 6)

The reinforcing steel with fine crossections of 6-12 mm is rolled in mill 6. The billets are fed in gradually into the hotter part of the furnace. If we compare this with a pusher type furnace, we find that on the whole the efficiency of both furnace, is very similar. A part of the exhaust heat is utilized in the recuperative heat exchanger to preheat the combustion air to about 350°C.

Recuperative heat exchanger (mill 6)

The energy and exergy efficiencies differ considerably in this heat exchanger, too, about 55% and 28%, respectively. (The direction of the flow in Fig. 6.2 is reversed in this case as well.) This is typical for all heat exchangers and is due to the fact that passive heat transfer generally causes large exergy losses. However, in this case, some of the exhaust heat is also utilized in a flue gas boiler.

Flue gas boiler (mill 6)

Some of the exhaust heat from the walking beam furnace is also used via the recuperative heat exchanger for steam production in a flue gas boiler. Whenever data is not available, this part is assumed to be 60% of the exhaust flow from the recuperative heat exchanger. The steam thus generated is transported to a boiler dome to be further used for domestic hot water heating, and to some extent, as industrial steam in the rolling mill.

Rolling mill (mill 6)

The cooling after rolling of a total of 1 000 kg of steel at 85°C in both rolling mills yields, as we can see, an energy loss of 558 MJ, see Appendix 2, and an exergy loss of 311 MJ.

The total process

The energy and exergy losses of each subprocess and of the entire plant are shown in Table 6.1. The total losses consist partly of direct losses in the subprocess itself and during cooling, and partly of unutilized flows. Of the direct energy losses (column 1 and 2), the continuous casting, the first cooling stage, both rolling mills and the final cooling appear as the largest. Together, these account for 2 620 MJ/tr or 77.7% of the direct energy losses. If we include the unutilized flows (columns 3 and 4), the electric steel furnaces and the continuous casting emerge as the largest sources of loss. More or less the same picture is maintained when we calculate the exergy losses. Moreover, both furnaces contribute considerable exergy losses. These furnaces also consume fuel oil which is used by the mill. It would be possible to utilize the exhaust from all of the furnaces using conventional technology so that the exhaust temperature is lowered to below 200°C before it leaves the mill (Hiwatashi 1981). All of the heat losses could also be utilized for electricity production in a low temperature turbine plant (Horio 1982). A simplified compilation of the losses of the mill can be made in order to further point out the differences between an energy and an exergy treatment, Table 6.2. In the energy calculation, the losses in the unutilized outflows appear most important beside the direct losses in the process itself. An important difference is that in the exergy calculation, the direct losses constitute the entirely dominant losses. The unutilized outflows, such as waste heat and cooling losses are less important.

Table 6.1. Energy and exergy losses in the steel plant

	Energy losses				Exergy losses			
Process:	Direct	%	Total	%	Direct	%	Total	%
Steel process								
Electric steel furnaces	247	7.3	1462	23.8	1172	24.2	1859	32.0
Continuous casting	517	15.3	1217	19.8	989	20.4	1019	17.5
Cooling	611	18.1	611	10.0	353	7.3	353	6.1
Mill 5								
Pusher type furnace	175	5.2	175	2.9	556	11.5	556	9.6
Recuperative heat ex.	85	2.5	585	9.5	144	3.0	335	5.8
Rolling mill	481	14.3	494	8.0	436	9.0	446	7.7
Mill 6								
Walking beam furn.	131	3.9	131	2.1	352	7.3	352	6.1
Recuperative heat ex.	104	3.1	179	2.9	109	2.3	132	2.3
Flue gas boiler	10	0.3	84	1.4	8	0.2	26	0.4
Rolling mill	420	12.5	427	7.0	391	8.1	397	6.8
Mill 5 and 6								
Cooling water			183	3.0			5	0.1
Cooling	591	17.5	591	9.6	329	6.8	329	5.7
Total	3372	100	6139	100	4839	100	5809	100

Earlier in this paper, we mentioned losses in connection with cooling of the hot billets. However, these losses should be examined more closely since the preheating prior to rolling is a direct function if the earlier cooling stage. We could argue that when the billets are allowed to cool, the total losses should also include the total heating cost later in the process. The total loss during cooling is thus 2257 MJ/tr (exergy) or about 39% of the total losses of the mill. This indicates that the casting-rolling process ought to be continuous. However, a completely continuous process is usually impossible to achieve. Instead, various alternatives should be developed, for example, to prevent heat emissions or to utilize the heat for other purposes. Today’s steel plants already are attempting to keep the time between the casting and rolling to an absolute minimum. This particular measure ought to be further examined with regard to the large savings, particularly of oil, this could mean. The exergy flows in the heating of steel have also been studied at Kyshu University and by the Nippon Steel Company (Nishikawa 1980), whose conclusions are in good agreement with this study. Oil consumption alone accounts for over 15 000 m^3/yr which, at an oil price of SEK 2 000/m^3, is equivalent to SEK 30 million in operating costs alone. There are thus good economic reasons to investigate whether better ways can be found of re-allocating these funds within the process.

Table 6.2. Energy and exergy losses

	Energy losses	%	Exergy losses	%
Direct losses	2170	35.3	4157	71.6
Cooling losses	1202	19.6	682	11.7
Unutilized outflows	2767	45.1	970	16.7
Total	6139	100	5809	100

7. SPACE HEATING

The most common energy conversion process in Sweden is the conversion of low-temperature heat. Today, this takes place independently of the industrial processes, under entirely different conditions and objectives. The difference in efficiency is thus very substantial. Space heating presently accounts for 40% of Sweden’s energy consumption. Space heating is the largest single energy user in Sweden. At the same time, it represents the largest exergy loss in the country, but also the simplest to improve. Let us first see what space heating actually is about by looking at the whole picture from a scientific point of view. We maintain the temperature of a system with defined boundaries, a building, at about 293K (=20°C) in surroundings at about 273K. If we view the process in this way, we can also see how relatively small the temperature increase really is, the task is to maintain the temperature at about 7% over ambient temperature.

Many people today are very pleased to assert that the efficiencies of certain space heating systems are nearly 100%. They claim that the efficiency of an oil-fired boiler is 85% and that of electric heating, 100%. This may be true, but the maximum value of efficiency thus defined is about 1500%. Thus, a heat pump can supply more thermal energy than it consumes as work in the form of oil or electricity. However, this relationship is never mentioned (to my knowledge). This way of thinking often projects an incorrect picture of a space heating system. The concept of exergy offers a better way to describe a system and it means, among other things, that the maximum possible efficiency would never exceed 100%. Let us now take a closer look at the space heating of a house.

Assume that we can maintain a temperature of 20°C in a house that is located in surroundings at a lower and varying temperature. The energy requirement for heating the house will then vary more or less directly with the difference between indoor and outdoor temperature. The effects of wind and humidity are not considered in this case. At the same time, the exergy value of the supplied heat also varies in relation to the outdoor temperature as follows:

$$E = Q(T-T_0)/T \tag{7}$$

where T is the indoor temperature (293K), T_0 the varying outdoor temperature, and Q the heat quantity supplied to the house. We recognize the factor $(T-T_0)/T$ as the so called Carnot coefficient, see Eq. (1). At an outdoor temperature of 0°C, this will be about 6.8%. With data on how the outdoor temperature varies throughout the year, we can calculate the real exergy requirement during the heating season. We can then obtain the following results, valid for 1975 (Wall 1981), see Table 7.1.

Table 7.1. Mean annual temperature T_o, minimum five-day mean temperature T_{min}, number of heating days d, exergy value E/Q, portion of the population X and relative exergy value X·E/Q in 1975.

Representative town[a]	T_o°C	T_{min}°C	d days	E/Q%[b]	X%	X·E/Q%
Umeå	4.0	-11.0	277[c]	6.72	9.4	0.632
Östersund	4.2	-9.2	283	6.27	8.5	0.533
Karlstad	7.7	-4.4	235	5.00	9.9	0.495
Stockholm	8.4	-3.2	230	4.84	24.0	1.160
Jönköping	7.9	-3.6	237	4.82	17.3	0.834
Göteborg	9.3	0.3	226	4.00	16.6	0.664
Malmö	9.1	-1.6	225	4.54	14.3	0.649
				Total	100.0%	4.97%

[a] The country is divided into areas according to: (the letters represent counties) Umeå: BD, AC, Y, Östersund: X., Z, W, Karlstad: S, T, U, Stockholm: A, B, C, D, Jönköping: E, F, G, H, I, R, Göteborg: N, O, P, Malmö: K, L, M.

[b] Calculated at an indoor temperature of 20°C and a diurnal temperature variation of 4°C.

[c] Value refers to Luleå.

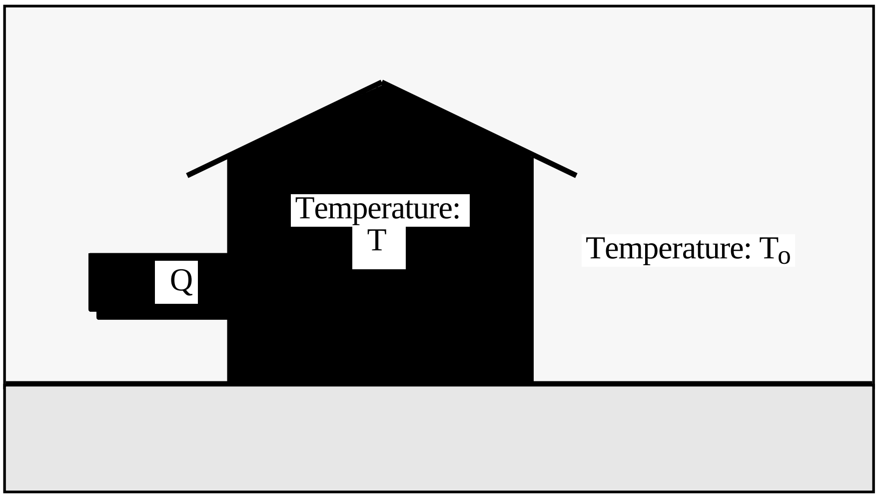


Fig. 7.1. Indoor temperature T in a house at ambient temperature T_o is maintained by a heat flow Q, which exactly counterbalances the heat flow to the surroundings.

The urban areas with colder temperatures have higher exergy values, since warm house heat represents a higher contrast to the surroundings. On the other hand, more energy is required for space heating. Since energy consumption is concentrated to densely populated areas, a weighted average value for all of Sweden can be calculated at about 5%. This result can be interpreted is such a way that the space heating requirement in terms of exergy constitutes only about 5% of the energy requirement. The above-mentioned oil-fired boiler thus yields an exergy efficiency of 4.3% and the electric heater 5%. Assuming an ideal heat pump, the energy consumption for space heating could theoretically be reduced to one twentieth. This enormous waste of resources, which results from an inadequate technology more than justifies a stronger commitment to limit space heating requirements by means of such measures as insulation and sealing of joints. Today's deplorable space heating technology, which results in a huge energy use and environmental destruction, is worse and more dangerous than when Englishmen wrecked their forests for making fire-wood during the 18th century. New efficient space heating systems such as heat pumps and better building construction and materials can save considerable resources of which environmental resources are not least important, e.g., forest destruction due to acid rain.

8. ENERGY AND EXERGY PRICES

The choice of energy source for industrial and other uses is primarily governed by prices. The energy conversion system thus created places corresponding demands on the energy supply system. Sometimes, these systems are shown to be uneconomical with time or in a long-term perpective, i.e., prices are incorrect or insufficient as a basis for planning. One example of this is when prices are set based on short-sighted political assessments or on insufficient knowledge of the resource in question and the consequences of its use. It is therefore important to find a sounder method for price setting. Prices based on exergy values could be designed so as to benefit resource-saving and efficient technology. Large exergy losses should also mean large economic losses. The prices of physical resources ought to be set more in relation to the physical value of these resources, i.e., exergy.

This chapter explains the differences between the price setting of several common energy sources and their respective exergy values (Liljenstam et al. 1982). All prices are valid for Göteborg in spring 1982 and include taxes.

Electricity

Electrical energy can be treated as totally converible to work. The energy price is therefore also the exergy price. The price of electricity varies considerably, among other things, with respect to the maximum output and consumption (fixed and variable cost). However, the varation between small consumers such as various categories of households, are relatively minor. The average cost to a subscriber using electricity for space heating is about SEK 0.23/kWh, and to a subscriber without electric heating about SEK 0.27/kWh. This yields an energy and exergy price of about SEK 64/GJ and SEK 75/GJ, respectively. To large subscribers, such as industries, the cost is often significantly lower.

Gasoline and diesel

Gasoline consists mainly of octane C_8H_{18} for which the exergy content is calculated at about 94% of the energy value. Regular gasoline (44.2 MJ/kg) is assigned an energy price of SEK 114/GJ and an exergy price of SEK 121/GJ which corresponds to a price of approx. SEK 3.68/l. Premium gasoline (44.0 MJ/kg) has an energy price of SEK 118/GJ and an exergy price of SEK 126/GJ which corresponds to a price of SEK 3.80/l.

The exergy content of diesel (42.7 MJ/kg) is assumed to be 104%, which is valid for kerosene. (The exergy value is higher than the energy value since, among other things, the partial pressure of carbon dioxide is included in the exergy calculation): At a price of SEK 2.09/l, the exergy and energy prices are SEK 59/GJ and SEK 56/GJ, respectively. A kilometer tax on motor vehicles should be added to these costs.

Fuel oil

The exergy content of fuel oil is assumed at 97%, which is valid for the havier oils. The following table is then obtained for the prices of several common classes of oil. The energy and exergy prices vary between SEK 43/GJ and SEK 44/GJ for the heavier oils, and SEK 56/GJ and 58/GJ for the lighter oils.

Table 8.1. Energy and exergy prices of several common fuel oils

Fuel oil no.	Heating value (MJ/kg)		Price (SEK/GJ)	
	Energy	Exergy	Energy	Exergy
I[a]	42.8	41.5	56	58
III	41.7	40.4	47	48
IV	41.4	40.2	46	47
V	41.4	40.2	43	44

[a] Oil no. I is used for domestic oil-fired boilers since it is liquid at room temperature.

Town gas

According to the Energy Authority of Göteborg, town gas consists of 65% hydrogen, 20% carbon dioxide, and other substances. The energy and exergy content of town gas can be calculated at 92.2 MJ/kg and 75.5 MJ/kg, respectively, i.e. the exergy content constitutes about 82% of the energy. Considering that prices are determined on the basis of such factors as output requriements and energy needs, and assuming an annual consumption of 200 MWh, we get an energy price of about SEK 63/GJ. The exergy price will thus be SEK 77/GJ.

Coal

The exergy content and price of coal varies for each coal type, see Table 8.2. As we can see, the variations are minimal and both the energy and the exergy prices are around SEK 20/GJ.

Table 8.2. Energy and exergy prices of several common types of coal

Coal type	Heating value (MJ/kg)		Price (SEK/GJ)	
	Energy	Exergy	Energy	Exergy
Sorted (8-30 mm), sulphur cont. ≤ 0.6 %	29.7	29.4	21	21
Sorted (0-30 mm), sulphur cont. ≤ 0.6 %	23.8	23.6	20	20
Unsorted, sulphur cont. ≥ 0.6 %	27.2	26.4	18	19

Wood products

The fuel value of wood products varies considerably depending on the water content. In the case of wood with a 50% water content, the energy and exergy value is calculated at 12.4 MJ/kg and 12.1 MJ/kg, respectively. These values are valid when the water vapor used is condensed in the process. It is difficult to calculate a relevant price due to the relatively small amounts of wood that are sold for space heating purposes. On the other hand, the prices of woodpulp are fixed. The price may vary between SEK 110-160/m^3 depending on the wood type. These prices refer to stacked wood with bark. Recalculating for the real volume of a whole debarked trunk (by a factor of 0.83), we get a price per kg (density 450 kg/m^3) of SEK 0.2 - 0.3/kg. The energy and exergy price will thus be SEK 16 - 24/GJ.

Paper with a water content of 40% yields an energy and exergy value of 15.6 MJ/kg and 15.0 MJ/kg, respectively. At a 10% water content, these values are 23.4 MJ/kg and 22.5 MJ/kg, respectively. In this report the water content of waste paper is assumed at 25%, which yields the values 19.4 MJ/kg and 18.7 MJ/kg. The price of waste paper varies considerably. The Jönköping municipality sells its reclaimed waste paper at SEK 0.35/kg, while the municipality of Göteborg sells its at SEK 0.21/kg. The price will thus vary from SEK 11 - 18/GJ (energy) and from SEK 11 -19/GJ (exergy).

The water content of wood powder varies between 3% and 15% which results in an energy value of between 24.1 MJ/kg and 21.2 MJ/kg and and exergy value of between 23.4 MJ/kg and 20.5 MJ/kg. Assuming a moisture content of 10%, the energy value is 22.4 MJ/kg and the exergy value 22.7 MJ/kg. The price is about SEK 0.73/kg which yields an energy price of SEK 33/GJ and an exergy price of SEK 34/GJ, respectively.

District heating

The exergy of a given quantity of district heat can be calculated as:

$$E = Q\,(1 - T_{outdoor}/[T_{supply} - T_{outdoor}]\ \ln[T_{supply}/T_{return}]) \qquad (8)$$

The supply and return temperatures within the district heating system in Sweden are regulated with respect to the outdoor temperature. The supply temperature is maintained at about 85°C at outdoor temperatures above +2°C and is subsequently raised in inverse proportion to the outdoor temperature, up to 120°C at an outdoor temperature of -20°C. The exergy content will thus vary with the outdoor temperature according to Fig. 8.1 below. For Göteborg, the mean exergy content is calculated at about 17% of the total heat quantity required for the heating season. The district heating subscriber in Göteborg is charged a fixed rate plus an estimated energy rate. Under conditions similar to the case of town gas, the energy price is SEK 58/GJ and the exergy price SEK 340/GJ. We see that the exergy price is thus 6 times that of energy.

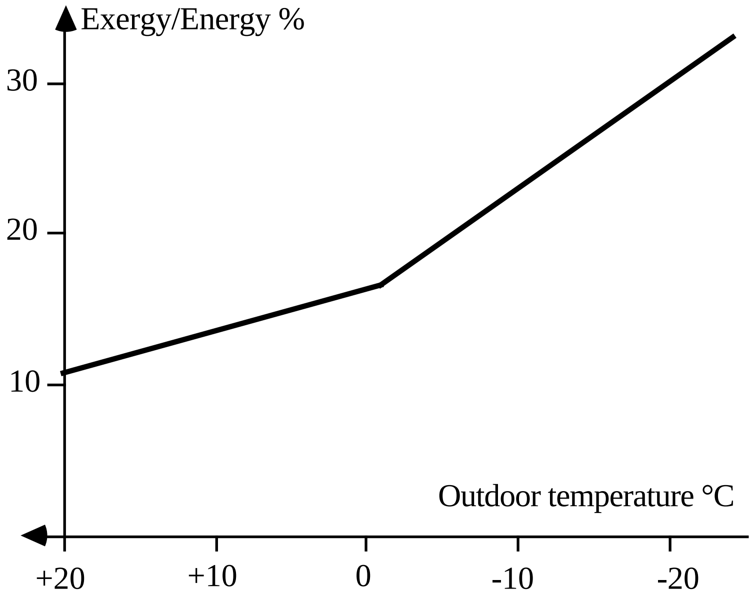


Fig. 8.1. The relationship between exergy and energy for district heating at different outdoor temperatures

Conclusion

We now obtain the following energy and exergy prices for the energy sources under study, see Table 8.3. The highest energy price is that of gasoline, which is a refined fuel with special areas of use. The lowest energy price is that of paper, which is also probably the most expensive and least efficient to handle as fuel. The prices of coal and wood products are low. The differences in energy and exergy prices are small for all the energy sources except district heating. The district heating subscriber pays much more for exergy than other energy users. In many cases, the consumer could reduce his heating bill by instead using a heat pump to produce heat. The current price situation is such that it is cost-effective to produce heat with the aid of heat pumps rather than subscribe to district heating, but it is also cost-effective to use heat pumps in district heating systems. In this case, too, it should be expected that the price will be adapted with respect to this condition. A conscientious energy policy could speed up development towards efficient resource-saving technology by ensuring exergy, rather than energy use.

Table 8.3. Energy and exergy prices of several common energy forms

Energy form	Energy price SEK/GJ	Exergy price SEK/GJ
Electricity	64-75	64-75
Gasoline	114-118	121-126
Diesel	59	56
Fuel oil no. 1	56	58
Fuel oil no. 3-4	43-47	44-48
Town gas	63	77
Coal	18-21	19-21
Fire wood	16-24	16-24
Paper	11-18	11-19
Wood powder	33	34
District heating	58	340

9. GENERAL CONCLUSION

The main lesson of the present study is that, of the studied processes, the exergy treatment reveals heating processes as highly inefficient. This is almost always the case for exergy calculations and is due to the fact that the exergy value of heat is often much lower than its energy value, particularly at temperatures close to ambient temperature. Thus, processes using higher temperatures, such as melting of iron, are better since the exergy value increases with the temperature above ambient temperature. Wastewater at one or two degrees above ambient temperature has, for all practical purposes, no exergy value at all.

At the pulp and paper mill, the soda recovery and the steam production units appeared as the least efficient subprocesses. Within the framework of the earlier mentioned demands of the soda recovery unit, it should be possible to develop better technology for these subprocesses. Perhaps in the future, bacteria will be able to decompose the wood substances and give us a more efficient technology. An ideal process, which incurs no losses whatsoever, would effect about 50% reduction in the use of current resources. Today’s pride in the paper and pulp industry over the fact that certain mills do not require external fuel supply such as oil is entirely justified. In the future, when the mill will become a supplier of paper as well as fuel and electricity, there will be even more reason to boast.

The steel industry’s energy and exergy losses primarily refer to the electric steel furnaces and continuous casting. Just as in the pulp and paper mill, the exergy value of the unutilized flows will be significantly lower than the energy value. It may also be noted that efficiency at the steel mill in question has been improved by the replacement of two furnaces with one, built for a higher capacity. Technology ought to be developed to prevent heat losses between casting and rolling.

Compared to industrial processes, space heating appears to be highly inefficient. One explanation for this may be that the demand for profitability in industry results in a better management of resources. There is often less emphasis on profitability in non-industrial processes. Moreover, the ability of the private consumer to influence his own space heating costs is limited. Efficiencies below 5% for present day space heating systems leave plenty of room for technical improvements, e.g. heat pumps. The efficiency is even less for example, if we examine the space heating system: nuclear - electric heat. The chain of energy conversion nuclear - electricity - heat yields an efficiency of about 1.5%. If we also take into account the fact that only a minor part of uranium’s exergy content is utilized in today’s light water reactors, the efficiency is extremely low. System efficiencies on this order ought to be avoided in the future.

The price of various energy sources is determined, among other things, by the energy value. Calculated in terms of exergy, the price of district heating is about 5 times too high. Consequently, the development of efficient heat production technology such as heat pumps is highly commendable. In the long run, this must also influence district heating prices. A more exergy conscious price setting of various energy sources would help advance technological development towards resource-saving and efficient technology.

In conclusion, it should also be mentioned that the application of the exergy concept provides information for long-term planning of resource management. Today, there is competence and experience for short-term planning. Unfortunately, this is not the case for longer-term planning. This often obstructs development of new efficient technology. The concept of exergy is thus a worthwhile complement to present-day planning instruments.

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Appendix 1. Material, energy and exergy flows in a paper mill

Wood room	Weight:	Energy		Exergy	
	tonnes/tp	MJ/tp	%	MJ/tp	%
Inflow:					
Wood -16°C	2.67	33430	87.3	32660	87.7
Bark -16°C	0.44	4357	11.4	4316	11.6
Ice -16°C[a]	0.70	-306	-0.8	25	0.1
Electricity	-	225	0.6	225	0.6
Water 50°C	5.43	569	1.5	22	0.1
Total: 9.24	38275	100	37248	100	
Outflow:					
Chips 25°C	2.67	33674	88.0	32587	87.5
Bark 25°C	0.44	4407	11.5	4275	11.5
Water 30°C	6.13	129	0.3	1	0.0
Total: 9.24	38210	99.836863		99.0	
Loss 0	65	0.2	385	1.0	
Unutilized outflow	6.13	129	0.3	1	0.0
Efficiency		99.8		99.0	

[a]The negative energy values are due to the reference temperature which is assumed to be 25°C. (Please note that this temperature is assumed to be 0°C in the energy study to which we refer (Fors and Nord 1980).)

Continuous digester	Weight:	Energy		Exergy	
	tonnes/tp	MJ/tp	%	MJ/tp	%
Inflow:					
Chips	2.67	33674	38.8	32587	40.6
White liquor 85°C	1.97	3946	4.5	2875	3.6
Liquor 70°C	13.80	47398	54.6	44099	55.0
Steam[a]	0.64	1717	2.0	502	0.6
Electricity	-	153	0.2	153	0.2
Total:	19.08	86888	100	80216	100
Outflow:					
Pulp & liquor 70°C	10.64	65665	75.6	62401	77.8
Stripping liquor 145°C	6.29	20949	24.1	17531	21.9
Water 118°C	0.27	105	0.1	14	0.0
Water 25°C	1.88	0		0	
Total:	19.08	886719	99.8	79946	99.7
Loss	0169	0.2	270	0.3	
Unutilized outflow	1.3	0		0	
Efficiency			99.8		99.7

[a]0.25 tonnes/tp 0.5 MPa, 175°C, 0.12 tonnes/tp (flashed steam) 130°C, 0.27 tonnes/tp 1.3 MPa, 205°C.

Screening, washing and refining	Weight: tonnes/tp	Energy MJ/tp	Energy %	Exergy MJ/tp	Exergy %
Inflow:					
Pulp & liquor 70°C	10.64	65665	96.5	62401	99.0
Water 74°C	8.99	1840	2.7	129	0.2
Steam 1.3 MPa, 205°C	0.07	178	0.3	57	0.1
Electricity	-	378	0.6	378	0.6
Total:	19.70	68061	100	62965	100
Outflow:					
Pulp 55°C	5.90	19576	28.8	18296	29.1
Liquor 70°C	13.80	47398	69.6	44099	70.0
Total:	19.70	66974	98.4	62395	99.1
Loss	01087	1.6	570	0.9	
Unutilized outflow	0	0		0	
Efficiency			98.4		99.1

Mixers and heat exchangers	Weight: tonnes/tp	Energy MJ/tp	Energy %	Exergy MJ/tp	Exergy %
Inflow:					
Stripping liquor 145°C	6.29	20949	51.0	17531	48.0
Heavy black liquor 102°C	1.52	18294	44.5	16920	46.3
Waste liquor 55°C	0.47	2209	5.4	2028	5.6
Water 1°C	3.44	-347	-0.8	31	0.1
Total:	11.72	41105	100	36510	100
Outflow:					
Mixed liquor 76°C	7.84	38058	92.6	34436	94.3
Steam[a]	0.37	943	2.3	261	0.7
Water 55°C	3.44	432	1.1	21	0.1
Soap 76°C[b]	0.07	1630	4.0	1586	4.3
Total:	11.72	41063	99.9	36304	99.4
Loss	042	0.1	206	0.6	
Unutilized outflow	0	0		0	
Efficiency			99.9		99.4

[a] 0.12 tonnes/tp 130°C and 0.25 tonnes/tp 109°C

[b] Corresponds to a production of 45 kg of resin oil per tonne of pulp.

Evaporator plant	Weight: tonnes/tp	Energy MJ/tp	 %	Exergy MJ/tp	 %
Inflow:					
Mixed liquor 76°C	7.84	38058	94.2	34436	96.9
Steam 0.5 MPa, 175°C	1.28	3448	8.5	948	2.7
Water 108°C	0.02	8	0.0	1	0.0
Water 1°C	11.47	-1155	-2.9	102	0.3
Electricity	-	50	0.1	50	0.1
Total:	20.61	40409	100	35537	100
Outflow:					
Heave black and black liquor 102°C	2.90	34903	86.4	32282	90.8
Waste liquor 55°C	0.47	2209	5.5	2028	5.7
Condensate 52°C och 93°C	5.77	1257	3.1	141	0.4
Water 50°C	11.47	1200	3.0	47	0.1
Total:	20.61	39569	97.9	34498	97.1
Loss	0840		2.11039	2.9	
Unutilized outflow	0	0		0	
Efficiency			97.9		97.1

Soda recovery unit	Weight: tonnes/tp	Energy MJ/tp	 %	Exergy MJ/tp	 %
Inflow:					
Black liquor 102°C	1.38	16609	89.9	15362	94.9
Weak liquor 55°C	1.93	730	3.9	439	2.7
Water 110°C	2.97	972	5.2	117	0.7
Steam 1.3 MPa, 205°C	0.03	89	0.5	29	0.2
Electricity	-	121	0.6	121	0.7
Air 25°C	8.9	0		0	
Na_2SO_4	0.03	152	0.8	118	0.7
Total:	15.21	18673	100	16186	100
Outflow:					
Steam 3.6 MPa 420°C	2.54	7620	40.8	2956	18.3
Bottom blow 255°C	0.34	338	1.8	93	0.6
Green liquor 90°C	2.43	3487	18.7	2588	16.0
Exhaust gas 145°C	9.71	2154	11.5	545	3.4
Soot steam 3.6 MPa, 420°C	0.22	589	3.2	115	0.7
Total:	15.21	14188	76.0	6297	38.9
Loss	04485		24.09889	61.1	
Unutilized outflow	9.9	2743	14.7	660	4.1
Efficiency			71.8		36.3
Ditto excluding the green liquor	70.5		27.3		

Steam plant	Weight: tonnes/tp	Energy MJ/tp	 %	Exergy MJ/tp	 %
Inflow:					
Bark 25°C	0.44	4407	33.7	4275	36.8
Bottom blow 255°C	0.34	338	2.6	93	0.8
Water 108°C	3.75	1307	10.0	172	1.5
Fuel oil	0.16	7059	53.9	6843	59.0
Air 25°C	4.48	0		0	
Water 1°C	2.26	-228	-1.7	20	0.2
Electricity	-	203	1.6	203	1.7
Total:	11.43	13086	100	11606	100
Outflow:					
Steam 3.6 MPa, 404°C	2.79	8709	66.6	3360	29.0
Water 110°C	2.97	972	7.4	117	1.0
Exhaust gas 165°C-170°C	5.10	2134	16.3	513	4.4
Wastewater 25°C	0.57	0		0	
Total:	11.43	11815	90.3	3990	34.4
Losses	01271		9.77616	65.6	
Unutilized outflow	5.67	2134	16.3	513	4.4
Efficiency			88.4		31.3

Turbine plant	Weight: tonnes/tp	Energy MJ/tp	 %	Exergy MJ/tp	 %
Inflow:					
Steam 3.6 MPa, 411°C	5.20	16329	98.9	6316	99.6
Water 108°C	0.53	185	1.1	25	0.4
Total:	5.73	16514	100	6341	100
Outflow:					
Steam 1.3 MPa, 205°C	0.79	2138	12.9	688	10.9
Steam 1.0 MPa, 200°C	2.55	6942	42.0	2159	34.0
Steam 0.5 MPa, 175°C	2.39	6454	39.1	1775	28.0
Electricity	-	977	5.9	977	15.4
Total:	5.73	16511	100	5599	88.3
Losses	0 3	0	742	11.7	
Unutilized outflow	0	0		0	
Efficiency			100.0		88.3

Lime sludge reburning kiln and causticizing department	Weight:	Energy		Exergy	
	tonnes/tp	MJ/tp	%	MJ/tp	%
Inflow:					
Green liquor 90°C	2.43	3487	72.5	2588	67.7
Water 50°C	0.99	104	2.2	4	0.1
Fuel oil	0.3	1200	25.0	1163	30.4
Air 25°C	0.16	0		0	
Water 1°C	0.48	-48	-1.0	4	0.1
Electricity	-	65	1.4	65	1.7
Total:	4.09	4808	100	3825	100
Outflow:					
White liquor 85°C	1.97	3946	82.1	2875	75.2
Weak liquor 55°C	1.93	730	15.2	439	11.5
Exhaust gas 250°C	0.19	116	2.4	31	0.8
Total:	4.09	4792	99.7	3345	87.5
Losses	016	0.3	479	12.5	
Unutilized outflow	0.19	116	2.4	31	0.8
Efficiency			99.7		87.4

Paper mill	Weight:	Energy		Exergy	
	tonnes/tp	MJ/tp	%	MJ/tp	%
Inflow:					
Pulp 55°C	5.90	19576	62.3	18296	69.3
Steam 1.0 MPa, 200°C	2.55	6942	22.4	2159	8.2
Water 50°C	9.87	1033	3.3	42	0.2
Waste paper -16°C	0.27	4023	13.0	3911	14.8
Water 1°C	7.39	-744	-2.4	65	0.2
Air -16°C	43.52	-1711	-5.5	130	0.5
Electricity	-	1809	5.8	1809	6.8
Total:	69.50	30928	100	26412	100
Outflow:					
Condensate 118°C	2.12	829	2.7	108	0.4
Air 30°C	43.52	213	0.7	2	0.0
Paper 65°C	1	23011	74.4	22177	84.0
Damp air 55°C	2.07	4680	15.1	479	1.8
Water 55°C	13.01	1635	5.3	77	0.3
Wastewater 25°C	7.78	0		0	
Total:	69.50	30368	98.2	22843	86.5
Losses	0560		1.83569	13.5	
Unutilized outflow	22.86	6315	20.4	556	2.1
Efficiency			99.7		86.2

Appendix 2. Material, energy och exergy flows in a steel mill

Electric furnaces	Weight: kg/tr	Energy Total (thermal) MJ/tr	Energy %	Exergy Total (thermal) MJ/tr	Exergy %
Inflow:					
Scrap iron	1075	7651	65.2	6936	63.9
Electricity	-	2363	20.1	2363	21.8
Cast-iron	96	838	7.1	774	7.1
Pig-iron	16	138	1.2	128	1.2
Sinter	24	34	0.3	26	0.2
Alloys	22	310	2.6	288	2.7
Burnt lime	57	181	1.5	119	1.1
Limestone	1	0		0	
Magnesite	9	9	0.1	3	0.0
Bricks	11	-	-		
Electrodes	6	210	1.8	219	2.0
Water 25°C	17000	0		0	
Total:	18317	11734	100	10856	100
Outflow:					
Steel 1650°C	1141	10272(1662)	87.5	8997(1189)	82.9
Slag 1650°C	96	418 (170)	3.6	292 (113)	2.7
Water 30°C	17000	356 (356)	3.0	3 (3)	0.0
Loss by burning 1650°C	68	157 (73)	1.3	127 (51)	1.2
Exhaust gas 1000°C[a]	28	284 (27)	2.4	265 (14)	2.4
Total:	18333	11487(2288)	97.9	9684(1379)	89.2
Loss[b]	16	247	2.1	1172	10.8
Unutilized outflow		1215	10.4	687	6.3
Efficiency			97.7		88.5

[a] The temperature of the exhaust gas from the melt varies between 500 and 1500°C. As the carbon monoxide is combusted, it generates heat which is given off outdoors prior to the stack cleaner.

[b] The air flow into the process cannot be calculated. However, this does not effect the energy and exergy flows.

Continuous casting	Weight: kg/tr	Energy Total MJ/tr	(thermal)	% 	Exergy Total MJ/tr	(thermal)	%
Inflow:							
Steel 1650°C	1141	10272	(1662)	98.5	8997	(1189)	98.3
Water 25°C	7020	0			0		
Electricity	-	160		1.5	160		1.7
Total: 8161	10432	(1662)	100	9157	(1189)	100	
Outflow:							
Steel 850°C	1089	8826	(608)	84.6	7794	(340)	85.1
Scrap 850°C	48	389	(28)	3.7	344	(15)	3.8
Embers 4	-			-			
Water 55°C	4860	610	(610)	5.8	29	(29)	0.3
Water 35°C	2160	90	(90)	0.9	1	(1)	0.0
Total: 8161	9915	(1336)		95.08168	(385)	89.2	
Loss 0	517			5.0989		10.8	
Unutilized outflow		517		6.7	30		0.3
Efficiency				94.5			89.1

Pusher type furnace (mill 5)	Weight: kg/tr	Energy Total MJ/tr	(thermal)	% 	Exergy Total MJ/tr	(thermal)	%
Inflow:							
Steel 75°C[a]	657	4973	(15)	77.0	4498	(1)	78.0
Fuel oil	29	1247		19.3	1198		20.8
Air 330°C	752	235	(235)	3.6	74	(74)	1.3
Total:	1438	6455	(250)	100	5770	(75)	100
Outflow:							
Steel 1150°C	657	5460	(502)	84.6	4805	(308)	83.3
Exhaust gas 850°C[a]	781	820	(820)	12.7	409	(401)	7.1
Total:	1438	6280	(1322)	97.3	5214	(709)	90.4
Loss	0	175		2.7	556		9.6
Unutilized outflow		0			0		
Efficiency				97.3			90.4
Efficiency[b]				88.2			55.7
Efficiency[c]				73.6			35.2

[a] Estimated value
[b] Total heating
[c] Heating of the steel

Recuperative heat exchanger (mill 5)	Weight:	Energy			Exergy		
		Total	(thermal)		Total	(thermal)	
	kg/tr	MJ/tr		%	MJ/tr		%
Inflow:							
Exhaust gas 850°C[a]	781	820	(820)	100	409	(401)	100
Air 25°C	752	0			0		
Total:	1533	820	(820)	100	409	(401)	100
Outflow:							
Exhaust gas 500°C	781	500	(500)	61.0	191	(183)	46.7
Air 330°C	752	235	(235)	28.7	74	(74)	18.1
Total:	1533	735	(735)	89.6	265	(257)	64.8
Loss	0	85		10.4	144		35.2
Unutilized outflow		500		61.0	191		46.7
Efficiency				73.4			33.9

[a] Estimated value

Rolling-mill (mill 5)	Weight:	Energy			Exergy		
		Total	(thermal)		Total	(thermal)	
	kg/tr	MJ/tr		%	MJ/tr		%
Inflow:							
Steel 1150°C	657	5460	(502)	96.2	4805	(308)	95.5
Electricity	-	217		3.8	217		4.3
Total:	657	5677	(502)	100	5022	(308)	100
Outflow:							
Steel 850°C	614	4974	(340)	87.6	4393	(191)	87.5
Scrap 850°C	23	186	(13)	3.3	165	(7)	3.3
Embers 850°C	20	36	(8)	0.6	28	(6)	0.6
Total:	657	5196	(361)	91.5	4586	(204)	91.3
Loss	0	481		8.5	436		18.7
Unutilized outflow		13		0.2	10		0.2
Efficiency				91.5			91.3

Walking beam furnace (mill 6)	Weight:	Energy			Exergy		
	kg/tr	Total MJ/tr	(thermal)	%	Total MJ/tr	(thermal)	%
Inflow:							
Steel 75°C[a]	432	3270	(10)	78.9	2958	(1)	79.5
Fuel oil	17	744		18.0	721		19.4
Air 350°C	384	128	(128)	3.1	42	(42)	1.1
Total:	833	4142	(138)	100	5770	(43)	100
Outflow:							
Steel 1150°C	432	3590	(330)	86.7	3159	(203)	84.9
Exhaust gas 850°C	401	421	(421)	10.2	210	(206)	5.6
Total:	833	4011	(751)	96.8	3369	(409)	90.5
Loss	0	131		3.2	352		9.5
Unutilized outflow		0			0		
Efficiency				96.8			90.5
Efficiency[a]				85.0			53.5
Efficiency[b]				71.0			36.5

[a] Total heating
[b] Heating of steel

Recuperative heat exchanger (mill 6)	Weight:	Energy			Exergy		
	kg/tr	Total MJ/tr	(thermal)	%	Total MJ/tr	(thermal)	%
Inflow:							
Exhaust gas 850°C	401	421	(421)	100	210	(206)	100
Air 25°C	384	0			0		
Total:	785	421	(421)	100	210	(206)	100
Outflow:							
Exhaust gas 350°C	401	189	(189)	44.9	59	(55)	28.1
Air 350°C	384	128	(128)	30.4	42	(42)	20.0
Total:	785	317	(317)	75.3	101	(97)	48.1
Loss	0	104		24.7	109		51.9
Unutilized outflow		75		17.8	23		11.0
Efficiency				55.2			27.8

Flue gas boiler (mill 6)	Weight:	Energy			Exergy		
	kg/tr	Total MJ/tr	(thermal)	%	Total MJ/tr	(thermal)	%
Inflow:							
Exhaust gas 350°C[a]	241	114	(114)	100	36	(33)	100
Air 25°C	-	0			0		
Total:	241	114	(114)	100	36	(33)	100
Outflow:							
Steam[a]	-	30	(30)	26.3	10	(10)	27.8
Exhaust gas 200°C	241	74	(74)	64.9	18	(15)	50.0
Total:	241	104	(104)	91.2	28	(25)	77.8
Loss	0	10		8.8	8		22.2
Unutilized outflow		74		64.9	18		50.0
Efficiency				75.0[a]			55.6

[a] Estimated value.

Rolling-mill (mill 6)	Weight:	Energy			Exergy		
	kg/tr	Total MJ/tr	(thermal)	%	Total MJ/tr	(thermal)	%
Inflow:							
Steel 1150°C	432	3590	(330)	93.1	3159	(203)	92.2
Electricity	-	266		6.9	266		7.8
Total:	432	3856	(330)	100	3425	(203)	100
Outflow:							
Steel 850°C	386	3126	(218)	81.1	2762	(120)	80.6
Scrap 850°C	36	292	(20)	7.6	258	(11)	7.5
Embers 850°C	10	18	(4)	0.5	14	(3)	0.4
Total:	432	3436	(242)	89.1	3034	(60)	88.5
Loss	0	420		10.9	391		11.5
Unutilized outflow		7		0.2	6		0.2
Efficiency				89.1			88.4

Appendix 3. Computer program in BASIC for calculating the exergy, energy, enthalpy and entropy of steam

```
10 REM "STEAM" 830210
20 REM ref. J.H. Keenan et. al. "Steam Tables" and
30 REM W.C. Reynolds "Thermodynamic Properties in SI"
40 REM
50 REM TDS 500, CP/M
60 REM**************************************************
70 REM
80 REM Steam Properties in SI Units
90 REM
100 REM*************************************************
110 REM February 1983
120 REM Göran Wall
130 REM*************************************************
140 REM Pressure range: 001 to 100 MPa
150 REM
160 REM Temperature range: 0 to 1300 C
170 REM
180 REM Slow but steam table accurracy
190 REM
200 REM*************************************************
210 REM
220 GOSUB 1000: REM Initiate
230 GOSUB 2000: REM Input
240 GOSUB 3000: REM Calculate
245 GOSUB 8000: REM Calculate U, H, S and E
246 TH=T: PH=P: RH=RO : UH=U: HH=H: SH=S : EH=E
250 GOSUB 9000: REM Print
255 PRINT
260 INPUT " Do you want another run? yes=1/no=0 ",PL
270 IF PL=1 THEN 230
280 PRINT
290 PRINT "If you would like to calculate the reversible change to a
   lower pressure answer this question, if not, just print 0"
300 PRINT
310 INPUT "Low pressure in MPa: " ,PL
320 IF PL=0 THEN 900
330 GOSUB 4440: REM Calculate T, U, H, S, and E at PL and SR
340 GOSUB 4190: REM Calculate T, U, H, S, and E at PL and SR
350 TL=T: PL=P: RL=RO: UL=U:, HL=H: SL=S: EL=E
360 GOSUB 9000: REM Print
370 GOSUB 9150: REM Print the difference
900 END
1000 REM Initiate
1010 RETURN
2000 REM Input
2010 INPUT "Pressure in MPa: ",P
2020 INPUT "Temperature in °C: ",TC
2025 INPUT "Approximate inaccuracy in percent, 0 will give steam table
   accuracy: ",IC
2026 IC=IC/100+.000001
2030 T=TC+273.15
2040 RETURN
3000 REM Calculation of RO, Q, QR, F, and FT at T and P high
```

```
4000 REM Calculation of RO (the density) from given values of pressure
   and temperature by iteration
4010 REM
4020 TA=1000/T
4030 N=2
4040 X1=0: REM starting value
4050 F1=P: REM since RO=0
4060 RO=P/.46151/T
4070 GOSUB 5000: REM calculate Q, QT and QR
4080 F0=F1
4090 F1=P-RO*.46151*T*(1+RO*(Q+RO*QR))
4100 IF FO*F1< 0 THEN N=5
4110 X0=X1
4120 X1=RO
4130 RO=X1+SGN(FO*F1)*(X1-X0)*N
4140 IF ABS(X0-X1)> IC*ABS(X1) THEN 4070
4150 GOSUB 6000: REM Calculate F and FT
4160 RETURN
4170 REM
4180REM
4190 REM Calculation of T from given values of pressure and entropy by
   iteration
4200 REM
4210 N=2: REM First stepping in 10ths of degrees
4220 P=PL
4230 SR=S: REM Save the earlier value of the entropy
4240 T=TS-!==: REM Starting value 100 degrees under saturation curve
4250 GOSUB 4000: REM Calculate RO, Q, QT and QR at T and P
4260 GOSUB 6000: REM Calculate F and FT
4270 GOSUB 8000: REM Calculate S at T and P
4280 F1=SR-S
4290 X1=T
4300 T=T+10*K
4310 GOSUB 4000
4320 GOSUB 6000
4330 GOSUB 8000
4340 F0=F1
4350 F1=SR-S
4360 IF FO*F1<0 THEN N=.5
4370 X0=X1
4380 X1=T
4390 T=X1+SGN(F0*F1)*X1-X0)*N
4400 IF ABS(T-X1) > IC*ABS(T) THEN 4310
4410 RETURN
4420 REM
4430 REM
4440 REM Calculation of saturation temperature from given value of
   pressure by iteration
4450 REM
4460 N=2: REM Stepping in 10ths of degrees
4470 T=273: REM Starting value
4480 GOSUB 7000: REM Calculate the saturation pressure at T
4490 F1=PL-PS: REM Starting value
4500 X1=T
4510 T=T+10*N
4520 GOSUB 7000
4530 F0=F1
4540 F1=PL-PS
```

```
4550 IF F0*F1< 0 THEN N=.5
4560 X0=X1
4570 X1=T
4580 T=X1+SGN (F0*F1)*(X1-X0)*N
4581 PRINTT
4590 IF ABS 8T-X1) >IC*ABS(T) THEN 4520
4600 TS=T
4610 PRINT "Saturation temperature: TS = " , INT(TS-273.15)*100)/100,"
   C"
4620 RETURN
4630 REM
4640 REM
5000 X=RO-1: REM X=RO-R(AJ) where R(AJ) =1 for J >1
5010 Y=RO-.634: REM Y=RO-R (AJ) where R(AJ)=.634 for J=1
5020 Z=EXP(-4.8*RO): REM Z=EXP(-E*RO)
5030 T1=TA-1.544912#: REM T1=TA-TA(AJ) where TA(AJ)=TCRIT=1.544912 for
   J=1
5040 B=TA-2.5: REM B=TA-TA(AJ) where TA(AJ)=2.5 for J >1
5050 REM
5060 REM
5070 REM Calculation of Q (RO,TA) and QT (RO,TA)
5080 REM
5090 A1=29.492937#+(-132.13917#+(274.64632#+(-360.93826#+(342.18431#+(-
   244.50042#+(155.18535#+5.9728487#*Y)*Y)*Y)*Y)*Y)*Y)*Y-
   Z*(410.30848#+416.0586#*RO)
5100 A2=-5.198586#+(7.7779182#+(-33.301902#+(-16.254622#+(-
   177.31074#+(127.48742#+(137.46153#+155.97836#*X)*X)*X)*X)*X)*X)*X+Z*
   (337.3118#-209.88866#*RO)
5110 A3=6.8335354#+(-26.149751#+(65.326396#-26.181978#*X)*X)*X-
   Z*(137.46618#+733.96848#*RO)
5120 A4=-.1564104#+(-.72546108#+(-
   9.2734289#+4.312584#*X)*X)*X+Z*(6.7874983#+10.401717#*RO)
5130 A5=-6.3972405#+(26.409282#+(-
   47.740374#+56.32313#*X)*X)*X+Z*(136.87317#+645.8188#*RO)
5140 A6=-3.9661401#+(15.453061#+(-
   29.14247#+29.568796#*X)*X)*X+Z*(79.84797#+399.1757#*RO)
5150 A7=-.69048554#+(2.7407416#+(-
   5.102807#+3.9636085#*X)*X)*X+Z*(13.041253#+71.531353#*RO)
5160 A=A2+B*(A3+B*(A4+B*(A5+B*(A6+B*A7))))
5170 Q=A1+T1*A
5180 QT=A+T1*(A3+B*(2*A4+B*(3*A5+B*(4*A6+B*5*7))))
5190 REM
5200 REM
5210 REM Calculation of QR (RO,TA)
5220 REM
5230 R1=-132.13917#+(549.29264#+(-1082.81484#+(1368.73724#+(-
   1222.5021#+(931.1121#+41.8099409#*Y)*Y)*Y)*Y)*Y)*Y-Z*(416.0586#-
   4.8*(410.39848#+416.0586#*RO))
5240 R2=7.7779182#+(-66.603804#+(-48.763866#+(-
   709.24296#+(637.4371#+(824.76918#+10991.84842#*X)*X)*X)*X)*X)*X+Z*(-
   209.88866#-4.8*(337.3118#-209.88866#*RO))
5250 R3=-26.149751#+(130.652792#-78.545934#*X)*X+Z*(-
   733.96848#+4.8*(137.46618#+733.96848#*RO))
5260 R4=-.72546108#+(-18.5468578#+12.937752#*X)*X+Z*(10.401717#-
   4.8*(6.7874983#+10.401717#*RO))
5270 R5=26.409282#+(-95.480748#+168.96939#*X)*X+Z*(645.8188#-
   4.8*(136.87317#+645.8188#*RO))
```

```
5280 R6=15.453061#+(-58.28494#+88.706388#*X)*X+Z*(399.1757#-
   4.8*(79.84797#+399.1757#*RO))
5290 R7=2.7407416#+(-10.205614#+11.8908255#*X)*X+Z*(71.531353#-
   4.8*(13.041253#+71.531353#*RO))
5300 QR=R1+T1*(R2+B*(R3+B*(R4+B*(R5+B*(R6+B*R7)))))
5310 RETURN
5320 REM
5330 REM
6000 REM Calculation of F(TA) and FT(TA) where F=fi0
6010 REM
6020 F=1857.065#+((((-20.5516+4.85233/TA)/TA+36.6649)/TA-
   419.465)/TA+3229.12)/TA+(6.90775528#-LOG(TA))*(46-1011.249#/TA)
6030 FT=(-1*((((-82.2064+24.26165#/TA)/TA+109.9947#)/TA-
   838.93)/TA+3229.12)/TA-(46-1011.249#/TA)+(6.90775528#-
   LOG(TA))*(1011.249#/TA))/TA
6040 RETURN
6050 REM
6060 REM
7000 REM Calculation of saturation pressure from given value of
   temperature
7010 REM
7020 AS=.01*(T-338.15)
7030 PS=22.089*EXP((1-T/647.286)*(-7.419242#+AS*(.29721+AS*(-
   .1155286#+AS*(.008685635#+AS*(.001094098#+AS*(-4.39993E-
   03+AS*(.002520658#-AS*.0005218684#))))))))
7040 RETURN
7050 REM
7060 REM
8000 REM Calculation of U, H, S and E
8010 REM
8020 U=RO*461.51*QT+TA*FT+F
8030 H=U+P/RO
8040 S=-.46151*(LOG(RO)+RO*Q-RO*TA*QT)+TA*TA*FT/1000
8050 E=H-298.15*S
8060 RETURN
8070 REM
8080 REM
9000 PRINT
9010 PRINT "Temperature: ", INT( (T-273.15)*100)/100, "C"
9020 PRINT "Pressure: ", INT(P*1000) /1000, " MPa"
9030 PRINT "Density: ", INT(1E+06*RO) /1000," kg/m3
9040 PRINT "Specific volume: "INT(1000/RO) /1000, " *1000m 3/kg"
9050 PRINT
9060 PRINT "Energy : U= ", INT(100*U)/100," kJ/kg
9070 PRINT "Enthalpy: H= ", INT(100*H)/100," kJ/kg
9080 PRINT "Entropy: S= ", INT(100000!*S) /100000!," kJ/kg K"
9090 PRINT "Exergy: E= ", INT(100*E) /100," kJ/kg"
9100 PRINT
9110 PRINT "Remember the innaccuracy in the input values of ",
   INT(IC*1000) /10," %"
9120 PRINT
9130 PRINT
9140 RETURN
9150 PRINT
9160 PRINT"The difference between the two states is"
9170 PRINT
9180 PRINT "Temperature: ", INT( (TH-TL)*100) /100," C"
9190 PRINT "Pressure: ", INT( (PH-PL)*1000) /1000," MPa"
```

```
9200 PRINT "Energy: ", INT( (UH-UL)*100) /100," kJ/kg
9210 PRINT "Enthalpy: ", INT( (HH-HL)*100) /100," kJ/kg
9220 PRINT "Entropy: ", INT( (SH-SL)*1E+06," kJ/kg K"
9230 PRINT "Exergy: ", INT ( (EH-EL)*100) /100," kJ/kg
9240 PRINT
9250 PRINT "Remember the inaccuracy in the input values of ",
   INT(IC*1000) /10," %"
9260 RETURN
```

Appendix 4. Computer program in BASIC for calculating the thermal and chemical energies and exergies of some substances

```
1 REM "EXERGY"
2 REM 830407-
3 REM References: CRC "Rubber book" 63rd ed pp. D-45 etc.
4 REM
5 REM
6 REM Thermal and chemical exergies of some substances
7 REM
8 REM April 1983
9 REM Göran Wall
10 REM
11 REM This program calculates the thermal and chemical exergies of some
   elements and ideal or nonideal mixtures of theme at constant
   pressure
12 REM
20 GOSUB 11000: REM initialize
21 GOSUB 11500: REM input
22 GOSUB 11900: REM calculate
23 GOSUB 12490: REM convert
24 GOSUB 12820: REM calculate the chemical exergy
26 REM GOSUB 15000: rem print
27 GOSUB 13370: REM mass flow
40 PRINT
50 INPUT "Another run? Yes=1/No=0 ",Q
60 PRINT
61 FOR I=1 TO 26 : FOR K=0 TO 3:C(I,K)=100*C(I,K): NEXT K: NEXT I
70 IF Q=0 THEN GOTO 96
71 GOSUB 11580: REM input
72 GOTO 22
96 END
97 REM
100 REM Hydrogen, £1,0
101 A=6.62:B=,81: GOSUB 12340
102 HT(1,0)=H:ST(1,0)=S
103 RETURN
104 REM
105 REM H20, £1,1
106 IF T <373.16 THEN GOTO 109
107 HT=9.77:ST=26.18
108 A=7.17:B=2.56:D=-.08:T1=373.16: GOSUB 12340
109 A=18.03: GOSUB 12340
110 HT(1,1)=HT:ST(1,1)=ST
111 RETURN
112 REM
200 REM Helium, £2, 0
201 A=4.96793: GOSUB 12340: REM Ideal monoatomic gas
202 HT(2,0)=HT:ST(2,0)=ST
203 RETURN
204 REM
600 REM Carbon £6,0
601 A=4.1:B=1.02:D=-2.1: GOSUB 12340
602 HT(6,0)=H:ST(6,0)=S
603 RETURN
604 REM
```

```
605 REM CO, £6,1
606 A=6.6:B=1.2: GOSUB 12340
607 HT(6,1)=HT:ST(6,1)=ST
608 RETURN
609 REM
610 REM CO2, £6,2
611 A=7.7:B=5.3:C=-.83: GOSUB 12340
612 HT(6,2)=HT:ST(6,2)=ST
613 RETURN
614 REM
615 REM CH4, £6,3 to 1500 K ref. Zemansky
616 A=3.38:B=17.905:C=-4.188: GOSUB 12340
617 HT(6,3)=HT:ST(6,3)=ST
618 RETURN
619 REM
700 REM Nitrogen, £7
701 A=6.76:B=.606:C=.13: GOSUB 12340
702 HT(7,0)=H:ST(7,0)=S
703 RETURN
704 REM
705 REM N20, £7,1
706 A=10.92:B=2.06:D=-2.04: GOSUB 12340
707 HT(7,1)=HT:ST (7,1)=ST
708 RETURN
709 REM
800 REM Oxygen, £8,0
801 A=8.27:B.258:D=-1.877: GOSUB 12340
802 HT(8,0)=H:ST(8,0)=ST
803 RETURN
804 REM
1000 REM Neon, £10,0
1001 A=4.96793: GOSUB 12340
1002 HT(10,0)=HT:ST(10,0)=ST
1003 RETURN
1004 REM
1100 REM Sodium, Na 11,0
1101 IF T < 371 THEN GOTO 1107
1102 HT=.63:ST=1.7
1103 IF T<1187 THEN GOTO 1106
1104 HT=HT+23.4:ST=ST+20.1
1105 A=4.97:T1=1187: GOSUB 12340
1106 A=8.954:B=-4.577:C=2.54:T1=371: GOSUB 12340
1107 A=5.657:B=3.252:C=.5785: GOSUB 12340
1108 HT(11,0)=HT:ST(11,0)=ST
1109 RETURN
1110 REM
1111 REM Na2CO3 11,1 (Simple model)
1112 GOSUB 1100
1113 GOSUB 600
1114 GOSUB 800
1115 HT(11,1)=HT(11,0)/3+HT(6,0)/6+HT(8,0)/4
1116 ST(11,1)=ST(11,0)/3+ST(6,0)/6+ST(8,0)/4
1117 RETURN
1118 REM
1119 REM NaOH 11,2 (Simple model)
1120 GOSUB 1100
1121 GOSUB 800
1122 GOSUB 100
```

```
1123 HT(11,2)=HT(11,0)/3+HT(8,0)/6+HT(1,0)/6
1124 ST(11,2)=ST(11,0)/3+ST(8,0)/6+ST(1,0)/6
1125 RETURN
1126 REM
1127 REM Na2S 11,3 (Simple model)
1128 GOSUB 1100
1129 GOSUB 1600
1130 HT(11,3)=HT(11,0)*2/3+HT(16,0)/3
1131ST(11,3)=ST(11,0)*2/3+ST(16,0)/3
1132 RETURN
1133 REM
1300 REM Aluminium, #13,0
1301 IF T<931.7 THEN GOTO 1310
1302 HT=2.57:ST=2.76
1303 IF T<2600 THEN GOTO 1309
1304 IF INT(T)=2600 THEN GOTO 1307
1305 PRINT "The temperature must not exceed 2600 K for Aluminum"
1306 RETURN
1307 PRINT "Aluminum boils"
1308 HT=HT+67.9:ST=ST+26
1309 A=7:T1=931.7: GOSUB 12340
1310 A=4.94:B=2.96: GOSUB 12340
1311 HT(13,0)=HT:ST(13,0)=ST
1312 RETURN
1313 REM
1314 REM Al2O3, #13,1
1315 IF T<2300 THEN GOTO 1319
1316 PRINT "Al2O3 decays"
1317 HT=26:ST=11
1318 A=33:T1=230: GOSUB 12340
1319 A=26.12:B=4.388:D=-7.269: GOSUB 12340
1320 HT(13,1)=HT:ST(13,1)=ST
1321 RETURN
1322 REM
1400 REM Silicon, Si 14,0
1401 IF T < 1683 THEN GOTO 1410
1402 HT=11.1:ST=6.6
1403 IF T<2750 THEN GOTO 1409
1404 IF INT(T)=2750 THEN GOTO 1407
1405 PRINT "The temperature must not exceed 2750 K for Silicon"
1406 RETURN
1407 PRINT "Silicon boils"
1408 HT=HT+71:ST=ST+26
1409 A=7.4:T1=1683: GOSUB 12340
1410 A=5.7:B=1.02:D=-1.06: GOSUB 12340
1411 HT(14,0)=HT:ST(14,0)=ST
1412 RETURN
1413 REM
1414 REM SiO #14,1
1415 IF T<2550 THEN GOTO 1421
1416 IF INT(T)=2550 THEN GOTO 1419
1417 PRINT "SiO decays over 2550 K"
1418 GOTO 1423
1419 PRINT "SiO decays"
1420 HT=12:ST=4.7
1421 A=7.3:B=2.4: GOSUB 12340
1422 HT(14,1)=HT:ST(14,1)=ST
1423 RETURN
```

```
1424 REM
1425 REM SiO2, #14,2
1426 IF T<856 THEN GOTO 1435
1427 HT=.15:ST=.18
1428 IF T<1883 THEN GOTO 1434
1429 HT=HT+2.04:ST=ST+1.08
1430 IF T<2250 THE GOTO 1433
1431 PRINT "SiO decays over 2250 K"
1432 GOTO 1437
1433 A=20:T1=1883: GOSUB 12340
1434 A=14.41:B=1.94:T1=856: GOSUB 12340
1435 A=11.22:B=8.2:D=-2.7: GOSUB 12340
1436 HT(14,2)=HT:ST(14,2)=ST
1437 RETURN
1438 REM
1500 REM Phosphorus, #15,0
1501 IF T < 317.4 THEN GOTO 1507
1502 HT=.601:ST=1.89
1503 IF T<553 THEN GOTO 1506
1504 HT=HT+11.9:ST=ST+21.5
1505 A=19.5:B=-.4:C=1.3:T1=553: GOSUB 12340
1506 A=19.23:B=.51:C=-2.98:T1=317.4: GOSUB 12340
1507 A=13.62:B=28.72: GOSUB 12340
1508 HT(15,0)=HT:ST(15,0)=ST
1509 RETURN
1510 REM
1600 REM Sulphur, #16,0
1601 IF T < 368.6 THEN GOTO 1610
1602 HT=.088:ST=.24
1603 IF T<392 THEN GOTO 1609
1604 HT=HT+.293:ST=ST+.747
1605 IF T<717.76 THEN GOTO 1608
1606 HT=HT+2.5:ST=ST+3.5
1607 A=4.25:B=.15:D=-1:T1=717.76: GOSUB 12340
1608 A=5.4:B=5:T1=392: GOSUB 12340
1609 A=3.56:B=6.95:T1=368.6: GOSUB 12340
1610 A=3.58:B=6.24: GOSUB 12340
1611 HT(16,0)=HT:ST(16,0)=ST
1612 RETURN
1613 REM
1614 REM SO2, #16,1
1615 A=11.4:B=1.414:C=-2.045: GOSUB 12340
1616 HT(16,1)=HT:ST(16,1)=ST
1617 RETURN
1618 REM
1800 REM Argon, #18, 0
1801 A=4.96793: GOSUB 12340: REM Ideal monoatomic gas
1802 HT(18,0)=HT:ST(18,0)=ST
1803 RETURN
1804 REM
2000 REM Calcium, #20,0
2001 IF T < 723 THEN GOTO 2010
2002 HT=.24:ST=.33
2003 IF T<1123 THEN GOTO 2009
2004 HT=HT+2.2:ST=ST+1.96
2005 IF T<1755 THEN GOTO 2008
2006 HT=HT+38.6:ST=ST+22
2007 A=4.97:T1=1755: GOSUB 12340
```

```
2008 A=7.4:T1=1123: GOSUB 12340
2009 A=6.29:B=1.4:T1=723: GOSUB 12340
2010 A=5.24:B=3.5: GOSUB 12340
2011 HT(20,0)=HT:ST(20,0)=ST
2012 RETURN
2013 REM
2014 REM CaO, #20,1
2015 IF T<2860 THEN GOTO 2021
2016 IF INT(T)=2860 THEN GOTO 2019
2017 PRINT "CaO decays over 2860 K"
2018 GOTO 2023
2019 PRINT "CaO decays"
2020 HT=18:ST=6.3
2021 A=10:B=4.84:D=-1.08: GOSUB 12340
2022 HT(20,1)=HT:ST(20,1)=ST
2023 RETURN
2024 REM
2300 REM Vanadium, 23,0
2301 IF T < 2003 THEN GOTO 2308
2302 HT=4:ST=2
2303 IF T<3800 THEN GOTO 2307
2304 IF INT(T)=3800 THEN GOTO 2307
2305 PRINT "The temperature must not exceed 3800 K for Vanadium"
2306 RETURN
2307 A=8.6:T1=2003: GOSUB 12340
2308 A=5.57:B=.97: GOSUB 12340
2309 HT(23,0)=HT:ST(23,0)=ST
2310 RETURN
2311 REM
2400 REM Cromium, Na 24,0
2401 IF T < 2173 THEN GOTO 2407
2402 HT=3.5:ST=1.6
2403 IF T<2495 THEN GOTO 2406
2404 HT=HT+72.97:ST=ST+29.25
2405 A=4.97:T1=2495: GOSUB 12340
2406 A=9.4:T1=2173: GOSUB 12340
2407 A=5.35:B=2.36:C=-44: GOSUB 12340
2408 HT(24,0)=HT:ST(24,0)=ST
2409 RETURN
2410 REM
2500 REM Manganese, #25,0
2501 IF T < 1000 THEN GOTO 2516
2502 HT=.535:ST=.535
2503 IF T<1374 THEN GOTO 2515
2504 HT=HT+.545:ST=ST+.397
2505 IF T<1410 THEN GOTO 2514
2506 HT=HT+.43:ST=ST+.305
2507 IF T<1517 THEN GOTO 2513
2508 HT=HT+3.5:ST=ST+2.31
2509 IF T<2368 THEN GOTO 2512
2510 HT=HT+53.7:ST=ST+22.7
2511 A=6.26:T1=2368: GOSUB 12340
2512 A=11:T1=1517 GOSUB 12340
2513 A=11.3:T1=1410: GOSUB 12340
2514 A=10.7:T1=1374: GOSUB 12340
2515 A=8.33:B=.66:T1=1000: GOSUB 12340
2516 A=5.7:B=3.38:D=-.377: GOSUB 12340
2517 HT(25,0)=HT:ST(25,0)=ST
```

```
2518 RETURN
2519 REM
2520 REM MnO, #25,1
2521 IF T<2058 THEN GOTO 2525
2522 HT=13:ST=6.32
2523 PRINT "MnO decays 2058"
2524 A=13.5:T1=2058: GOSUB 12340
2525 A=11.11:B=1.94:D=-.88: GOSUB 12340
2526 HT(25,1)=HT:ST(25,1)=ST
2527 RETURN
2528 REM
2600 REM Iron, Fe #26,0
2601 IF T < 1033 THEN GOTO 2619
2602 HT=.41:ST=.397
2603 IF T<1180 THEN GOTO 2618
2604 HT=HT+.217:ST=ST+.184
2605 IF T<1673 THEN GOTO 2617
2606 HT=HT+.15:ST=ST+.084
2607 IF T<1808 THEN GOTO 2616
2608 HT=HT+3.86:ST=ST+2.14
2609 IF T<3008 THEN GOTO 2615
2610 IF INT(T)=3008 THEN GOTO 2613
2611 PRINT"The temperature must not exceed 3008 K for Iron"
2612 RETURN
2613 PRINT"Iron boils"
2614 HT=HT+84.62:ST=ST+28.1
2615 A=10:T1=1808: GOSUB 12340
2616 A=10.3:T1=1673 GOSUB 12340
2617 A=4.85:B=3:T1=1180: GOSUB 12340
2618 A=10.4:T1=1033: GOSUB 12340
2619 A=3.37:B=7.1:D=.43: GOSUB 12340
2620 HT(26,0)=HT:ST(26,0)=ST
2621 RETURN
2622 REM
2623 REM FeO 26,1
2624 IF T<1641 THEN GOTO 2633
2625 HT=7.5:ST=4.6
2626 IF T<2700 THEN GOTO 2632
2627 IF INT(T)=2700 THEN GOTO 2630
2628 PRINT "The temperature must not exceed 2700 K for FeO"
2629 RETURN
2630 PRINT "FeO boils"
2631 HT=HT+55:ST+20
2632 A=14.5:T1=1641: GOSUB 12340
2633 A=9.27:B=4.8: GOSUB 12340
2634 HT(26,1)=HT:ST(26,1)=ST
2635 RETURN
2636 REM
2637 REM Fe2O3 26,2
2638 IF T<950 THEN GOTO 2643
2639 HT=.16:ST=.17
2640 IF T<1050 THEN GOTO 2643
2641 PRINT"Fe2O3 decays"
2642 A=23.46:B=18.6:D=-3.55:T1=1050: GOSUB 12340
2643 A=48:T1=950: GOSUB 12340
2644 A=21.88:B=48.2: GOSUB 12340
2645 HT(26,2)=HT:ST(26,2)=ST
2646 RETURN
```

```
2647 REM
2648 REM Fe3O4 26,3
2649 IF T<900 THEN GOTO 2652
2650 PRINT " Fe3O4 decays"
2651 A=14.5:T1=900: GOSUB 12340
2652 A=12.38:B=1.62:D=-.38: GOSUB 12340
2653 HT (26,3)=HT:ST(26,3)=ST
2654 RETURN
2655 REM
11000 REM Initialize
11010 R=8314.34:REM J/Kmol K
11020 N=26:K=7:DIMHT(N,K):DIMST(N,K):DIMET(N,K):DIMC(N,K):D
IMM(N,K):DIMX(N,K):DIMEC(N,K):DIMCF(N,K):DIMCA(N,K):DIMHC(N,K)
11030 EC=1:HC=0
11040 REM
11050 REM Molweight (kg/kmol)
11060 M(1,0)=2*1.0079
11070 M(1,1)=18.0152
11080 M(2,0)=4.0026
11090 M(6,0)=12.011
11100 M(6,1)=28.0104
11110 M(6,2)=44.0098
11120 M(6,3)=16.0426
11130 M(7,0)=2*14.0067
11140 M(7,1)=72.0262
11150 M(8,0)=2*15.9994
11160 M(10,0)=20.179
11170 M(11,0)=22.9898
11180 M(11,1)=105.989
11190 M(11,2)=39.9972
11200 M(11,3)=78.0436
11210 M(13,0)=26.9815
11220 M(13,1)=101.96128#
11230 M(14,0)=28.0855
11240 M(14,1)=44.0849
11250 M(14,2)=60.0843
11260 M(15,0)=4*30.9738
11270 M(16,0)=32.06
11280 M(16,1)=64.0588
11290 M(18,0)=39.948
11300 M(20,0)=40.08
11310 M(20,1)=56.0794
11320 M(20,2)=100.089
11330 M23,0)=50.9415
11340 M(24,0)=51.996
11350 M(25,0)=54.938
11360 M(25,1)=70.9374
11370 M(26,0)=55.847
11380 M(26,1)=71.8464
11390 M(26,2)=159.692
11400 M(26,3)=231.539
11410 RETURN
11420 REM
11430 REM Initialize H, S, T1 and T2
11440 HT=0
11450 ST=0
11460 T1=T0
11470 T2=T
```

```
11480 RETURN
11490 REM
11500 REM Input
11510 C=0
11520 INPUT"Element ? ?, Concentration in weight percent (-,-,0=no
   more)", I,K,C(I,K)
11530 C=C+C(I,K)
11540 IF C(I,K)=0 THEN GOTO 11580
11550 IF I=0 THEN GOTO 11890
11560 IF C=100 THEN GOTO 11580
11570 GOTO 11520
11580 PRINT
11590 CP=100
11600 FOR I=1 TO N: FOR K=0 TO 3
11610 IF C(I,K)=0 THEN GOTO 11640
11620 PRINT "C(",I,",",K,")=",C(I,K)," %"
11630 CP=CP-C(I,K)
11640 NEXT K: NEXT I
11650 I=0:K=0
11660 IF ABS(CP)<.01 THEN CP=0
11670 PRINT: IF CP<0 THEN GOSUB 11820: GOTO 11580
11680 PRINT"Unknown part: ",CP," %"
11690 INPUT"OK? yes=1/no=0 ",Q
11700 IF Q=0 THEN GOTO 11520
11710 FOR I=1 TO N: FOR K=0 TO 3
11720 C(I,K)=C(I,K) /100: REM Convertion to weight fraction
11730 NEXT K:NEXT I
11740 I=0:K=0:C=0
11750 CF=CP /100:REM Convertion to fraction
11760 PRINT
11770 PRINT"Reference temperature 25˚C = 298.15 Kelvin": T0=298.15
11780 PRINT
11790 INPUT "Actual temperature (Celsius): T=",T:T=T+273.15
11800 RETURN
11810 REM
11820 REM Normalization if sum C(I,K)>100
11830 FOR I=1 TO N: FOR K=0 TO 3
11840 C(I,K)=C(I,K) / (1-CP/100)
11850 NEXTK:NEXTI
11860 I=0:K=0:CP=0
11870 RETURN
11880 REM
11890 REM Special compositions
11900 REM Calculation of HT(I,K) and ST(I,K)
11910 A=0:B=0:C=0:D=0
11920 FOR I=1 TO N:FOR K=0 TO 3:REM Calculate HT(I,K) and ST(I,K),
   kcal/mol and cal/mol
11930 IF C(I,K)=0 THEN GOTO 12300
11940 GOSUB 11430
11950 IK=I+.1*K
11960 IF IK=1! THEN GOSUB 100
11970 IF IK=1.1 THEN GOSUB 105
11980 IF IK=2! THEN GOSUB 200
11990 IF IK=6! THEN GOSUB 600
12000 IF IK=6.1 THEN GOSUB 605
12010 IF IK=6.2 THEN GOSUB 610
12020 IF IK=6.3 THEN GOSUB 615
12030 IF IK=7! THEN GOSUB 700
```

```
12040 IF IK=7.1 THEN GOSUB 705
12050 IF IK=8! THEN GOSUB 800
12060 IF IK=10! THEN GOSUB 1000
12070 IF IK=11! THEN GOSUB 1100
12080 IF IK=11.1 THEN GOSUB 1111
12090 IF IK=11.2 THEN GOSUB 1119
12100 IF IK=11.3 THEN GOSUB 1127
12110 IF IK=13! THEN GOSUB 1300
12120 IF IK=13.1 THEN GOSUB 1314
12130 IF IK=14! THEN GOSUB 1400
12140 IF IK=14.1THEN GOSUB1414
12150 IF IK=14.2 THEN GOSUB 1425
12160 IF IK=15! THEN GOSUB 1500
12170 IF IK=16! THEN GOSUB 1600
12180 IF IK=16.1 THEN GOSUB 1614
12190 IF IK=18! THEN GOSUB 1800
12180 IF IK=11.1 THEN GOSUB 1614
12190 IF IK=11.2 THEN GOSUB 1800
12200 IF IK=20! THEN GOSUB 2000
12210 IF IK=20.1 THEN GOSUB 2014
12220 IF IK=23 THEN GOSUB 2300
12230 IF IK=24! THEN GOSUB 2400
12240 IF IK=25 THEN GOSUB 2500
12250 IF IK=25.1 THEN GOSUB 2520
12260 IF IK=26! THEN GOSUB 2600
12270 IF IK=26.1 THEN GOSUB 2623
12280 IF IK=26.2 THEN GOSUB 2637
12290 IF IK=26.3 THEN GOSUB 2648
12300 NEXT K: NEXT I
12310 I=0:K=0:IK=0
12320 RETURN
12330 REM
12340 REM Calculation of H and S at T (Kelvin)
12350 X=T2/T1
12360 H1=A*(X-1)
12370 H2=B*1E-03/2*(X^2-1)
12380 H3=C*-1E-06/3*(X^3-1)
12390 H4=D*100000! /T1*(1/X-1)
12400 H=T1*(H1+T1*(H2+T1*H3) )-H4
12410 H=H/1000: REM Mcal/kmol
12420 HT=HT+H
12430 S=A*LOG(X)+T1*(B*1E-03*(X-1)+T1*C*1E-06/2*(X*X-1) )-D*100000!
   /2/T1/T1*(1/X/X-1)
12440 ST=ST+S: REM kcal/kmol
12450 A=0:B=0:C=0:D=0
12460 T2=T1:T1=T0
12470 RETURN
12480 REM
12490 REM Calculation of thermal structural enthalpy, entropy and exergy
12500 REM Also conversion from weight fraction to mole fraction
12510 X=0
12520 FOR I=1 TO N: FOR K=0 TO 3
12530 IF C(I,K)=0 THEN GOTO 12550
12540 X=X+C(I,K)/M(I,K): REM Total number of kmol/kg known part of the
   mixture
12550 NEXT K: NEXT I
12560 X=X/(1-CF): REM Correction due to the unknown part assuming equal
   molar density
```

```
12570 I=0
12580 HM=0:SM=0:SS=0
12590 SX=0
12600 FOR I=1 TO N: FOR K=0 TO 3
12610 IF C(I,K)=0 THEN GOTO 12670
12620 X(I,K)=C(I,K)/M(I,K)/X: REM mole fraction
12630 IF X(I,K)=0 THEN GOTO 12670
12640 HM=HM+X(I,K)*HT(I,K)*4.184: REM mole fraction
12650 SM=SM+X(I,K)*ST(I,K)*4.184E-03-R*1E-06*X(I,K)*LOG(X(I,K)): REM
   kcal to MJ and J to MJ
12660 SS=SS-R*1E-06*X(I,K)*LOG(X(I,K) ): REM J TO MJ, structural part
12670 NEXT K: NEXT I
12680 SM=SM-SS: REM Instead adding the structural part to the chemical
   exergy
12690 I=0:K=0
12700 IF T=0 THEN GOTO 12710
12710 HM=HM*X
12720 SM=SM*X
12730 CF=CF+1E-10
12740 SS=(SS-R*1E-06*CF*LOG(CF) )*X: REM Correction due to the unknown
   part
12750 IF T=T0 THEN GOTO 12780
12760 HM=HM/(1-CF)
12770 SM=SM/(1-CF)
12780 EM=HM-T0*SM
12790 ES=T0*SS: REM Only the structural exergy
12800 RETURN
12810 REM
12820 REM Calculation of chemical enthalpy and exergy
12830 REM TO=298.15 K and p0=1 atm
12840 REM Ref. calculation 821209-17
12850 EC=0:HC=0
12860 FOR I=1 TO N: FOR K=0 TO 3
12870 IF X(I,K)=0 THEN GOTO 13290
12880 IK=I+.1*K
12890 H=0
12900 IF IK=1! THEN E=235.34:H=285.83:REM MJ/kmol
12910 IF IK=1.1 THEN E=0
12920 IF IK=2! THEN E=30.14166267#
12930 IF IK=6! THEN E=410.35:H=393.51
12940 IF IK=6.1 THEN E=275.14:H=282.98:REM
12950 IF IK=6.2 THEN E=19.87206245#
12960 IF IK=6.3THEN E=830.28:H=890.36
12970 IF IK=7! THEN E=.61322689#
12980 IF IK=7.1THEN E=106.73:H=82.05
12990 IF IK=8! THEN E=3.875104228#
13000 IF IK=10! THEN E=27.05788414#
13010 IF IK=11! THEN E=367.29:H=447.48
13020 IF IK=11.1 THEN E=94.87:H=85.81
13030 IF IK=11.2 THEN E=226.98:H=307.7
13040 IF IK=11.3 THEN E=1383.8:H=1656.91
13050 IF IK=13! THEN E=791.2:H=837.85
13060 IF IK=13.1 THEN E=5.83
13070 IF IK=14! THEN E=853.965:H=910.94
13080 IF IK=14.1THEN E=729.546:H=811.36
13090 IF IK=14.2 THEN E=1.167
13100 IF IK=15.1 THEN E=674.211:H=760.44
13110 IF IK=16! THEN E=1087.28:H=1209.22
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13120 IF IK=16.1 THEN E=790.97:H=912.39
13130 IF IK=18! THEN E=11.58510846#
13140 IF IK=20! THEN E=719.27:H=813.41
13150 IF IK=20.1 THEN E=117.17:H=178.32
13160 IF IK=20.2 THEN E=7.09
13170 IF IK=23! THEN E=716.47:H=775.3
13180 IF IK=24! THEN E=740.725:H=881.15
13190 IF IK=25! THEN E=478.079:H=520.03
13200 IF IK=25.1THEN E=117.097:H=134.81
13210 IF IK=26! THEN E=372.632:H=412.12
13220 IF IK=26.1 THEN E=128.174:H=140.16
13230 IF IK=26.2 THEN E=8.834
13240 IF IK=26.3 THEN E=110.189:H=117.98
13250 EC(I,K)=E*C(I,K)/M(I,K): REM Chemical exergy of substance I,K
13260 HC(I,K)=H*C(I,K)/M(I,K): REM Chemical enthalpyy of substance I,K
13270 EC=EC+EC(I,K)
13280 HC=HC+HC(I,K)
13290 NEXT K: NEXT I
13300 I=0: K=0: IK=0: E=0: H=0
13310 EC=EC-ES: REM Subtracting the structural exergy for ideal mixtures
13320 RETURN
13330 REM
13340 REM Printing
13350 PRINT
13360 PRINT
13370 REM Printing result with actual mass flow
13380 INPUT "Mass in kg 0 ",M
13390 PRINT "Chemical enthalpy: ",M*INT(HC*100000!+.5) 7100000!," MJ"
13400 PRINT "Thermal enthalpy: ",M*INT(HM*100000!+.5) 7100000!," MJ"
13410 PRINT "Total enthalpy: ",M*INT((HC+HM)*100000!+.5)/100000!," MJ"
13420 PRINT "Entropy: ",M*INT(SM*100000000!+.5) /100000000#," MJ/K"
13430 PRINT "Chemical exergy: ",M*INT(EC*100000!+.5) 100000!," MJ"
13440 PRINT "Structural exergy: ",M*INT(ES*100000!+.5)/100000!," MJ"
13450 PRINT "Thermal exergy: ",M*INT(EM*100000!+.5) /100000," MJ/K"
13460 PRINT "Total exergy: ",M*INT((EC+ES+EM)*100000!+.5)/100000!," MJ"
13470 RETURN
13480 REM
```

THERMOECONOMIC OPTIMISATION OF A HEAT PUMP SYSTEM

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Abstract. We present the application of Thermoeconomics to the optimisation of a single-stage heat-pump cycle. The method is well suited for application to thermodynamic processes and yields exergy losses. The marginal cost of an arbitrary variable can also be calculated. The efficiencies of the compressor, condenser, evaporator, and electric motor are chosen as the decision variables which are to be optimised. Parameters such as the price of electricity, the temperature of the delivered heat, and the operation time may vary among optimisations, and results are presented for different parameter values.

INTRODUCTION

Contemporary technical systems are often constructed without detailed prior analysis of the effects of different potential solutions for a given system in terms of cost. Instead, constructions are often based on experience, educated guesswork and personal evaluations. Sometimes energy reallocations are made, for example when the investment budget is based on calculation of energy (or, better, exergy) losses in each zone of the system. Irrespective of the method used, the maximum cost permitted for each zone is obtained, and the market prices then determine to what extent efficient components can be afforded. Such systems always cost at least as much as and often more than they would if optimisation were used.

Tribus and El-Sayed(1, 2) developed the concept of Thermoeconomics, in which the objective function is optimised, subject to given economic and technical constraints. The purpose of Thermoeconomics is to improve analyses of systems by introducing ways of concurrently suggesting improvements.

The result of an insufficient analysis is that we never know the best solution or how to find it. By optimising the total system in operation, we always find the best system within the given conditions. We can also calculate the marginal costs of the exergy losses in each component. These values are very important in the selection of research and development measures, or in the improvement of an existing system.

The system is described in relation to the physical (pressure p_0, temperature T_0, and chemical potentials of the appropriate substances $m_{c,0}$) and economic environments (prices of goods c_i and prices of capital or interest rates a_i). These two environments are interrelated by cost relations for physical quantities.

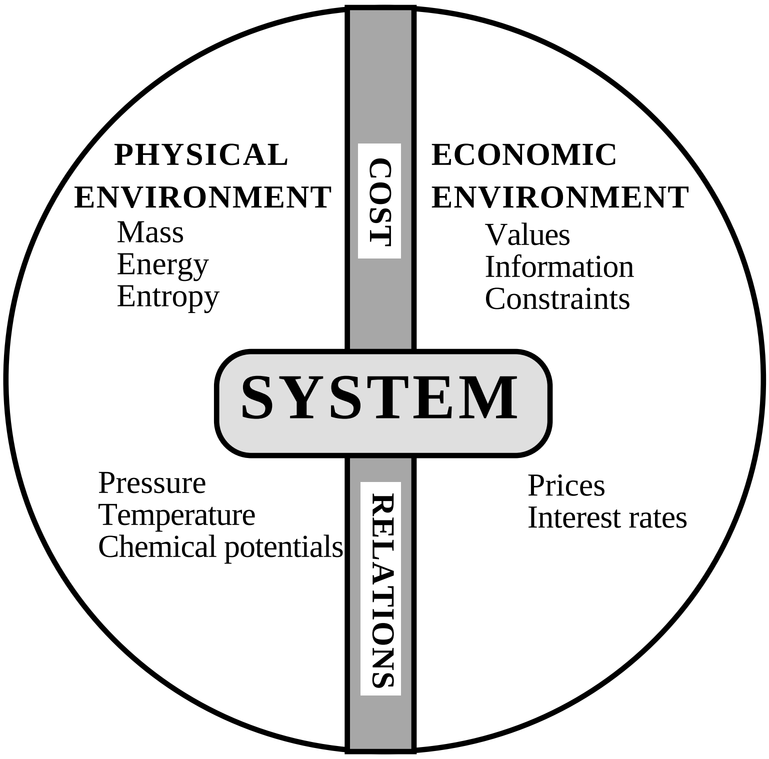

Fig. 1. The system in two environments.

Briefly, the method involves the following steps:

1. A concise description of the system under study,
2. Definition of system boundaries, zones, components, etc. (a detailed flow chart or a draft of the process),
3. Definitions of the physical environment or, alternatively, of the local physical environment,
4. Declarations of the sources of the thermophysical data,
5. Development of a computational algorithm with inputs and outputs clearly identified, based on mass and energy balances for the system and a complete thermodynamic description, within the given conditions,
6. Definitions of the cost equations and the economic objective function,
7. Determinations of the exergy flows and sources of entropy, i.e. exergy sinks, in the system (related to the in and outflows of exergy),
8. Determination of the monetary flows in the process,
9. Suggestions of possible improvements of the configuration of the system and adjustments of associated relations (5),
10. Optimisations of the objective of the process, i.e. the cost,
11. Carrying out of a sensitivity study,
12. Suggested improvements of the design and areas for further research and development.

The initial stages in this working scheme are self-explanatory and generally accepted. The new element is introduction of the environment and its effects on the system. This makes it possible to use the exergy concept to calculate the amount of work lost due to irreversibilities in the system. Thermoeconomics find the optimum economic design within physical feasibility. All costs are based on life-time costs, which may also include maintenance costs, etc. We might not be able to realise this optimum solution for an existing system, but we can learn how to improve it. The method also provides new insights, which often lead to new, unexpected improvements. Interest in Thermoeconomics from industrial management is increasing today (3).

Thermodynamic systems can be completely described using equations of mass balance (for each substance), energy and entropy, in conjunction with thermophysical property relations and/or equations of state, equipment performance characteristics, thermokinetic or rate equations, and boundary/initial conditions. Given an adequate description of the process, it can be optimised using any current technique. The exergy flow gives a unique description of the potentials for improving efficiency.

The variables describing the system can usually be divided into basic state variables, variable decision variables, and fixed decision variables (2). These variables are all interrelated by the objective function and the equations of constraints. We might substitute the constraint equations into the objective function, leaving only the independent variables, i.e. the variable decision variables, to be optimised. However, this is not always mathematically desirable. Using Lagrange’s method, we can maintain the fixed or dependent variables in the optimisation. Their shadow, i.e. marginal, prices are then given by the Lagrange multipliers.

The application of Lagrange’s method to large scale systems is well known and widespread (4). Methods are also available whereby a complex thermal system is decomposed into its component parts, each component buying and selling exergy with other components (5). However, this approach requires that the problem is described in terms of exergy co-ordinates, i.e. the constraint equations representing the internal economic transactions (supply and demand equations) must be explicitly given in terms of exergy flows. The benefit of such a transformation is that the Lagrange multipliers represent prices describing the internal sales and purchases of exergy. These prices can be used in turn to show the economic trade-offs between capital investment costs and exergy losses for each component of the system.

In order to obtain the exergy balance equations, all the relevant thermodynamic constraints must be incorporated. Usually there is no general way to find these constraint equations. All state variables (temperature, pressure, mass flows, etc.) must also be transformed into exergy variables, which may be problematical. Usually this transformation ends up in a number of non-linear equations which must be solved to get the optimum values for the decision variables. We avoid these problems by using numerical treatment.

When constructing a system, attempts should be made to attain the highest possible technical efficiency at the lowest cost within the existing technical, economical and legal constraints. (Sometimes we must also consider ethical, ecological or social consequences.) The analysis should also include different operating points (pressures, temperatures, etc.), configurations (components, flow charts, etc.), purposes (dual purpose, use of waste streams, etc.), and environments (global or local environment, new prices, etc.). As mentioned above, new areas for research and development should also be identified.

Computer programs and suitable strategies allow for examination of a large number of solutions, and determination of competitive solutions. A good strategy should include the use of new components and a suitable level of accuracy for available and assumed quantities representing different properties, performances and costs. The purpose of this study is to develop such a strategy from a fundamental theoretical basis and to formalise what many people regard as common sense. The point of departure is in regarding the system as surrounded by a physical and economic environment, see Fig. 1.

With regard to the physical environment, the energy and mass flows are evaluated in physical terms, i.e. in terms of exergy per unit time. The difference between all incoming exergy flows and all outgoing exergy flows must be minimised and the efficiency must be maximised. In the economic environment all energy and mass flows are evaluated instead in terms of economic value or costs. The main function is now the cost per unit time, (i.e. operation and capital costs minus income), which should be minimal. Thermoeconomic optimisation is economic optimisation in conjunction with thorough thermodynamic description of the system.

EXERGY

The exergy losses due to irreversibilities in a stationary state can be determined for each zone, a single component or a number of components, by regarding in and outflows of exergy. The exergy content E of a flow is

$$E = H - T_0 S - \sum_c \mu_{c0} n_c \tag{1}$$

where H is the enthalpy, T_0 the absolute temperature of the environment, S the entropy, and $\mu_{c,0}$ the chemical potential of substance c of quantity n_c. The exergy loss can be determined for each zone. For the system, we obtain a sum for all zones, which gives the total rate of exergy loss. This may also be written as the product of the environment temperature and total rate of entropy production, i.e. $T_0\ \Delta S^{tot}$.

COSTS OF EXERGY LOSSES

There are 2 main reasons for placing a price on exergy losses, irrespective of whether the purpose is physical or economic optimisation. The first is to obtain a description of how the variable mass and energy flows in the objective function are distributed over the process and the second is to find a redistribution that fulfils the objectives. This corresponds to 2 kinds of analysis: *Thermoeconomics accounting* with the use of direct prices which allows comparison between zones and their costs, disregarding other parts of the system, and *Thermoeconomics optimisation* using differential prices, which allows comparison between the local and global responses of the system to a particular change of state. This leads to a sensitivity analysis and an optimisation of the defined objective function.

The differential prices indicating the direction of improving the objective function are marginal prices and shadow prices. A marginal price indicates the change of the objective function at a unit change of a variable decision variable. The shadow price indicates the corresponding direction for the other variables. Marginal prices of exergy can then be calculated using the chain rule of derivation.

EFFICIENCY AND COST OPTIMISATION

The calculation of exergy flows and their costs requires a thermodynamic and economic description of the system.[†] A suitable level of description, when comparing alternative solutions, is the level at which efficiencies and costs for each subsystem are measured (as part of the system) in common quantities. A more detailed description can thus be made by dividing the subsystem into even smaller parts.

Important relations for describing the subsystems are equations for mass, energy, performances and costs as functions of performance. Cost relations as functions of capacity parameters such as areas, mass flows and powers are suitable in a preliminary analysis (6). These relations may later be rewritten to include other parameters such as temperatures, pressures or efficiencies.

THERMOECONOMIC ACCOUNTING

This method is one based on the exergy flows in the process, by which a price is put on the exergy. The exergy inflows are shared between useful outflows, wasted outflows and exergy losses. Thermoeconomic accounting simply means determining the exergy flows and assigning values to the exergy flows and losses. When there are various in and outflows the prices may vary. If the price per exergy unit does not vary too greatly we can define an “average price”. This method allows comparison of the economic cost of a zone with the cost of its exergy loss.

Thermoeconomic accounting does not include consideration of the system effects. It does not describe how the capital investments in one part on the system affect exergy losses in other parts of the system. In the Thermoeconomic accounting method the exergy losses are only figures not functions. However, this simple type of analysis sometimes gives ideas for unusual improvements.

[†] Second law considerations are not needed in the optimization. The exergy concept is only used to discover possible future improvements beyond the economic improvements.

THERMOECONOMIC OPTIMISATION

Direct prices are not affected when a change in one part of the system affects other parts. Marginal and shadow prices are affected, but they are difficult to determine. According to the system equations they are dependent on the first derivatives of the parameters in question and not only on their absolute values.

The objective function Φ_0 must be defined as a function of dependent state variables or state parameters $\{x_j\}$, where $\{x_j\}$ is abbreviation for $x_1,\ x_2,\dots x_j\dots x_n$., variable decision variables or just decision variables $\{y_k\}$, and fixed decision variables or decision parameters $\{z_l\}$, i.e.

$$\Phi_0 = \Phi_0\ (\{x_j\},\{y_k\},\{z_l\}), \tag{2}$$

where j=1, 2,…, n, k=1, 2,…, m, and l=1, 2,…, r.

The equations of state may be divided into 2 groups. One group fixes the dependent variables $\{x_j\}$, appearing in the objective function Φ_0 and in the constraints, $\{\Phi_j = 0\}$, in Lagrange’s method. The other group is related to the Lagrange multipliers $\{\lambda_j\}$. The equations of state are written as

$$\Phi_j = \bar{\Phi}_j - x_j, \tag{3}$$

where Φ_j is the function used in Lagrange’s method since it must be zero at optimum, i.e. when $x_j = \bar{\Phi}_j$. $\bar{\Phi}_j$ gives the relations between the state variable in question x_j and the other state variables $\{x_i\}_{i \neq j}$ and the decision variables $\{y_k\}$ and $\{z_l\}$. With these definitions, the equations of state become

$$\Phi_j\ (\{x_i\},\{y_k\},\{z_l\}) = 0,\quad j = 1, 2,\dots, n. \tag{4}$$

The problem can now be formulated as follows:

$$\text{minimise } \Phi_0 = \Phi_0\ (\{x_i\},\{y_k\},\{z_l\}), \tag{5}$$

$$\text{subject to } \Phi_j\ (\{x_i\},\{y_k\},\{z_l\}) = 0,\quad j = 1, 2,\dots, n. \tag{6}$$

With the defined objective function and equations of state, the Lagrangian becomes

$$L = \Phi_0 + \sum_j \lambda_j \Phi_j. \tag{7}$$

According to Lagrange’s method,

$$\partial L/\partial x_i = 0,\quad i = 1, 2,\dots, n. \tag{8}$$

This procedure gives n equations, which are linearly dependent through the unknown Lagrange multipliers $\{\lambda_j\}$, which may be regarded as shadow prices (7).

When the objective function and the equations of state are not too complicated, the optimum is given by

$$\partial L/\partial y_k = 0, \quad k=1, 2,\ldots, m. \tag{9}$$

The optimum solution is found by solving these equations for the variable decision variables $\{y_k\}$.

In real world applications, it is often better to define a marginal price θ_k, related to each variable decision variable y_k, i.e.

$$\sum_c \mu_{c0} n_c$$

$$\theta_k = \frac{\partial L}{\partial y_k} = \frac{\partial \Phi_0}{\partial y_k} + \sum_{i=1}^{n} \lambda_i \frac{\partial \Phi_i}{\partial y_k}, \quad k = 1, 2,\ldots\ m. \tag{10}$$

The physical interpretation of these prices is that they constitute the gradients for each variable decision variable, y_k, i.e. they give the direction for improving the system.

Equation (8) represents n linear equations for the unknown Lagrange multipliers and Eq. (9) represents m equations with the variable decision variables as unknowns. In many real world applications of this method the n+m equations defined by Eqs. (8) and (9) are strongly non-linear and difficult to solve. Numerical treatment is therefore often necessary. Numerical values must then be calculated for the shadow prices $\{\lambda_j\}$ for every set of the variable decision variables $\{y_k\}$. These shadow prices are then inserted into Eq. (10) to determine the marginal prices $\{\theta_k\}$. The marginal prices represent the derivatives of the objective function Φ_0 in the state i. From the values of the marginal prices we can now indicate the direction for improving the system. A new state, i+1, is chosen in this direction according to

$$y_{k,i+1} = y_{k,i} \pm \Delta y_k \tag{11}$$

where Δy_k is a predefined step.

When the marginal price $\theta_{k,i}$ is negative then the derivative of the objective function is negative. If we want to minimise the objective function, we must increase the variable decision variable $y_{k,i}$ to reach the optimum. If the marginal price is positive we must decrease the variable decision variable.

SYSTEM MODEL

Heat pump systems offer much more efficient means of producing heat than traditional combustion or electrical short circuit technologies. Heat pump systems are therefore becoming more common as the prices of fuels and electricity increase. The configuration of the system is defined in Fig. 2. It consists of a compressor, a condenser, an expansion valve, an evaporator, and an electric motor.

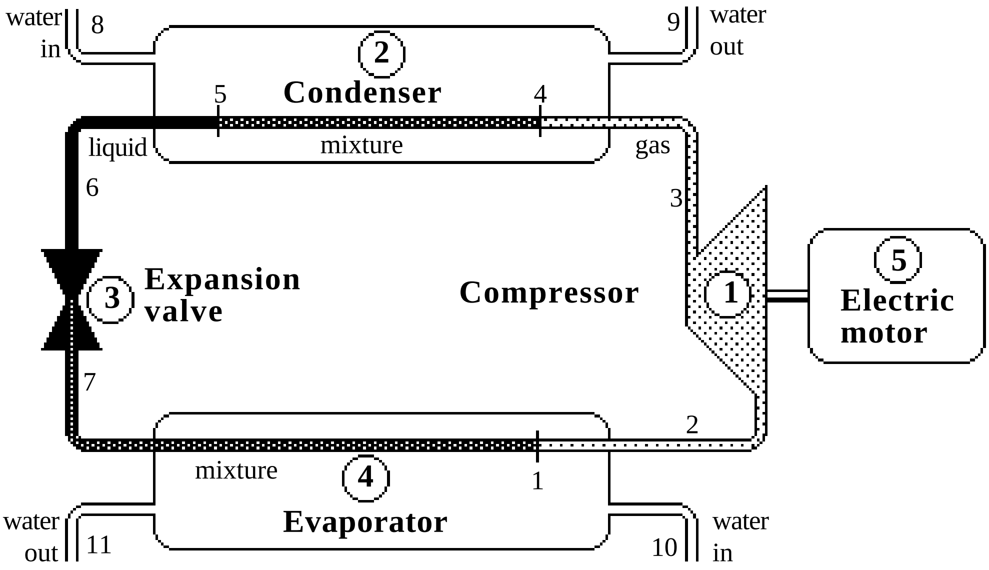

Fig. 2. Heat pump system with 5 components and 11 flows.

The refrigerant is superheated after passing through the evaporator, step 1-2, and super cooled after passing through the condenser, step 5-6. The actual state of the refrigerant after the compression, 3, differs from that of a reversible process, 3_{rev}, due to the limited efficiency of the compressor. The heat produced from the system is $h_3 - h_6$, the heat input is $h_2 - h_7$, and the work supplied to the compressor is $h_3 - h_2$. The electricity input required to operate the system becomes $(h_3 - h_2)/\eta_5$, where η_5 is the efficiency of the electric motor.

Variable decision variables are the efficiencies of the compressor, the condenser, the evaporator, and the electric motor. These are defined as follows

$$\eta_1 = \frac{h_{3rev} - h_2}{h_3 - h_2}, \tag{12}$$

$$\eta_2 = \frac{T_9 - T_8}{T_4 - T_8}, \tag{13}$$

$$\eta_4 = \frac{T_{11} - T_{10}}{T_1 - T_{10}}, \tag{14}$$

$$\eta_5 = \frac{m_r\,(h_3 - h_2)}{P} \tag{15}$$

where m_r is the mass flow of the refrigerant, and P is the electric power.

The system is completely defined apart from the variable decision variables $\{y_k\}$, each set of which determines a state of the system. The exergy flows and exergy losses are also determined for each component.

The objective is to minimise the cost for a given amount of produced heat. The cost includes both the operating (electricity) cost and the capital cost. The operating cost increases if the investments decrease and vice versa. The income from the product (heat) and a given required value of the profit sets an upper limit for the total cost of the system.

The problem is to split this cost between the operating cost and the capital cost for each component. (The costs for parts not affected by alternative constructions of the system, such as pipes connecting the components, are just added as constants and have no effect on the optimisation.) The costs, C, for each of the 5 components will now be given.

Compressor

$$C_1 = a_1\, k_1\, \frac{V_2}{0.9-\eta_1}\, \frac{p_3}{p_2}\, \ln\frac{p_3}{p_2} \tag{16}$$

where k_1 is the cost per volume flow, V_2, p_3/p_2 is the pressure ratio over the compressor, and η_1 is the enthalpy efficiency.

Condenser

$$C_2 = a_2\, k_2\, m_{wh} \sqrt{\frac{\eta_2}{1-\eta_2}} = a_2\, k_2\, m_{wh} \sqrt{e^{NTU_2} - 1}, \tag{17}$$

where k_2 is the cost per mass flow of water, m_{wh}, on the hot side, η_2 is the temperature efficiency, and NTU_2 is the number of heat transfer units.

Expansion Valve

$$\mathrm{C_3 = a_3\, k_3\, m_r}, \tag{18}$$

where k_3 is the cost per mass flow of the refrigerant.

Evaporator

$$C_4 = a_4\, k_4\, m_{wc} \sqrt{\frac{\eta_4}{1-\eta_4}} = a_4\, k_4\, m_{wc} \sqrt{e^{NTU_4} - 1}, \tag{19}$$

where k_4, η_4 and NTU_4 are analogous to the condenser above and m_{wc} is the mass flow of water on the cold side.

Electric Motor

$$C_5 = a_5\, k_5\, P\, \frac{\eta_5}{1-\eta_5}, \tag{20}$$

where k_5 is the cost per unit power and η_5 is the efficiency. Furthermore a_1-a_5 are annuity factors of the different capital investments defined as

$$a_i = \frac{r}{1 - (1+r)^{-n_i}}\,. \tag{21}$$

where r is the interest rate and n_i is the depreciation time for component i. The depreciation time may vary for each component due to variations in economic lifetime and maintenance costs such as renovations, etc.

Figure 3 shows the investment costs as a function of the efficiencies. The values of the fixed decision variables are set, for instance as follows: heat produced 6500 W (energy-power), operation time/yr 5000 hr, price of electricity 0.25 SEK/kWh, and temperature of the produced heat (T_9) 60°C.

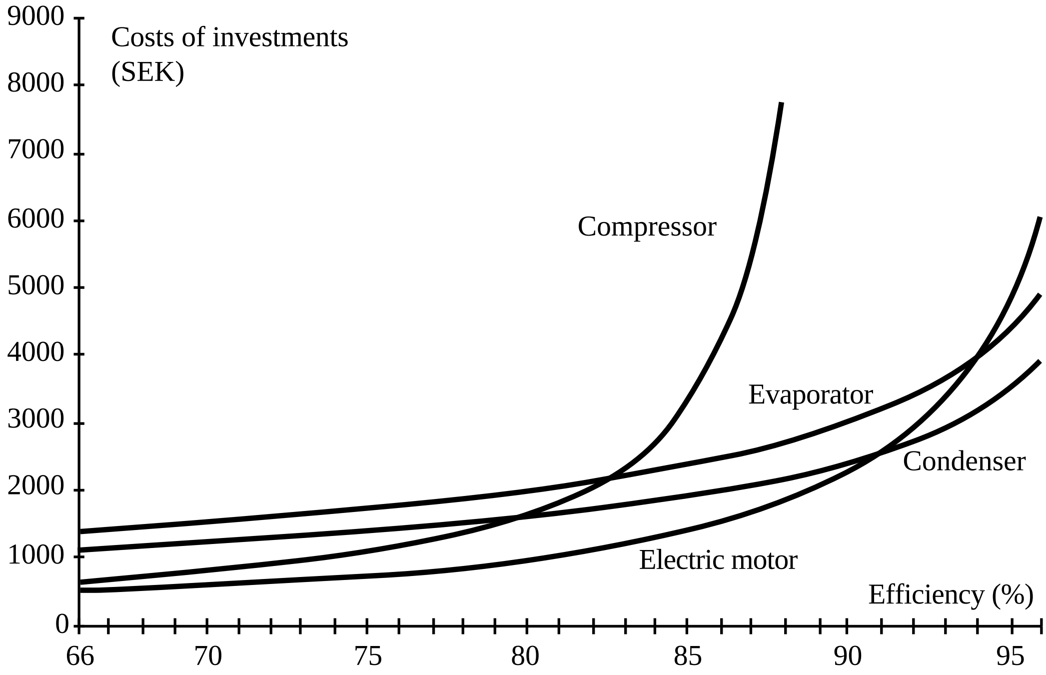

Fig. 3. Costs of investments as a function of the efficiencies.

The investment costs are depreciated according to the annuity method, which gives a cost per unit time for every component. The total cost per unit time Φ_0 (= objective function) is the sum of these costs and the cost of the electricity used, E_{el}, i.e.

$$\Phi_0 = \sum_{i=1}^{5} C_i \ + t\, p_{el}\, E_{el}. \tag{22}$$

where t is the operating time per unit time and p_{el} is the price of electricity.

RESULTS AND CONCLUSIONS

This optimisation problem is too complicated to be solved by Lagrange's method. Instead, the optimisation is achieved by calculating the value of the objective function Φ_0 and the marginal costs $\{\theta_k\}$ for every set of the variable decision variables $\{y_k\}$ according to

$$\theta_k = \Delta\Phi_0/\Delta y_k, \quad k = 1, 2, 3, 4. \tag{23}$$

From these values a new set of variable decision variables $\{y_k\}$ is determined by using the Newton-Raphson method (8). Thus the system moves towards the nearest minimum from the given start values. However, the problem is strongly non-linear which means that there is no general method for finding the global minimum. Instead common sense and insight into how the system works must be used to determine the value of a solution.

A computer program has been developed for finding the optimum system. The program begins by calculating the thermodynamic data for the assumed refrigerant R12. (Other refrigerants may also be used.) These calculations are based on similar computer-based calculations by Reynolds (9). The equations of state for the system are formulated so as to avoid iterations. The actual minimising procedure is carried out with a small number of iterations. When the sum of the marginal prices is less than a predefined value the optimisation is completed.

Let us assume a system with the values 0.7, for all efficiencies, which roughly correspond to real values of a system of this size, the variable decision variables, which are to be optimised. The calculated total cost then becomes SEK 4221/yr of which SEK 3617/yr relate to electricity. The optimisation gives the following efficiency values: compressor 0.80, condenser 0.83, evaporator 0.73 and electric motor 0.91, the total cost now amounting to SEK 3388/yr of which SEK 2416/yr is for the electricity. By increasing the investments from SEK 604/yr to SEK 972/yr, the total cost of the system becomes SEK 833/yr less than for the assumed system, see Fig. 4. At the same time the exergy losses decrease from 1933 W to 979 W, i.e. 954 W! From Fig. 5 we see that it is the improvement of the electric motor that gives the largest single exergy saving. The optimisation saves both money and exergy.

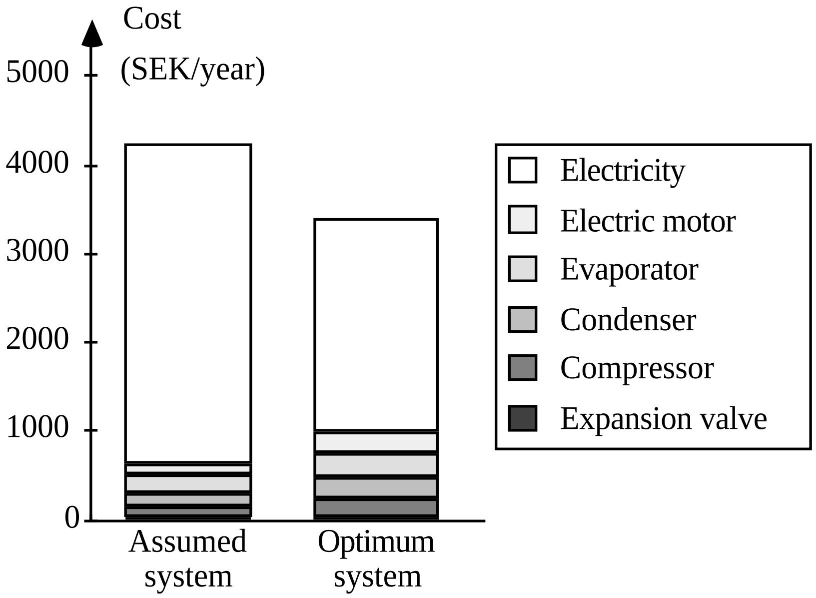

Fig. 4. Costs for the assumed and the optimum systems.

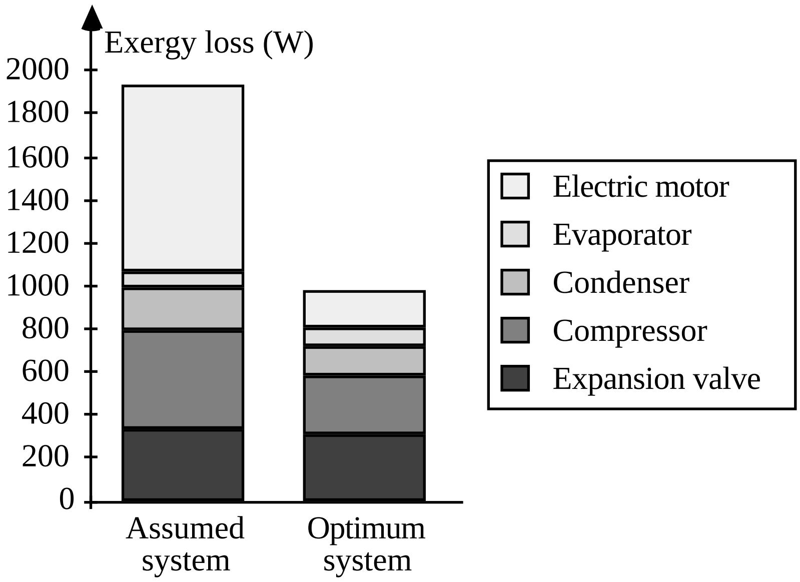

Fig. 5. Exergy losses for the assumed and the optimum systems.

The expansion valve accounts for the largest exergy loss in the optimum system, which justifies investment in research and development to improve it (10).

The result indicates the electric motor to be the most critical component to improve. The electric motor is assumed to cost approximately 3 times as much at 91% efficiency than at 70% efficiency, which must be regarded as realistic. (It may even cost up to 9 times as much and still be competitive with the assumed system.) It may also be added that the coefficient of performance (COP) increases from 2.25 for the assumed system to 3.36 for the optimal system.

The dependence on or sensitivity to the fixed decision variables (price of electricity, temperature of the produced heat, and operation time) has also been studied. Figure 6 shows the relationship between the costs and the price of electricity, when this varies between SEK 0.15 and 0.6/kWh. The total cost then increases from SEK 2073/yr to SEK 5522/yr at SEK 0.6/kWh. This can be seen in relation to the fact that if the optimum system at SEK 0.15/kWh had been used at SEK 0.6/kWh, then the total cost would be SEK 5947, i.e. an increase in the cost of SEK 425/yr. (For the assumed system the total cost would instead be SEK 9284, i.e. a cost increase of SEK 3762/yr.) Figure 7 shows more clearly the relationship between component costs and the price of electricity. All components should become more efficient (and therefore more expensive) when the price of electricity increases. This might have been anticipated, but the exact interrelations could not have been hypothesised.

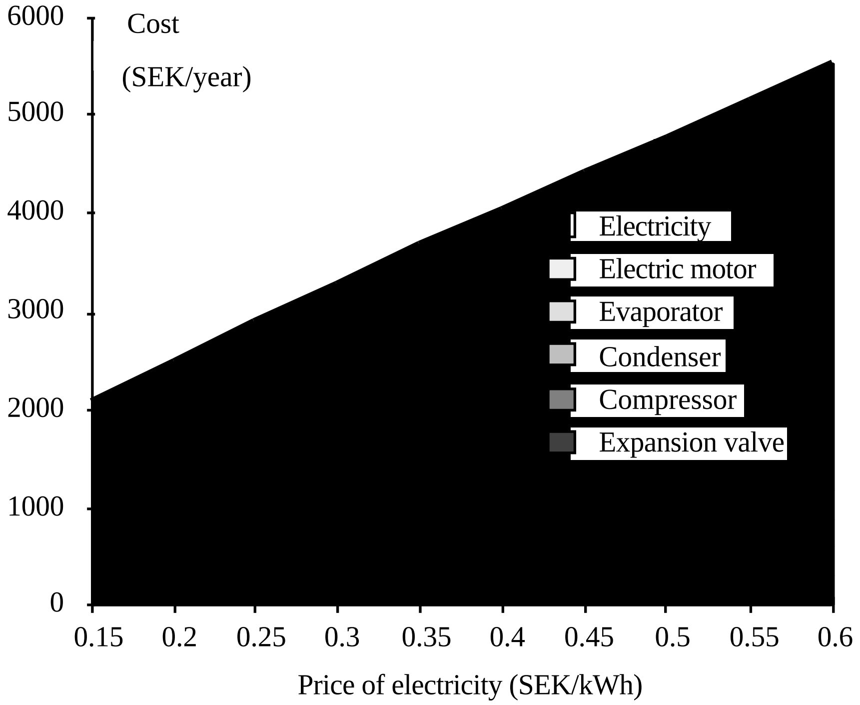

Fig. 6. Costs as a function of the price of electricity.

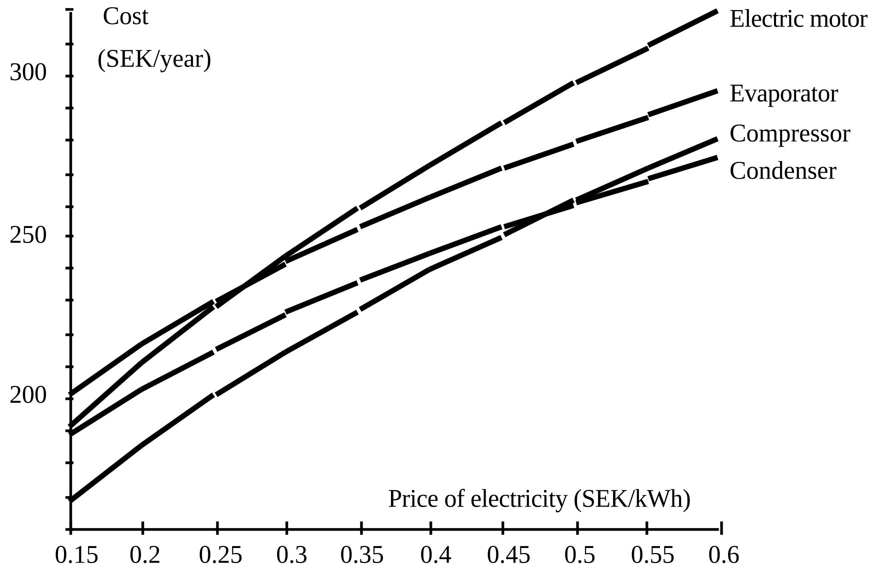

Fig. 7. Component costs as a function of the price of electricity.

When the temperature of the condenser, i.e. the temperature of the produced heat, is changed interesting things occur (Figs 8 and 9). The total cost doubles from 2336 at 40°C to SEK 4680/yr at 75°C. The heat produced in energy per time units is the same, i.e. 6500 W, but in exergy per time units it changes from 434 to 713 W which better explains the increased cost. When the temperature increases from 40 to 75°C the total system, but not necessarily each component, must be more efficient see Fig. 9. Within a total increase of component costs and efficiencies, it is more economical to choose a less expensive evaporator. The explanation is simply that investments in other parts of the system pay off better.

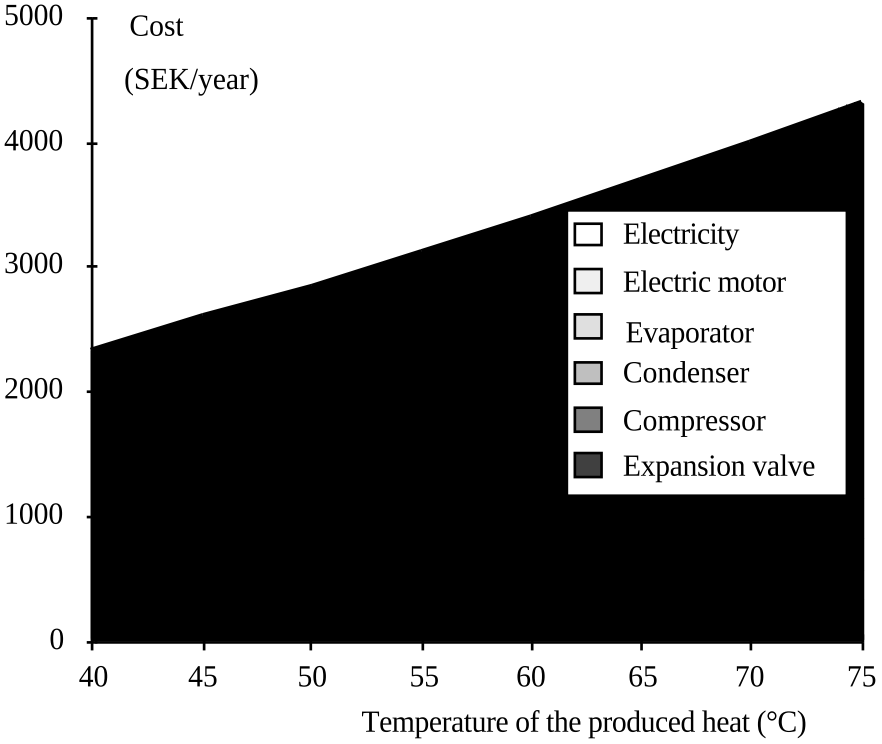

Fig. 8. Costs as a function of the temperature of the produced heat.

The system is very sensitive to the operating time which is shown in Figs 10 and 11.

Similarly, all other relations may be described using the computer program for the system. The program can easily be rewritten for other refrigerants or cost relations. The purpose of this study is merely to show the gain achieved by applying the method of Thermoeconomics to a heat pump process. The exact numerical results for describing Thermoeconomics as a method for improving technical processes have therefore been neglected.

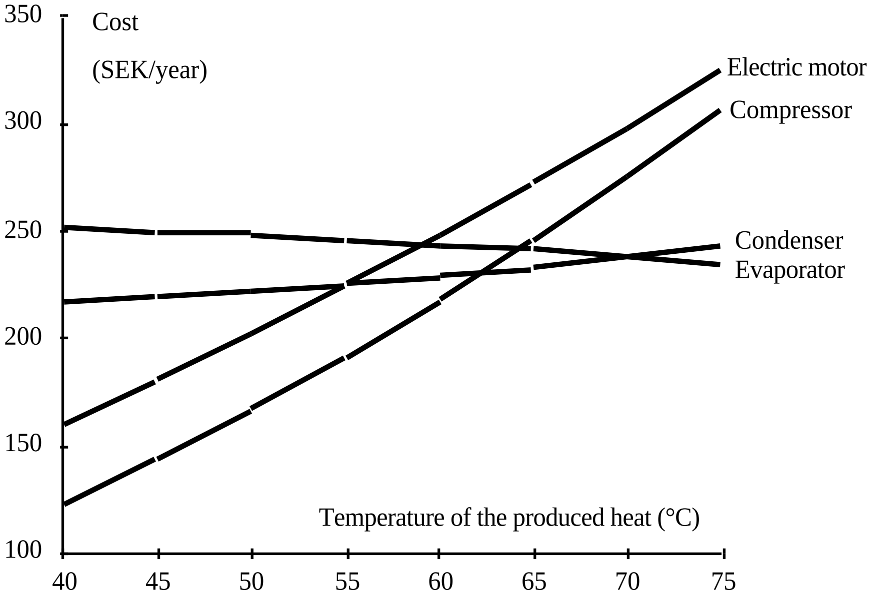

Fig. 9. Component costs as a function of the temperature of the produced heat.

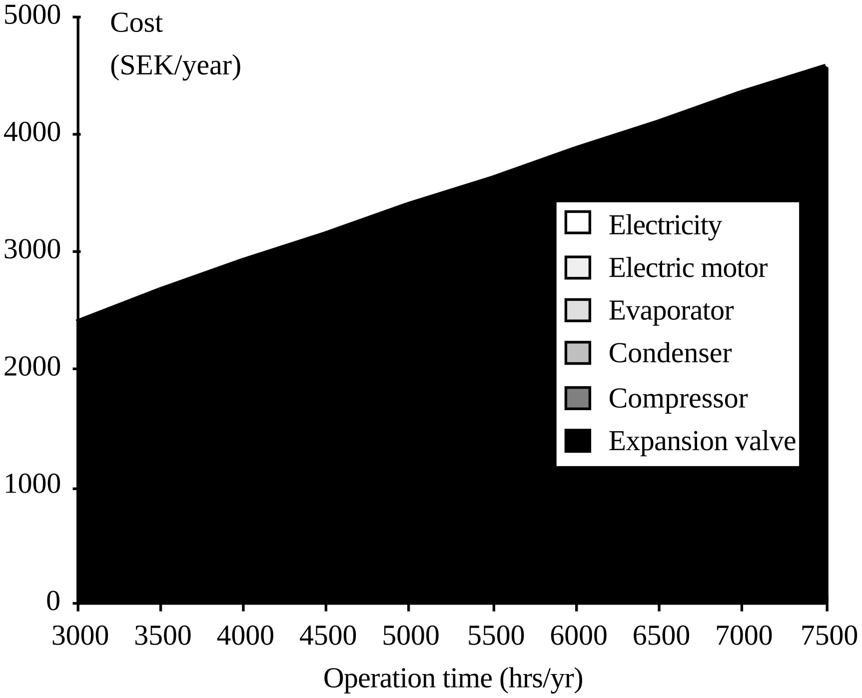

Fig. 10. Costs as a function of the operating time.

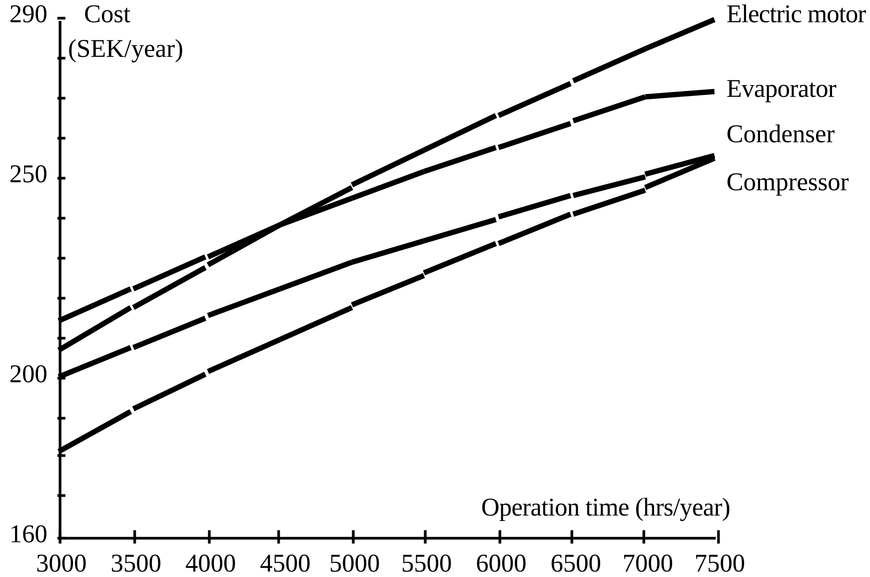

Fig. 11. Component costs as a function of the operating time.

Thermoeconomics can never replace long experience and high technical and economic competence, but it might be an important complementary tool.

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Note — All computer programs are listed below in a separate paper.

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THERMOECONOMIC OPTIMIZATION OF A HEAT PUMP SYSTEM - COMPUTER PROGRAMS

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September, 1985

Abstract - This is a presentation of two programs and calculated results that are used in the Paper *Thermoeconomic Optimization of a Heat Pump System*. The programs are written in Pascal. The first program, consisting of two sub-programs, COSTEQ.PAS and COSTIN.LIS, is only used to generate the diagram in Fig. 3 in the main paper. The second program contains first a documentation, HPMIN.DOK, of the used files and parameters followed by the main program, HPMIN.PAS, which also describes the operation of the program. First it calculates the thermodynamic data for the assumed refrigerant in the sub-programs R12.PAS and PROP.PAS. (Other refrigerants may also be used.) The state equations for the system are presented in HPCYCLE.PAS. These equations are formulated so that iterations are avoided. The minimizing procedure in MIN.PAS is done through a small number of iterations. When the sum of the marginal prices reaches a predefined value the optimization is completed and the result is printed. The values of the fixed decision variables are found in INFILE.LIS. Calculated values for the assumed system and the optimal system are also included.

Note - The programs are also available on disk (Macintosh™) by sending an empty disk to the auther.

Thermoeconomic Optimization of a Heat Pump System - Computer Programs

Contents

Program in Pascal for calculating the costing relations:

Program in Pascal for optimizing the heat pump system:

Printout of values for the assumed system and related optimal values:

COSTEQ.PAS

```
{Costing equations for each zone}

PROGRAM COSTEQ (COSTIN,COSTOUT);

VAR i,steps:integer;
    etastart,etastop,etastep,V2,p2,p3,mwh,mwc,mr,El,eta:double;
    TZ,cpc:ARRAY[1..5] OF double;
    COSTIN,COSTOUT:text;

BEGIN
  rewrite(COSTOUT);
  reset(COSTIN);
  readln(COSTIN,etastart);
  readln(COSTIN,etastop);
  readln(COSTIN,steps);
  readln(COSTIN,V2);
  readln(COSTIN,p2);
  readln(COSTIN,p3);
  readln(COSTIN,mwh);
  readln(COSTIN,mwc);
  readln(COSTIN,mr);
  readln(COSTIN,El);
  readln(COSTIN,cpc[1]);
  readln(COSTIN,cpc[2]);
  readln(COSTIN,cpc[3]);
  readln(COSTIN,cpc[4]);
  readln(COSTIN,cpc[5]);

  etastep:=(etastop-etastart)/steps;

  FOR i:=0 TO steps DO
  BEGIN
    eta:=etastart+i*etastep;

    TZ[1]:=cpc[1]*V2/(0.9-eta)*p3/p2*ln(p3/p2);
     IF TZ[1]<0 THEN TZ[1]:=0;
    TZ[2]:=cpc[2]*mwh*sqrt(eta/(1-eta));
    TZ[3]:=cpc[3]*mr;
    TZ[4]:=cpc[4]*mwc*sqrt(eta/(1-eta));
    TZ[5]:=cpc[5]*El*eta/(1-eta);

    write(COSTOUT,eta:6:3);
    write(COSTOUT,TZ[1]:10:2);
    write(COSTOUT,TZ[2]:10:2);
    write(COSTOUT,TZ[3]:10:2);
    write(COSTOUT,TZ[4]:10:2);
    write(COSTOUT,TZ[5]:10:2);
    writeln(COSTOUT);
  END;
END.

{*************************************************************}
```

INFILE.LIS

```
0.5             etastart
0.99            etastop
10              steps
2.5E-3          V2, m3/s
3.5             p2, bar
19              p3,bar
0.16            mwh, kg/s in condenser
0.2             mwc, kg/s in evaporator
0.05            mr, kg/s of refrigerant
2500            El, W
7E3             cpc[1] in SEK per flow in m3/s, cost per capacity for compressor
5E3             cpc[2] in SEK per flow in kg/s
5E3             cpc[3] in SEK per flow in kg/s
5E3             cpc[4] in SEK per flow in kg/s
0.1             cpc[5] in SEK/W
```

HPMIN.DOK

{841210 - 850628}

List of files:

CHARTFILE	Data for Microsoft Chart™
CHECK	List of steps in optimization (convergens, etc)
DECVAR	Variable decision variables, renewed after every run
INFILE	Fix decision variables easy to change
MIN	Result: Dec. var. & costs at optimum
OUTFILE	Result: Start values & optimal values
R12	Data for refrigerant R12
SENS	Sensitivity in optimal values

List of parameters:

an[1..5]	Annuity coefficient for each zone
Ar[1..5]	Constants for refrigerant
answer	Character for question: rerun?
b	Constant for refrigerant
Br[1..5]	Constants for refrigerant
calc	Program cycle variable 1,2,...,10
cpc[1..5]	Cost per capacity for each zone
cpr[1..5]	Constants for heat capacity for refrigerant
cprl	Specific heat of refrigerant as liquid
cpw	Specific heat of water
Cr[1..5]	Constants for refrigerant
dpdT	dp/dT
dpdT1	dp/dT1
dpdT4	dp/dT4
Dr[1..7]	constants for refrigerant
dTsc	Supercooling temperature in condenser
dTsh	Superheating temperature in evaporator
D[1..4]	Derivate of each decision variable
dy[1..4]	Step in change of each decision variable
e[1..11]	Specific exergy of each flow, J/kg
EE[1..11]	Exergy of each flow, W
EEmin	Exergy min value, help variable in HPEXERGY.PAS
El	Electricity, W
El0	Electricity, last calculated value, W
eta[1..5]	Efficiency of each zone, fraction
etamax[1..5]	Maximum efficiency of each zone, fraction
etamin[1..5]	Minimum efficiency of each zone, fraction
Fr[1..5]	Constants for refrigerant
f[1..4]	Function for each decision variable
Gr[1..5]	Constants for refrigerant
h[1..11]	Specific enthalpy of each flow, J/kg
HH[1..11]	Enthalpy of each flow, W
hlg	Enthalpy change from liquid to gas of refrigerant
Hout	Enthalpy output as heat from the heat pump
hrs	Numbers of hour in use per year
h3rev	Enthalpy of reversible change at 3
h[1..11]	Specific enthalpy of each flow, J/ks
i	Counter
infile	Text, file for input data
inter [1..5]	Interest factor for each zone
k	Counter for actual decision variable
kappa	
LW[1..5]	Lost Work for each zone, W
LW0[1..5]	Lost Work for each zone, last calculated value, W
LWoptimum[1..5]	Lost Work for each zone at optimum, W
LWTadd[1..4]	Change in total lost work when small increase in decision variable
LWToptimum	Lost Work Total, W
LWTsub[1..4]	Change in total lost work when small decrease in decision variable
M	Molecular weight of refrigerant
MC[1..5]	Marginal Cost of lost work in each zone, SEK/J
MCEl	Marginal Cost of Electricity, SEK/J
MCT	Marginal Cost of lost work tot
mr	Mass flow of refrigerant, kg/s
mwc	Mass flow of water, cold side, kg/s

mwh	Mass flow of water, hot side, kg/s
NTUc	Number of Heat Transfer Units, cold side
NTUh	Number of Heat Transfer Units, hot side
outfile	Text, file for writing results
p[1..11]	Pressure of each flow, Pascal
pc	Critical pressure of refrigerant
pel	Price of electricity, SEK/J
psat	Saturation pressure of refrigerant, Pa
p0	Pressure of the environment, Pa
p[1..11]	Pressure of each flow, Pa
R	Gas constant of refrigerant, J/kg K
RCEl	Ratio cost of electricity, SEK/J
RT	Ratio cost of lost work total, SEK/J
RC[1..5]	Ratio cost of of lost work of each zone, SEK/J
roc	Critical density of refrigerant
rowc	Density of water, cold side, kg/m3
rowh	Density of water, hot side, kg/m3
R12	Text, data for refrigerant 12
s[1..11]	Specific entropy of each flow, J/K/kg
slg	Entropy(gas)-entropy(liquid)
SS[1..11]	Entropy of each flow, W/K
s0r	Zero entropy level of refrigerant
T[1..11]	Temperature of each flow, K
Tc	Critical temperature of refrigerant
TCadd[1..4]	Change in total cost when small increase of decision variable
TCmin	Total Cost minimum value, SEK
TCost	Total Cost, SEK
TCsub[1..4]	Change in total cost when small decrease of decision variable
TC0	Total Cost last calculated value, SEK
TLW	Total Lost Work
TLW0	Total Lost Work, last calculated value
TLWadd	Total Lost Work when small increase in dec. var.
TLWsub	Total Lost Work when small decrease in dec. var.
TLWoptimum	Total Lost Work at optimum, W
T0	Temperature of environment, K
T0r	Zero temperature level of refrigerant
TK	Constant: 273.15, relation between Celsius and Kelvin
Tlmc	Logarithmic mean temperature difference, cold side, K
Tlmh	Logarithmic mean temperature difference, hot side, K
TZ[1..5]	Total cost of each zone, costing functions
u[1..11]	Specific energy of each flow, J/kg
UAc	Overall thermal conductance, cold side, W/K
UAh	Overall thermal conductance, hot side, W/K
UU[1..11]	Energy of each flow, W
ulg	Energy change from gas to liquid of refrigerant
u0r	Zero energy level of refrigerant
v[1..11]	Specifik volume of each flow, m3/kg
vc	Critical specific volume of refrigerant
VV[1..11]	Volume of each flow, m3
x	Gas fraction of gas-liquid mixture of refrigerant
y[1..4]	Actual decision variable
yadd[1..4]	Decision variable + 1%
year[1..5]	Economic life time for each zone
ymax[1..4]	Maximum value for each decision variable
ymin[1..4]	Minimum value for each decision variable
yoptimum[1..4]	Optimum value for each decision variable
ystart[1..4]	Start value for each decision variable
ysub[1..4]	Decision variable - 1%
Z[1..5]	Cost per year for each zone, SEK/yr
Z0[1..5]	Last cost per year for each zone, SEK/yr
Zoptimum[1..5]	Cost per year for each zone at optimum, SEK/yr

HPMIN.PAS

```
PROGRAM HPMIN(output,CHARTFILE,CHECK,DECVAR,INFILE,MIN,OUTFILE,R12,SENS);
{850627}
LABEL 9999;
CONST tab5='     ';                    {5 blanks}
      tab10='          ';              {10 blanks}

VAR k,calc:integer;
    answer:char;
    CHARTFILE,CHECK,DECVAR,INFILE,MIN,OUTFILE,R12,SENS:text;
    T0,p0,cpw,TK,M,R,Tc,pc,roc,vc,kappa,b,T0r,u0r,s0r,dpdT,slg,
    hlg,ulg,psat,dTsh,dTsc,dpdT1,dpdT4,h3rev,x,Hout,hrs,mr,mwh,
    mwc,rowh,rowc,El,cprl,NTUc,NTUh,Tlmc,Tlmh,UAc,UAh,TCost,TC0,
    RCT,MCT,RCEl,MCEl,TCmin,pel,TLW,TLW0,TLWoptimum,El0,step:double;
    ystart,y,yoptimum,dy,D,ymin,ymax,f,yadd,ysub,TCadd,TCsub,
    TLWadd,TLWsub:ARRAY[1..4] OF double;
    cpc,eta,etamin,etamax,Z,Z0,Zoptimum,TZ,LW,LW0,LWoptimum,RC,
    MC,an,inter,year:ARRAY[1..5] OF double;
    T,p,v,u,h,s,e,VV,UU,HH,SS,EE:ARRAY[1..11] OF double;

FUNCTION pwr(x,y:double):double;
  BEGIN pwr:=exp(y*ln(x)); END;

FUNCTION sgn(x:double):double;
  BEGIN sgn:=x/abs(x); END;

%INCLUDE 'R12.PAS/nolist'
%INCLUDE 'PROP.PAS/nolist'
%INCLUDE 'HPINIT.PAS/nolist'
%INCLUDE 'HPCYCLE.PAS/nolist'
%INCLUDE 'HPCOST.PAS/nolist'
%INCLUDE 'HPEXERGY.PAS/nolist'
%INCLUDE 'MIN.PAS/nolist'
%INCLUDE 'HPPRINT.PAS/nolist'
%INCLUDE 'HPCHART.PAS/nolist'

BEGIN
  Refrigerant;
  rewrite(CHARTFILE);
  rewrite(CHECK);
  rewrite(MIN);
  rewrite(OUTFILE);
  rewrite(SENS);
  Init;
  Printstart;
{FOR calc:=0 TO 9 DO}
  BEGIN
    writeln(tab5,'Run # ',calc:1);
    Init;
    Minimum;
    Printoptimum;
    Printmin;
    Chart;
  END;
9999:
END.
```

R12.PAS

```
{ref. Reynolds, W. C.,Thermodynamic properties in SI, Departmant of
  Mechanical Engineering, Stanford University, Stanford, CA 94305, 1979}
{************** Property procedures for Freon-12 ******************}

VAR Gr,Ar,Br,Cr,Fr,cpr:ARRAY[1..5] OF     {Refrigerant constants}
      double;
      Dr:ARRAY[1..7] OF double;           {Refrigerant constants}

PROCEDURE Refrigerant;

VAR i,j:integer;

BEGIN
  reset(R12);
  M:=120.93;
  R:=68.7480;
  FOR i:=2 TO 5 DO readln(R12,Ar[i]);
  FOR i:=2 TO 5 DO readln(R12,Br[i]);
  FOR i:=2 TO 5 DO readln(R12,Cr[i]);
  FOR i:=1 TO 4 DO readln(R12,Gr[i]);
  FOR i:=1 TO 4 DO readln(R12,Fr[i]);
  FOR i:=1 TO 7 DO readln(R12,Dr[i]);
  Tc:=385.17;
  pc:=4.1159;
  roc:=588.08;
  vc:=1/roc;
  T0r:=200;
  b:=4.06366926D-4;
  kappa:=5.475;
  u0r:=1.6970187D5;
  s0r:=8.9448764D2;
END;

{**************************************************************}

FUNCTION pr(T,v:double):double;

VAR i:integer;
    p:double;

BEGIN
  p:=R*T/(v-b);
  FOR i:=2 TO 5 DO
  BEGIN
     p:=p+(Ar[i]+Br[i]*T+Cr[i]*exp(-kappa*T/Tc))/pwr(v-b,i);
  END;
  pr:=p;
END;

{***********************************************************}

FUNCTION ur(T,v:double):double;

VAR i:integer;
  u:double;

BEGIN
  u:=u0r-Gr[5]*(1/T-1/T0r);
  FOR i:=1 TO 4 DO u:=u+Gr[i]*(pwr(T,i)-pwr(T0r,i))/i;
  FOR i:=2 TO 5 DO u:=u+(Ar[i]+Cr[i]*exp(-kappa*T/Tc)*(kappa*T/Tc+1))/((i-1)*pwr(v-b,i-1));
  ur:=u;
END;

{********************************************************}

FUNCTION sr(T,v:double):double;

VAR i:integer;
    s:double;
```

```
BEGIN
  s:=s0r+Gr[1]*ln(T/T0r)-Gr[5]*(1/(T*T)-1/(T0r*T0r))/2;
  s:=s+R*ln(v-b);
  FOR i:=2 TO 4 DO s:=s+Gr[i]*(pwr(T,i-1)-pwr(T0r,i-1))/(i-1);
  FOR i:=2 TO 5 DO s:=s-(Br[i]-Cr[i]*kappa*exp(-kappa*T/Tc)/Tc)/((i-1)*pwr(v-b,i-1));
  sr:=s;
END;

{***************************************************************}

FUNCTION vsl(T:double):double;

VAR x,help:double;
    i:integer;

BEGIN
  x:=1-T/Tc;
  help:=Dr[6]*pwr(x,0.5)+Dr[7]*x*x;
  FOR i:=1 TO 4 DO help:=help+Dr[i]*pwr(x,(i-1)/3);
  vsl:=1/help;
END;

{*************************************************************}

{ref. Thermophysical Properties of Matter vol. 6, Purdue Univ.}

FUNCTION cpsl(T:double):double;

BEGIN
  cpsl:=40.296648+9.7120682*T-4.070781D-2*T*T+6.2564189D-5*T*T*T;
END;

{*************************************************************}

FUNCTION satpr(T:double):double;

BEGIN
  satpr:=exp(Fr[1]+Fr[2]/T+Fr[3]*ln(T)+Fr[4]*T);
END;

FUNCTION satdpdTr(T,p:double):double;

BEGIN
  satdpdTr:=(-Fr[2]/(T*T)+Fr[3]/T+Fr[4])*p;
END;

{************************************************************}

PROCEDURE lr(T1,T2:double;VAR dh,ds:double);

VAR i:integer;

BEGIN
  dh:=0;
  FOR i:=1 TO 4 DO dh:=dh+cpr[i]*(pwr(T2,i)-pwr(T1,i))/i;
  ds:=cpr[1]*ln(T2/T1);
  FOR i:=2 TO 4 DO ds:=ds+cpr[i]*(pwr(T2,i-1)-pwr(T1,i-1))/(i-1);
END;

{*************************************************************}
FUNCTION vstart(T:double):double;      {Calculation of a start value for v}
BEGIN
  vstart:=-5.8529E-4*T+0.22025;
END;

{*************************************************************}
```

R12.LIS

```
-9.16210126d1      Ar[2]
 1.01049598d-1     Ar[3]
-5.74640225d-5     Ar[4]
 0                 Ar[5]
 7.71136428d-2     Br[2]
-5.67539138d-5     Br[3]
 0                 Br[4]
 4.08193371d-11    Br[5]
-1.52524293d3      Cr[2]
 2.19982681        Cr[3]
 0                 Cr[4]
-1.66307226d-7     Cr[5]
 3.389005260d1     Gr[1]
 2.507020671       Gr[2]
-3.274505926d-3    Gr[3]
 1.641736815d-6    Gr[4]
 9.33438056d1      Fr[1]
-4.39618785d3      Fr[2]
-1.24715223d1      Fr[3]
 1.96060432d-2     Fr[4]
 5.580845400d2     Dr[1]
 8.544458040d2     Dr[2]
 0                 Dr[3]
 2.994077103d2     Dr[4]
 0                 Dr[5]
 3.521500633d2     Dr[6]
-5.047419739d1     Dr[7]
40.296648          cpslr[1]
 9.7120682         cpslr[2]
-4.070781d-2       cpslr[3]
 6.2564289d-5      cpslr[4]
 1.126E3           cpslm
```

PROP.PAS

```
{PROCEDURE Property}
{ref. Reynolds, W. C.,Thermodynamic properties in SI, Departmant of
  Mechanical Engineering, Stanford University, Stanford, CA 94305, 1979}
{*************************************************************}

PROCEDURE Property(VAR T,p,v,u,h,s,vc,Tc,pc,R:double;option:integer);

LABEL 9999;

CONST erh=0.00001;
      erp=0.0001;
      ers=0.0001;
      maxiter=50;

TYPE choice=(TT,vv,pp,ss,hh);

VAR
dT,dv,dvbf,pmin,pmax,dvs1,dvs2,v1,v2,T1,T2,vmin,vmax,px,ux,hx,sx,p1,u1,h1,s1,dpdv,dvm,dTm,vt
,dva,dTa, p2,u2,h2,s2,det,dhdT,dhdv,dpdT,dsdT,dsdv:double;
    kbr,count:integer;
    flag,error:boolean;

{PROCEDURE perturb}
{               alter_v}
{               regulate}
{               init}
{FUNCTION no_convergence}
{*************************************************************}


PROCEDURE perturb(op:choice);

BEGIN
  CASE op OF
    TT:BEGIN
      dT:=0.001*T;
      T1:=T+dT;
      v1:=v;
    END;
    vv:BEGIN
      dv:=0.001*v;
      IF v<=vc THEN dv:=-dv;
      v2:=v+dv;
      T2:=T;
    END;
  END;  {CASE}
END;

PROCEDURE alter_v;

BEGIN
  IF v<=vc THEN dv:=-0.05*v
  ELSE dv:=0.2*v;
  IF vmin>0 THEN dv:=0.2*v;
  IF vmax<1d30 THEN dv:=-0.05*v;
END;

PROCEDURE regulate;

BEGIN
  dvm:=0.2*v;
  IF v<dvs1 THEN dvm:=0.5*dvm;
  IF v<dvs2 THEN dvm:=0.5*dvm;
  dTm:=0.1*T;
  dva:=abs(dv);
  dTa:=abs(dT);
  IF dva>dvm THEN dv:=dv*dvm/dva;
  IF dTa>dTm THEN dT:=dT* dTm/dTa;
END;
```

```
PROCEDURE init;

BEGIN
  dT:=0;
  kbr:=0;
  dvbf:=1;
  vmin:=0;
  vmax:=1d30;
  pmin:=0;
  pmax:=1d30;
  dvs1:=2*vc;
  dvs2:=0.7*vc;
  flag:=false;
  error:=false;
END;

FUNCTION no_convergence(op:choice):boolean;

BEGIN
  CASE op OF
    pp:no_convergence:=abs(p-px)>=erp*p;
    ss:no_convergence:=abs(s-sx)>=ers*R;
    hh:no_convergence:=abs(h-hx)>=erh*R*T;
  END;
END;

{***************************************}

BEGIN
  init;
  count:=1;
  CASE option OF

    1:p:=pr(T,v);                {T & v known find p}

    2:BEGIN                      {T & p known find v}
      px:=0;
      WHILE no_convergence(pp) AND (count<=maxiter) DO
      BEGIN
        px:=pr(T,v);
        IF px>=0 THEN
        BEGIN
          perturb(vv);
          p2:=pr(T2,v2);
          dpdv:=(p2-px)/dv;
          IF dpdv>0 THEN flag:=true
          ELSE
          BEGIN
            IF (px>p) AND (v>vmin) THEN
            BEGIN
              vmin:=v;
              pmin:=px;
            END;
            IF (px<p) AND (v<vmax) THEN
            BEGIN
              vmax:=v;
              pmax:=px;
            END;
            IF vmin>=vmax THEN {ERROR!} GOTO 9999;
            IF (vmin>0) AND (vmax<1d30) THEN kbr:=1;
            IF dpdv=0 THEN
            BEGIN
              dvbf:=0.5;
              flag:=true;
            END
            ELSE
            BEGIN
              dvbf:=1;
              dv:=(p-px)/dpdv;
              dT:=0;
            END;
```

```
   END;
  END;
  IF (px<0) OR flag THEN
  BEGIN
    IF kbr=0 THEN alter_v
   ELSE
   BEGIN
     dpdv:=(pmax-pmin)/(vmax-vmin);
     v:=vmax;
     px:=pmax;
     dv:=dvbf*(p-px)/dpdv;
    dT:=0;
     dvbf:=0.5*dvbf;
   END;
  END;
   dvm:=0.2*v;
   IF v<dvs1 THEN dvm:=0.5*dvm;
   IF v<dvs2 THEN dvm:=0.5*dvm;
  dTm:=0.1*T;
  IF kbr<>0 THEN
  BEGIN
    vt:=v+dv;
    IF NOT ((vt>=vmin) AND (vt<=vmax)) THEN dv:=vmin+(p-pmin)*(vmax-vmin)/(pmax-pmin)-v;
  END;
   dva:=abs(dv);
  dTa:=abs(dT);
   IF dva>dvm THEN dv:=dv*dvm/dva;
  IF dTa>dTm THEN dT:=dT*dTm/dTa;
  T:=T+dT;
   v:=v+dv;
   count:=count+1;
 END; {while}
 u:=ur(T,v);
 h:=u+p*v;
 s:=sr(T,v);
END;

3:BEGIN                    {p & v known}
 px:=pr(T,v);
 WHILE no_convergence(pp) AND (count<=maxiter) DO
 BEGIN
  IF px<0 THEN alter_v
  ELSE
  BEGIN
   perturb(TT);
    p1:=pr(T1,v1);
    dpdT:=(p1-px)/dT;
    dT:=(p-px)/dpdT;
   dv:=0;
  END;
  regulate;
  T:=T+dT;
   v:=v+dv;
   count:=count+1;
   px:=pr(T,v);
 END; {while}
 u:=ur(T,v);
 h:=u+p*v;
 s:=sr(T,v);
END;

4:BEGIN                {v & h known}
 px:=pr(T,v);
 ux:=ur(T,v);
 hx:=ux+px*v;
 WHILE no_convergence(hh) AND (count<=maxiter) DO
 BEGIN
  IF px<0 THEN alter_v
  ELSE
  BEGIN
   perturb(TT);
    p1:=pr(T1,v1);
```

```
      u1:=ur(T1,v1);
      h1:=u1+p1*v1;
      dhdT:=(h1-hx)/dT;
      dT:=(h-hx)/dhdT;
     dv:=0;
   END;
    regulate;
   T:=T+dT;
    v:=v+dv;
    count:=count+1;
    px:=pr(T,v);
    ux:=ur(T,v);
    hx:=ux+px*v;
  END; {while}
  p:=px;
  u:=ux;
  h:=hx;
  s:=sr(T,v);
END;

5:BEGIN               {T & h known}
  px:=pr(T,v);
  ux:=ur(T,v);
  hx:=ux+px*v;
  WHILE no_convergence(hh) AND (count<=maxiter) DO
  BEGIN
    IF px<0 THEN alter_v
   ELSE
   BEGIN
      perturb(vv);
      p2:=pr(T2,v2);
      u2:=ur(T,v);
      h2:=u2+p2*v2;
      dhdv:=(h2-hx)/dv;
      dv:=(h-hx)/dhdv;
     dT:=0;
   END;
    regulate;
   T:=T+dT;
    v:=v+dv;
    count:=count+1;
    px:=pr(T,v);
    ux:=ur(T,v);
    hx:=ux+px*v;
  END; {while}
  p:=px;
  u:=ux;
  h:=hx;
  s:=sr(T,v);
END;

6:BEGIN                {v & s known}
  px:=pr(T,v);
  sx:=sr(T,v);
  WHILE no_convergence(ss) AND (count<=maxiter) DO
  BEGIN
    IF px<0 THEN alter_v
   ELSE
   BEGIN
     perturb(TT);
      p1:=pr(T1,v1);
      s1:=sr(T1,v1);
      dsdT:=(s1-sx)/dT;
      dT:=(s-sx)/dsdT;
     dv:=0;
   END;
    regulate;
   T:=T+dT;
    v:=v+dv;
    count:=count+1;
    px:=pr(T,v);
    sx:=sr(T,v);
```

```
  END; {while}
  p:=px;
  u:=ur(T,v);
  h:=u+p*v;
  s:=sx;
END;

7:BEGIN       {T & s known}
  px:=pr(T,v);
  sx:=sr(T,v);
  WHILE no_convergence(ss) AND (count<=maxiter) DO
  BEGIN
    IF px<0 THEN alter_v
    ELSE
    BEGIN
      perturb(vv);
      p2:=pr(T2,v2);
      s2:=sr(T,v);
      dsdv:=(s2-sx)/dv;
      dv:=(s-sx)/dsdv;
      dT:=0;
    END;
    regulate;
    T:=T+dT;
    v:=v+dv;
    count:=count+1;
    px:=pr(T,v);
    sx:=sr(T,v);
  END; {while}
  p:=px;
  u:=ur(T,v);
  h:=u+p*v;
END;

8:BEGIN         {p & s known}
  px:=pr(T,v);
  sx:=sr(T,v);
  WHILE (no_convergence(ss) OR no_convergence(pp)) AND
    (count<=maxiter) DO
  BEGIN
    IF px<0 THEN alter_v
    ELSE
    BEGIN
      perturb(TT);
      p1:=pr(T1,v1);
      s1:=sr(T1,v1);
      perturb(vv);
      p2:=pr(T2,v2);
      s2:=sr(T,v);
      dsdT:=(s1-sx)/dT;
      dsdv:=(s2-sx)/dv;
      dpdT:=(p1-px)/dT;
      dpdv:=(p2-px)/dv;
      det:=dsdT*dpdv-dpdT*dsdv;
      dT:=((s-sx)*dpdv-(p-px)*dsdv)/det;
      dv:=(dsdT*(p-px)-dpdT*(s-sx))/det;
    END;
    regulate;
    T:=T+dT;
    v:=v+dv;
    count:=count+1;
    px:=pr(T,v);
    sx:=sr(T,v);
  END; {while}
  u:=ur(T,v);
  h:=u+p*v;
END;

9:BEGIN        {p & h known}
  px:=pr(T,v);
  ux:=ur(T,v);
  hx:=ux+px*v;
```

```
  WHILE (no_convergence(hh) OR no_convergence(pp)) AND
    (count<=maxiter) DO
  BEGIN
    IF px<0 THEN alter_v
    ELSE
    BEGIN
      perturb(TT);
      p1:=pr(T1,v1);
      u1:=ur(T1,v1);
      h1:=u1+p1*v1;
      perturb(vv);
      p2:=pr(T2,v2);
      u2:=ur(T,v);
      h2:=u2+p2*v2;
      dhdT:=(h1-hx)/dT;
      dhdv:=(h2-hx)/dv;
      dpdT:=(p1-px)/dT;
      dpdv:=(p2-px)/dv;
      det:=dhdT*dpdv-dpdT*dhdv;
      dT:=((h-hx)*dpdv-(p-px)*dhdv)/det;
      dv:=(dhdT*(p-px)-dpdT*(h-hx))/det;
    END;
    regulate;
    T:=T+dT;
    v:=v+dv;
    count:=count+1;
    px:=pr(T,v);
    ux:=ur(T,v);
    hx:=ux+px*v;
  END; {while}
  s:=sr(T,v);
END;

10:BEGIN              {h & s known}
  px:=pr(T,v);
  ux:=ur(T,v);
  sx:=sr(T,v);
  hx:=ux+px*v;
  WHILE (no_convergence(ss) OR no_convergence(hh)) AND
    (count<=maxiter) DO
    BEGIN
      IF px<0 THEN alter_v
      ELSE
      BEGIN
        perturb(TT);
        p1:=pr(T1,v1);
        u1:=ur(T1,v1);
        s1:=sr(T1,v1);
        h1:=u1+p1*v1;
        perturb(vv);
        p2:=pr(T2,v2);
        u2:=ur(T,v);
        s2:=sr(T,v);
        h2:=u2+p2*v2;
        dsdT:=(s1-sx)/dT;
        dsdv:=(s2-sx)/dv;
        dhdT:=(h1-hx)/dT;
        dhdv:=(h2-hx)/dT;
        det:=dhdT*dsdv-dsdT*dhdv;
        dT:=((h-hx)*dsdv-(s-sx)*dhdv)/det;
        dv:=(dhdT*(s-sx)-dsdT*(h-hx))/det;
      END;
      regulate;
      T:=T+dT;
      v:=v+dv;
      count:=count+1;
      px:=pr(T,v);
      ux:=ur(T,v);
      sx:=sr(T,v);
      hx:=ux+px*v;
    END; {while}
    u:=ux;
```

```
      p:=px;
     END;
   END; {CASE}

  IF count>maxiter THEN
  BEGIN
    writeln('Property not convergent for option ',option:0);
    writeln('T = ',T);
    writeln('v = ',v);
    writeln('p = ',p);
    writeln('u = ',u);
    writeln('h = ',h);
    writeln('s = ',s);
  END;

  9999:IF (option=2) AND (vmin>=vmax) THEN     {ERROR MESSAGE}
  BEGIN
    writeln('Error in property');
    writeln('T = ',T);
    writeln('p = ',p);
    writeln('v = ',v);
    writeln('vmin = ',vmin);
    writeln('vmax = ',vmax);
  END;
END;
{***************************************************************}

PROCEDURE sat(VAR T,p,dpdT,vc,Tc,pc,R:double;option:integer);

CONST maxiter=150;

VAR err,px,dTa,dTm,dT:double;
    count:integer;

BEGIN
  CASE option OF

    1:BEGIN
      p:=satpr(T);
      dpdT:=satdpdTr(T,p);
    END;

    2:BEGIN
      count:=0;
      err:=1d-6*p;
      IF T>Tc THEN T:=Tc-0.001;
      px:=satpr(T);
      dpdT:=satdpdTr(T,px);
      WHILE (abs(p-px)>=err) AND (count<=maxiter) DO
      BEGIN
        dT:=(p-px)/dpdT;
        dTa:=abs(dT);
        dTm:=0.1*dT;
        IF dTa>dTm THEN dT:=dT*dTm/dTa;
        T:=T+dT;
        IF T>Tc THEN T:=Tc-0.001;
        px:=satpr(T);
        dpdT:=satdpdTr(T,px);
        count:=count+1;
      END;
      IF count>maxiter THEN writeln('Sat not convergent : p,T=',p,T);
    END;
  END;         {CASE}
END;
{***************************************************************}
```

HPINIT.PAS

```
{PROCEDURE Init}
{*************************** Initiation ****************************}

PROCEDURE Init;

VAR i:integer;

BEGIN
 TK:=273.15;                          {Relation between degr C and K}
 T0:=273.15;                          {0 degrees C}
 p0:=101325;                          {1 atm}
 cpw:=4180;                           {cp water J/kg*K}
 rowh:=983.2;                         {Density for water at 60 degr C}
 rowc:=1000;                          {Density for water at 5 degr C}

 {Fixed decision variables}

 reset(INFILE);
 readln(INFILE,step);                 {Step between each optimization}
 readln(INFILE,T[8]);                 {Water in hot side in degr C}
 readln(INFILE,T[9]);                 {Water out hot side in degr C}
 readln(INFILE,T[10]);                {Water in cold side in degr C}
 readln(INFILE,T[11]);                {Water out cold side in degr C}
 FOR i:=8 TO 11 DO T[i]:=T[i]+TK;     {From degr C to K}
 FOR i:=8 TO 11 DO p[i]:=p0;          {pressure for water}
 readln(INFILE,dTsh);                 {Superheating in evaporator}
 readln(INFILE,dTsc);                 {Supercooling in condenser}
 readln(INFILE,Hout);                 {Heat out}
 readln(INFILE,hrs);                  {Hours in action per year}
 readln(INFILE,etamin[1]);            {Minimum efficiency for compressor}
 readln(INFILE,etamin[2]);            {Minimum efficiency for condenser}
 readln(INFILE,etamin[4]);            {Minimum efficiency for evaporator}
 readln(INFILE,etamin[5]);            {Minimum efficiency for electric eng.}
 readln(INFILE,etamax[1]);            {Maximum efficiency for compressor}
 readln(INFILE,etamax[2]);            {Maximum efficiency for condenser}
 readln(INFILE,etamax[4]);            {Maximum efficiency for evaporator}
 readln(INFILE,etamax[5]);            {Maximum efficiency for electric eng.}

 FOR i:=1 TO 5 DO
 BEGIN
   readln(INFILE,inter[i]);           {Interest factor for each zone}
   readln(INFILE,year[i]);            {Life time for each zone}
   an[i]:=inter[i]/(1-pwr((1+inter[i]),-year[i]));            {Annuity for each zone}
   readln(INFILE,cpc[i]);             {1: Compressor: SEK per m3/s}
                                      {2: Condenser: SEK per kg/s}
                                      {3: Expansion valve: SEK per kg/s}
                                      {4: Evaporator: SEK per kg/s}
                                      {5: Electric engine: SEK per W}
 END;

 readln(INFILE,pel);                  {In SEK/kWh}

 {Calc routine}

 {pel:=pel+step*calc;                 {calc=0,1,2, ... 9}

 {T[8]:=T[8]+step*calc;               {calc=0,1,2, ... 9}
 {T[9]:=T[8]+10;                      {10 degrees differens}

 {hrs:=hrs+step*calc;                 {calc=0,1,2, ... 9}

 pel:=pel/(1000*3600);                {From SEK/kWh to  SEK/J}

 {Variable decision variables, start values}

 reset(DECVAR);
 readln(DECVAR,eta[1]);               {Efficiency for compressor}
 readln(DECVAR,eta[2]);               {Efficiency for condenser}
 readln(DECVAR,eta[4]);               {Efficiency for evaporator}
```

```
  readln(DECVAR,eta[5]);                {Efficiency for electric engine}

  ystart[1]:=eta[1];                    {Set start values for the variable       }
  ystart[2]:=eta[2];                    {decision variables, these values        }
  ystart[3]:=eta[4];                    {are kept constant throught the          }
  ystart[4]:=eta[5];                    {program                          }

  FOR k:=1 TO 4 DO y[k]:=ystart[k];     {Set start values}

  FOR k:=1 TO 4 DO dy[k]:=0.01*ystart[k];                     {Step=0.01*ystart}

  {Limits for variable decision variables}

  ymin[1]:=etamin[1]; ymax[1]:=etamax[1];                     {Compressor}
  ymin[2]:=etamin[2]; ymax[2]:=etamax[2];                     {Condenser}
  ymin[3]:=etamin[4]; ymax[3]:=etamax[4];                     {Evaporator}
  ymin[4]:=etamin[5]; ymax[4]:=etamax[5];                     {Electric engine}

END;

{***************************************************************}
```

INFILE.LIS

```
   0     step
  50     T[8]
  60     T[9]
  10     T[10]
   5     T[11]
  10     dTsh
  10     dTsc
6500     Hout
5000     hrs
   0.4   etamin[1], compressor
   0.4   etamin[2], condenser
   0.4   etamin[4], evaporator
   0.6   etamin[5], electric engine
   0.9   etamax[1], compressor
   0.99  etamax[2], condenser
   0.99  etamax[4], evaporator
   0.99  etamax[5], electric engine
     .10 inter[1], interest factor for compressor
  10     year[1], economic life time for compressor
   7E3   cpc[1] in SEK per flow in m3/s, cost per capacity for compressor
     .10 inter[2], dito for condenser
  15     year[2]
   5E3   cpc[2] in SEK per flow in kg/s
     .10 inter[3], dito for expansion valve
  15     year[3]
   5E3   cpc[3] in SEK per flow in kg/s
     .10 inter[4], dito for evaporator
  15     year[4]
   5E3   cpc[4] in SEK per flow in kg/s
     .10 inter[5], dito for electric engine
  15     year[5]
   0.1   cpc[5] in SEK/W
   0.25  pel in SEK/kWh
```

HPCYCLE.PAS

```
{PROCEDURE Cycle}
{************************** Heat pump cycle **************************}

PROCEDURE Cycle;

VAR i:integer;

BEGIN
  T[1]:=T[10]+(T[11]-T[10])/eta[4];              {Evaporator}
  T[4]:=(T[9]-T[8])/eta[2]+T[8];                 {Condenser}
  IF T[4]>Tc THEN
  BEGIN
    writeln('T4 exceeds Tc !!!');
   T[4]:=1/0;                                    {PANIC STOP}
  END;
  sat(T[1],p[1],dpdT1,vc,Tc,pc,R,1);
  v[1]:=vstart(T[1]);
  property(T[1],p[1],v[1],u[1],h[1],s[1],vc,Tc,pc,R,2);
  p[2]:=p[1];
  T[2]:=T[1]+dTsh;
  v[2]:=vstart(T[2]);
  property(T[2],p[2],v[2],u[2],h[2],s[2],vc,Tc,pc,R,2);
  sat(T[4],p[4],dpdT4,vc,Tc,pc,R,1);
  v[4]:=vstart(T[4]);
  property(T[4],p[4],v[4],u[4],h[4],s[4],vc,Tc,pc,R,2);
  p[3]:=p[4];
  T[3]:=T[4]+dTsh;
  v[3]:=vstart(T[3]);
  property(T[3],p[3],v[3],u[3],h3rev,s[2],vc,Tc,pc,R,8);
  h[3]:=h[2]+(h3rev-h[2])/eta[1];
  property(T[3],p[3],v[3],u[3],h[3],s[3],vc,Tc,pc,R,9);
  IF T[3]>Tc THEN
  BEGIN
    writeln('T3 exceeds Tc!!!!');
   T[3]:=1/0;                                    {PANIC STOP}
  END;
  T[5]:=T[4];
  p[5]:=p[4];
  v[5]:=vsl(T[5]);
  slg:=(v[4]-v[5])*dpdT4;
  hlg:=slg*T[5];
  h[5]:=h[4]-hlg;
  u[5]:=h[5];
  ulg:=u[4]-u[5];
  s[5]:=s[4]-slg;
  T[6]:=T[5]-dTsc;
  p[6]:=p[5];
  v[6]:=v[5];
  h[6]:=h[5]-cpr[5]*dTsc;
  u[6]:=h[6];
  s[6]:=s[5]+cpr[5]*ln(T[6]/T[5]);
  h[7]:=h[6];
  T[7]:=T[1];
  p[7]:=p[1];
  slg:=(v[1]-vsl(T[7]))*dpdT1;
  hlg:=slg*T[7];
  x:=(h[7]-h[1])/hlg+1;
  v[7]:=v[6]*(1-x)+v[1]*x;
  s[7]:=s[1]-(1-x)*slg;
  u[7]:=u[1]-(1-x)*ulg;
  mr:=Hout/(h[3]-h[6]);
  El:=mr*(h[3]-h[2])/eta[5];
  FOR i:=1 TO 7 DO e[i]:=h[i]-T0r*s[i];
END;

{*************************************************************}
```

HPCOST.PAS

```
{PROCEDURE Costs}
{               Margcosts}
{Costing equations for each zone and marginal prices for the decision variables}

PROCEDURE Costs;

VAR i:integer;

BEGIN
  TZ[1]:=cpc[1]*VV[2]/(etamax[1]-eta[1])*p[3]/p[2]*ln(p[3]/p[2]);
  TZ[2]:=cpc[2]*mwh*sqrt(eta[2]/(1-eta[2]));
  TZ[3]:=cpc[3]*mr;
  TZ[4]:=cpc[4]*mwc*sqrt(eta[4]/(1-eta[4]));
  TZ[5]:=cpc[5]*El*eta[5]/(1-eta[5]);

  TCost:=0;
  FOR i:=1 TO 5 DO
  BEGIN
   Z[i]:=an[i]*TZ[i];
   TCost:=TCost+Z[i];
  END;
  TCost:=hrs*3600*pel*El+TCost;
END;


PROCEDURE Margcosts;

VAR i:integer;

BEGIN                                        {Calculation of ratio and marginal costs}
  RCT:=TCost/(TLW*hrs*3600);                 {Ratio Cost Total}
  MCT:=(TCost-TC0)/((TLW-TLW0)*hrs*3600);    {Marginal Cost Total}
  FOR i:=1 TO 5 DO
  BEGIN
    RC[i]:=Z[i]/(LW[i]*hrs*3600);            {Ratio Costs}
    MC[i]:=(Z[i]-Z0[i])/((LW[i]-LW0[i])*hrs*3600);          {Marginal Costs}
  END;
  RCEl:=pel;                                 {pel in SEK/J}
  MCEl:=(TCost-(Z[1]+Z[2]+Z[3]+Z[4]+Z[5])-
       (TC0-(Z0[1]+Z0[2]+Z0[3]+Z0[4]+Z0[5])))/
       ((El-El0)*hrs*3600);                  {Should be equal RCEl}
END;

{****************************************************************}
```

HPEXERGY.PAS

```
{PROCEDURE Exergies}
{********** Exergies for all flows and lost work in all zones **********}

PROCEDURE Exergies;

VAR i:integer;
   EEmin:double;                              {Exergy min value in cycle}

BEGIN
 FOR i:=1 TO 7 DO
 BEGIN
   VV[i]:=mr*v[i];
   UU[i]:=mr*u[i];
   HH[i]:=mr*h[i];
   SS[i]:=mr*s[i];
   EE[i]:=HH[i]-T0*SS[i];
 END;

 EEmin:=EE[1];
 FOR i:=2 TO 7 DO
 BEGIN
   IF EE[i]<EEmin THEN EEmin:=EE[i];
 END;
 FOR i:=1 TO 7 DO EE[i]:=EE[i]-EEmin;         {Zerro level}

 mwh:=Hout/(cpw*(T[9]-T[8]));                 {Enthalpy cons.}
 mwc:=(HH[2]-HH[7])/(cpw*(T[10]-T[11]));      {Enthalpy cons.}

 FOR i:=8 TO 9 DO                             {Water in condenser, hot side}
 BEGIN
  VV[i]:=mwh/rowh;                            {Volume}
   EE[i]:=mwh*cpw*(T[i]-T0-T0*ln(T[i]/T0));   {Total=thermal exergy}
  HH[i]:=mwh*cpw*(T[i]-T0);                   {Enthalpies}
  UU[i]:=HH[i];                               {Energies, water}
 END;

 FOR i:=10 TO 11 DO                           {Water in evaporator, cold side}
 BEGIN
  VV[i]:=mwc/rowc;                            {Volume}
   EE[i]:=mwc*cpw*(T[i]-T0-T0*ln(T[i]/T0));   {Total=thermal exergy}
  HH[i]:=mwc*cpw*(T[i]-T0);                   {Enthalpies}
  UU[i]:=HH[i];                               {Energies, water}
 END;

 {Lost works in each zone 1-5}

 LW[1]:=EE[2]+El*eta[5]-EE[3];
 LW[2]:=EE[3]+EE[8]-EE[6]-EE[9];
 LW[3]:=EE[6]-EE[7];
 LW[4]:=EE[7]+EE[10]-EE[1]-EE[11];            {See comment below}
 LW[5]:=El*(1-eta[5]);
 TLW:=0;                                      {Reset TLW}
 FOR i:=1 TO 5 DO TLW:=TLW+LW[i];

{The work needed for superheating the refrigerant gas after the evaporator is assumed to be available
from losses in other parts of the cycle}

{Data for condenser and evaporator}

 NTUh:=-ln(1-eta[2]);
 UAh:=mwh*cpw*NTUh;
 Tlmh:=(T[9]-T[8])/(ln((T[4]-T[8])/(T[4]-T[9])));

 NTUc:=-ln(1-eta[4]);
 UAc:=mwc*cpw*NTUc;
 Tlmc:=(T[10]-T[11])/(ln((T[10]-T[7])/(T[11]-T[7])));

END;
```

```
{***************************************************************}
```

MIN.PAS

```
{FUNCTION Fi0}
{          DFi0}
{PROCEDURE Save}
{             Minimum }

{**** Objective function and its derivates and its minimum value ****}

FUNCTION Fi0(yk:double;k:integer):double;       {Object function = Total cost}

BEGIN
  y[k]:=yk;

  eta[1]:=y[1];
  eta[2]:=y[2];
  eta[4]:=y[3];
  eta[5]:=y[4];

  Cycle;

  Exergies;

  Costs;

  Fi0:=TCost;
END;


FUNCTION DFi0(yk:double;k:integer):double;   {d(Total cost)/d(decision variable)}
LABEL 10;

VAR n,h0,h:double;
    i,l,m:integer;
    A:ARRAY [0..10,0..10] OF double;

BEGIN
  n:=100;
  h0:=dy[k]/n;
  h:=h0;
  A[0,0]:=(Fi0(yk+h,k)-Fi0(yk-h,k))/(2*h);
  FOR m:=1 TO 10 DO
  BEGIN
    h:=h0/pwr(2,m);
    A[m,0]:=(Fi0(yk+h,k)-Fi0(yk-h,k))/(2*h);
    FOR l:=1 TO m DO
    BEGIN
      A[m,l]:=A[m,l-1]+(A[m,l-1]-A[m-1,l-1])/(pwr(2,2*l)-1);
      IF abs(A[m,l-1]-A[m-1,l-1])<(1+abs(A[m,l]))*0.001 THEN GOTO 10;
    END;
  END;
  writeln('DFi0(',k:0,') not found after 10 loops');
10:DFi0:=A[m,l-1];
END;


PROCEDURE Save;            {Save last values for marginal calculations}

VAR i:integer;

BEGIN
  FOR i:=1 TO 5 DO
  BEGIN
    Z0[i]:=Z[i];
    LW0[i]:=LW[i];
  END;
  TC0:=TCost;
  TLW0:=TLW;
  El0:=El;
END;
```

```
PROCEDURE Minimum;          {Find minimum and calculate costs}

VAR i:integer;
  sumdy,sumD:double;
  y0,y1,D0,D1:ARRAY[1..4]OF double;

BEGIN
 FOR k:=1 TO 4 DO D1[k]:=DFi0(y[k],k);    {Start values}
 FOR k:=1 TO 4 DO y1[k]:=y[k];            {Save start values}

 FOR k:=1 TO 4 DO
 BEGIN
  y[k]:=y1[k]-sgn(D1[k])*dy[k];           {First step}

  {Limits for variable decision variables}
  IF y[k]>ymax[k] THEN y[k]:=(9*y1[k]+ymax[k])/10;
  IF y[k]<ymin[k] THEN y[k]:=(9*y1[k]+ymin[k])/10;
 END;

 FOR k:=1 TO 4 DO D[k]:=DFi0(y[k],k);     {First derivates}

{Check of convergency}
writeln(CHECK,tab10,'TCost:',TCost:12:6,'SEK/yr');
writeln(CHECK,tab10,'Eff. compressor:',y[1]:12:9,'    Marg. cost:',D[1]:18:6,'SEK/yr');
writeln(CHECK,tab10,'Eff. condenser: ',y[2]:12:9,'    Marg. cost:',D[2]:18:6,'SEK/yr');
writeln(CHECK,tab10,'Eff. evaporator:',y[3]:12:9,'    Marg. cost:',D[3]:18:6,'SEK/yr');
writeln(CHECK,tab10,'Eff. el. engine:',y[4]:12:9,'    Marg. cost:',D[4]:18:6,'SEK/yr');

 REPEAT
  FOR k:=1 TO 4 DO                        {Save old values}
  BEGIN
   D0[k]:=D1[k];
   D1[k]:=D[k];
   y0[k]:=y1[k];
   y1[k]:=y[k];
  END;

  FOR k:=1 TO 4 DO
  BEGIN                                   {New values by Newton-Rapson}
   y[k]:=y1[k]-D1[k]*(y1[k]-y0[k])/(D1[k]-D0[k]);
   {Limits for variable decision variables}
   IF y[k]>ymax[k] THEN y[k]:=(y1[k]+ymax[k])/2;
   IF y[k]<ymin[k] THEN y[k]:=(y1[k]+ymin[k])/2;
  END;
  sumD:=0;
  FOR k:=1 TO 4 DO
  BEGIN
   D[k]:=DFi0(y[k],k);                    {New derivaties}
   f[k]:=Fi0(y[k],k);                     {Reset the y[k]'s in Fi0}
   sumD:=sumD+abs(D[k]);                  {Value for "REPEAT-UNTIL" condition}
  END;


{Check of convergency}
writeln(CHECK,tab10,'TCost:',TCost:12:6,'SEK/yr');
writeln(CHECK,tab10,'Eff. compressor:',y[1]:12:9,'    Marg. cost:',D[1]:18:6,'SEK/yr');
writeln(CHECK,tab10,'Eff. condenser: ',y[2]:12:9,'    Marg. cost:',D[2]:18:6,'SEK/yr');
writeln(CHECK,tab10,'Eff. evaporator:',y[3]:12:9,'    Marg. cost:',D[3]:18:6,'SEK/yr');
writeln(CHECK,tab10,'Eff. el. engine:',y[4]:12:9,'    Marg. cost:',D[4]:18:6,'SEK/yr');

 UNTIL sumD/TCost<0.01;     {The sum of the relative marginal costs < 0.01 SEK/yr}
 TCmin:=TCost;                            {Save the Total Cost}
 TLWoptimum:=TLW;                         {and Lost Work Total at optimum}
 rewrite(DECVAR);
 FOR k:=1 TO 4 DO
 BEGIN
  yoptimum[k]:=y[k];                      {Save decision var.}
  writeln(DECVAR,y[k]);                   {in file DECVAR}
 END;

 FOR i:=1 TO 5 DO
```

```
  BEGIN
    LWoptimum[i]:=LW[i];                    {lost works and}
    Zoptimum[i]:=Z[i];                      {costs at optimum}
  END;
END;
{********************************************************************}
```

HPPRINT.PAS

```
{PROCEDURE      Printcycle}
{               Printfile}
{               Print}
{               Printsens}
{               Printstart}
{               Printoptimum}
{               Printmin}
{************************** Print procedures ************************}

PROCEDURE Printcycle;

VAR i:integer;

BEGIN
  Cycle;
  writeln(tab10,'T1 = ',T[1]-273.15:6:1,' C');
  writeln(tab10,'T4 = ',T[4]-273.15:6:1,' C');
  writeln(tab10,'dTsh = ',dTsh:6:1,' C');
  writeln(tab10,'dTsc = ',dTsc:6:1,' C');
  writeln;
  writeln(tab10,' no    T       p      density     h       s       e');
  writeln(tab10,'      (C)     (kPa)     (kg/m3)    (kJ/kg)   (kJ/kg*K)  (kJ/kg)');
  writeln;
  FOR i:=1 TO 7 DO writeln(tab10,i:3,T[i]-273.15:7:1,'   ',p[i]/1000:7:2,'   ',1/v[i]:10:2,'    ',
    h[i]/1000:8:2,'    ',s[i]/1000:8:2,'    ',e[i]/1000:8:2);
  writeln;
  writeln(tab10,'Component      Energy     Exergy');
  writeln(tab10,tab10,'      kJ/kg       kJ/kg');
  writeln(tab10,'Compressor : ',(h[3]-h[2])/1000:10:2,(e[3]-e[2])/1000:10:2);
  writeln(tab10,'Evaporator : ',(h[2]-h[7])/1000:10:2,(e[2]-e[7])/1000:10:2);
  writeln(tab10,'Condenser  : ',(h[6]-h[3])/1000:10:2,(e[6]-e[3])/1000:10:2);
  writeln;
  writeln(tab10,'Lost work');
  writeln(tab10,'Compressor : ',(h[3]-h[2]-(e[3]-e[2]))/1000:8:2,' kJ/kg');
  writeln(tab10,'Exp. valve : ',(e[6]-e[7])/1000:8:2,' kJ/kg');
  writeln;
  writeln(tab10,'Efficiency : ',(e[3]-e[2])/(e[2]-e[7]+h[3]-h[2])*100:5:1,' %');
  writeln(tab10,'COP        : ',(h[3]-h[6])/(h[3]-h[2]):5:2);
  writeln(tab10,'COP Carnot : ',1/(T[4]/T[1]-1):5:2);
  writeln;
END;

PROCEDURE Printfile;

VAR i:integer;

BEGIN
  writeln(OUTFILE,tab10,'Flow   Temp.   Pressure   Volume   Energy  Enthalpy  Exergy');
  writeln(OUTFILE,tab10,'#:   Celsius:   bar:     l/s:      kW:      kW:      kW:');
  writeln(OUTFILE);
  FOR i:=1 TO 11 DO writeln(OUTFILE,tab10,'',i:2,T[i]-TK:10:2,p[i]/1E5:10:3,VV[i]*1000:10:3,
    UU[i]/1000:10:3,HH[i]/1000:10:3,EE[i]/1000:10:3);
  writeln(OUTFILE);
  writeln(OUTFILE,tab10,'Flow of refrigerant: ',mr:6:4,' kg/s');
  writeln(OUTFILE,tab10,'Waterflows: ',mwh:6:3,' kg/s in condenser and ',mwc:6:3,' kg/s in evaporator');
  writeln(OUTFILE);
  writeln(OUTFILE,tab10,'Variable decision variables          Marginal price (SEK/yr/unit)');
  writeln(OUTFILE);
  writeln(OUTFILE,tab10,'Efficiency compressor:     ',y[1]:10:4,D[1]:18:6);
  writeln(OUTFILE,tab10,'Efficiency condenser:      ',y[2]:10:4,D[2]:18:6);
  writeln(OUTFILE,tab10,'Efficiency evaporator:     ',y[3]:10:4,D[3]:18:6);
  writeln(OUTFILE,tab10,'Efficiency electric engine:',y[4]:10:4,D[4]:18:6);
  writeln(OUTFILE);
  writeln(OUTFILE,tab10,'                      Condenser, hot side   Evaporator, cold side');
  writeln(OUTFILE,tab10,'Number of H. T. Units:        ',NTUh:10:4,NTUc:20:4);
  writeln(OUTFILE,tab10,'Overall therm. conduct. [W/K]: ',UAh:10:4,UAc:20:4);
  writeln(OUTFILE,tab10,'Log. mean temp. diff. [K]:    ',Tlmh:10:4,Tlmc:20:4);
  writeln(OUTFILE);
  writeln(OUTFILE,tab10,'Zone           Total   Costs    Lost     Ratio     Marginal');
```

```
  writeln(OUTFILE,tab10,'              costs          Works    Costs      Costs');
  writeln(OUTFILE,tab10,'              SEK    SEK/yr    W      SEK/MJ     SEK/MJ');
  writeln(OUTFILE);
  writeln(OUTFILE,tab10,'Total:              ',TCost:10:1,TLW:10:1,RCT*1E6:12:6,MCT*1E6:12:6);
  writeln(OUTFILE,tab10,'Electricity:        ',pel*hrs*3600*El:10:1,El:10:1,RCEl*1E6:12:6,
    MCEl*1E6:12:6);
  writeln(OUTFILE,tab10,'Compressor: ',TZ[1]:10:1,Z[1]:10:1,LW[1]:10:1,RC[1]*1E6:12:6,
    MC[1]*1E6:12:6);
  writeln(OUTFILE,tab10,'Condenser:  ',TZ[2]:10:1,Z[2]:10:1,LW[2]:10:1,RC[2]*1E6:12:6,
    MC[2]*1E6:12:6);
  writeln(OUTFILE,tab10,'Exp. valve: ',TZ[3]:10:1,Z[3]:10:1,LW[3]:10:1,RC[3]*1E6:12:6,
    MC[3]*1E6:12:6);
  writeln(OUTFILE,tab10,'Evaporator: ',TZ[4]:10:1,Z[4]:10:1,LW[4]:10:1,RC[4]*1E6:12:6,
     MC[4]*1E6:12:6);
  writeln(OUTFILE,tab10,'El. engine: ',TZ[5]:10:1,Z[5]:10:1,LW[5]:10:1,RC[5]*1E6:12:6,
    MC[5]*1E6:12:6);
  writeln(OUTFILE);
  writeln(OUTFILE);
END;


PROCEDURE Print;

VAR i:integer;

BEGIN
  writeln(tab10,'Flow    Temp.    Pressure   Volume    Energy  Enthalpy  Exergy');
  writeln(tab10,'#:    Celsius:    bar:      l/s:       kW:      kW:      kW:');
  writeln;
  FOR i:=1 TO 11 DO writeln(tab10,'',i:2,T[i]-TK:10:2,p[i]/1E5:10:3,VV[i]*1000:10:3,UU[i]/1000:10:3,
    HH[i]/1000:10:3,EE[i]/1000:10:3);
  writeln;
  writeln(tab10,'Flow of refrigerant: ',mr:6:4,' kg/s');
  writeln(tab10,'Waterflows: ',mwh:6:3,' kg/s in condenser and ',mwc:6:3,' kg/s in evaporator');
  writeln;
  writeln(tab10,'Variable decision variables          Marginal price (SEK/yr/unit)');
  writeln;
  writeln(tab10,'Efficiency compressor:     ',y[1]:10:4,D[1]:18:6);
  writeln(tab10,'Efficiency condenser:      ',y[2]:10:4,D[2]:18:6);
  writeln(tab10,'Efficiency evaporator:     ',y[3]:10:4,D[3]:18:6);
  writeln(tab10,'Efficiency electric engine:',y[4]:10:4,D[4]:18:6);
  writeln;
  writeln(tab10,'                      Condenser, hot side   Evaporator, cold side');
  writeln(tab10,'Number of H. T. Units:        ',NTUh:10:4,NTUc:20:4);
  writeln(tab10,'Overall therm. conduct. [W/K]: ',UAh:10:4,UAc:20:4);
  writeln(tab10,'Log. mean temp. diff. [K]:     ',Tlmh:10:4,Tlmc:20:4);
  writeln;
  writeln(tab10,'Zone            Total   Costs     Lost      Ratio      Marginal');
  writeln(tab10,'                costs            Works    Costs      Costs');
  writeln(tab10,'                SEK    SEK/yr    W      SEK/MJ     SEK/MJ');
  writeln;
  writeln(tab10,'Total:              ',TCost:10:1,TLW:10:1,RCT*1E6:12:6,MCT*1E6:12:6);
  writeln(tab10,'Electricity:        ',pel*hrs*3600*El:10:1,El:10:1,RCEl*1E6:12:6,MCEl*1E6:12:6);
  writeln(tab10,'Compressor: ',TZ[1]:10:1,Z[1]:10:1,LW[1]:10:1,RC[1]*1E6:12:6,MC[1]*1E6:12:6);
  writeln(tab10,'Condenser:  ',TZ[2]:10:1,Z[2]:10:1,LW[2]:10:1,RC[2]*1E6:12:6,MC[2]*1E6:12:6);
  writeln(tab10,'Exp. valve: ',TZ[3]:10:1,Z[3]:10:1,LW[3]:10:1,RC[3]*1E6:12:6,MC[3]*1E6:12:6);
  writeln(tab10,'Evaporator: ',TZ[4]:10:1,Z[4]:10:1,LW[4]:10:1,RC[4]*1E6:12:6,MC[4]*1E6:12:6);
  writeln(tab10,'El. engine: ',TZ[5]:10:1,Z[5]:10:1,LW[5]:10:1,RC[5]*1E6:12:6,MC[5]*1E6:12:6);
  writeln;
  writeln;
END;


PROCEDURE Printsens;

VAR i:integer;

BEGIN {Calculation and printing (SENS) of the sensitivities in the costs and lost works from changes in
                 the decision variables by 1 % at the optimum}

  FOR k:=1 TO 4 DO
  BEGIN
```

```
    yadd[k]:=y[k]+0.01;                          {Add 1 %}
    ysub[k]:=y[k]-0.01;                          {Subtract 1 %}

    IF yadd[k]>ymax[k] THEN yadd[k]:=(9*y[k]+ymax[k])/10;
    IF ysub[k]<ymin[k] THEN ysub[k]:=(9*y[k]+ymin[k])/10;

    TCadd[k]:=Fi0(yadd[k],k)-TCmin;              {Diff when adding 1 % to yk}
    TLWadd[k]:=TLW-TLWoptimum;                   {Total lost work}
    TCsub[k]:=Fi0(ysub[k],k)-TCmin;              {Diff when sub. 1 % from yk}
    TLWsub[k]:=TLW-TLWoptimum;                   {Total lost work}
    y[k]:=yoptimum[k];                           {Reset optimum value for y[k]}
    f[k]:=Fi0(y[k],k);                           {Reset y[k] in FUNCTION Fi0}
  END;

  writeln(SENS,tab10,'Changes in the total cost and lost work from changes in');
  writeln(SENS,tab10,'the decision variables');
  writeln;
  writeln(SENS,tab10,'Dec. var.      Change   Change  in total  Change  Change  in total');
  writeln(SENS,tab10,'               (+1%)     cost   lost work  (-1%)   cost   lost work');
  writeln(SENS,tab10,'                         (SEK/yr)    (W)          (SEK/yr)    (W)');
  writeln;
  writeln(SENS,tab10,'Eff. compressor:',yadd[1]-y[1]:6:3,TCadd[1]:8:2,
    TLWadd[1]:10:2,ysub[1]-y[1]:8:3,TCsub[1]:8:2,TLWsub[1]:10:2);
  writeln(SENS,tab10,'Eff. condenser: ',yadd[2]-y[2]:6:3,TCadd[2]:8:2,
    TLWadd[2]:10:2,ysub[2]-y[2]:8:3,TCsub[2]:8:2,TLWsub[2]:10:2);
  writeln(SENS,tab10,'Eff. evaporator:',yadd[3]-y[3]:6:3,TCadd[3]:8:2,
    TLWadd[3]:10:2,ysub[3]-y[3]:8:3,TCsub[3]:8:2,TLWsub[3]:10:2);
  writeln(SENS,tab10,'Eff. el. engine:',yadd[4]-y[4]:6:3,TCadd[4]:8:2,
    TLWadd[4]:10:2,ysub[4]-y[4]:8:3,TCsub[4]:8:2,TLWsub[4]:10:2);
  writeln(SENS);
  writeln(SENS);
END;


PROCEDURE Printstart;

BEGIN
  FOR k:=1 TO 4 DO D[k]:=DFi0(y[k],k);           {Marginal costs}
  FOR k:=1 TO 4 DO y[k]:=ystart[k]*0.999;        {Small change}
  TCost:=Fi0(y[1],1);                            {Get new value}
  Exergies;
  Save;                                          {Save new values}
  FOR k:=1 TO 4 DO y[k]:=ystart[k];              {Reset start values}
  TCost:=Fi0(y[1],1);                            {Get start values}
  Exergies;
  Margcosts;                                     {Ratio & Marginal costs}
  writeln(OUTFILE);
  writeln(OUTFILE,tab10,'Start values');
  writeln(OUTFILE,tab10,'********************************************');
  writeln(OUTFILE);
  Printfile;
END;


PROCEDURE Printoptimum;

BEGIN
  FOR k:=1 TO 4 DO D[k]:=DFi0(y[k],k);           {Marginal costs}
  FOR k:=1 TO 4 DO y[k]:=yoptimum[k]*0.999;                 {Small change}
  TCost:=Fi0(y[1],1);                            {Get changed values}
  Exergies;
  Save;                                          {Save changed values}
  FOR k:=1 TO 4 DO y[k]:=yoptimum[k];            {Reset optimum values}
  TCost:=Fi0(y[1],1);                            {Get optimum values}
  Exergies;
  Margcosts;
  writeln(OUTFILE);
  writeln(OUTFILE,tab10,'Optimal values');
  writeln(OUTFILE,tab10,'********************************************');
  writeln(OUTFILE);
  Printfile;
  Printsens;
```

```
END;


PROCEDURE Printmin;

BEGIN
  FOR k:=1 TO 4 DO D[k]:=DFi0(y[k],k);           {Marginal costs}
  FOR k:=1 TO 4 DO y[k]:=yoptimum[k]*0.999;                {Small change}
  TCost:=Fi0(y[1],1);                            {Get changed values}
  Exergies;
  Save;                                          {Save changed values}
  FOR k:=1 TO 4 DO y[k]:=yoptimum[k];            {Reset optimum values}
  TCost:=Fi0(y[1],1);                            {Get optimum values}
  Exergies;
  Margcosts;
  writeln(MIN);
  writeln(MIN,tab10,'Min values');
  writeln(MIN,tab10,'**********');
  writeln(MIN);
  writeln(MIN,tab10,'pel (SEK/kWh): ',pel*3.6E6:6:2);
  writeln(MIN,tab10,'T[9] (degr. Celsius, T[8]=T[9]-10): ',T[8]-273.15:7:1);
  writeln(MIN,tab10,'hrs (hrs/yr): ',hrs:6:0);
  writeln(MIN);
  writeln(MIN,tab10,'Variable decision variables          Marginal price (SEK/yr/unit)');
  writeln(MIN);
  writeln(MIN,tab10,'Efficiency compressor:     ',y[1]:10:4,D[1]:18:6);
  writeln(MIN,tab10,'Efficiency condenser:      ',y[2]:10:4,D[2]:18:6);
  writeln(MIN,tab10,'Efficiency evaporator:     ',y[3]:10:4,D[3]:18:6);
  writeln(MIN,tab10,'Efficiency electric engine:',y[4]:10:4,D[4]:18:6);
  writeln(MIN);
  writeln(MIN,tab10,'                     Condenser, hot side   Evaporator, cold side');
  writeln(MIN,tab10,'Number of H. T. Units:         ',NTUh:10:4,NTUc:20:4);
  writeln(MIN,tab10,'Overall therm. conduct. [W/K]: ',UAh:10:4,UAc:20:4);
  writeln(MIN,tab10,'Log. mean temp. diff. [K]:     ',Tlmh:10:4,Tlmc:20:4);
  writeln(MIN);
  writeln(MIN,tab10,'Zone            Total   Costs     Lost      Ratio      Marginal');
  writeln(MIN,tab10,'                costs             Works     Costs      Costs');
  writeln(MIN,tab10,'                 SEK     SEK/yr    W        SEK/MJ     SEK/MJ');
  writeln(MIN);
  writeln(MIN,tab10,'Total:               ',TCost:10:1,TLW:10:1,RCT*1E6:12:6,MCT*1E6:12:6);
  writeln(MIN,tab10,'Electricity:          ',pel*hrs*3600*El:10:1,El:10:1,RCEl*1E6:12:6,MCEl*1E6:12:6);
  writeln(MIN,tab10,'Compressor: ',TZ[1]:10:1,Z[1]:10:1,LW[1]:10:1,RC[1]*1E6:12:6,MC[1]*1E6:12:6);
  writeln(MIN,tab10,'Condenser:  ',TZ[2]:10:1,Z[2]:10:1,LW[2]:10:1,RC[2]*1E6:12:6,MC[2]*1E6:12:6);
  writeln(MIN,tab10,'Exp. valve: ',TZ[3]:10:1,Z[3]:10:1,LW[3]:10:1,RC[3]*1E6:12:6,MC[3]*1E6:12:6);
  writeln(MIN,tab10,'Evaporator: ',TZ[4]:10:1,Z[4]:10:1,LW[4]:10:1,RC[4]*1E6:12:6,MC[4]*1E6:12:6);
  writeln(MIN,tab10,'El. engine: ',TZ[5]:10:1,Z[5]:10:1,LW[5]:10:1,RC[5]*1E6:12:6,MC[5]*1E6:12:6);
  writeln(MIN);
  writeln(MIN);

  {Calculation and printing of the sensitivities in the costs and lost works from changes in the decision
                         variables by 1 % at the optimum}

  FOR k:=1 TO 4 DO
  BEGIN
    yadd[k]:=y[k]+0.01;                          {Add 1 %}
    ysub[k]:=y[k]-0.01;                          {Subtract 1 %}

    IF yadd[k]>ymax[k] THEN yadd[k]:=(9*y[k]+ymax[k])/10;
    IF ysub[k]<ymin[k] THEN ysub[k]:=(9*y[k]+ymin[k])/10;

    TCadd[k]:=Fi0(yadd[k],k)-TCmin;              {Diff when adding 1 % to yk}
   TLWadd[k]:=TLW-TLWoptimum;                    {Total lost work}
    TCsub[k]:=Fi0(ysub[k],k)-TCmin;              {Diff when sub. 1 % from yk}
   TLWsub[k]:=TLW-TLWoptimum;                    {Total lost work}
   y[k]:=yoptimum[k];                            {Reset optimum value for y[k]}
   f[k]:=Fi0(y[k],k);                            {Reset y[k] in FUNCTION Fi0}
  END;

  writeln(MIN,tab10,'Changes in the total cost and lost work from changes in');
  writeln(MIN,tab10,'the decision variables');
  writeln;
  writeln(MIN,tab10,'Dec. var.      Change   Change  in total  Change  Change  in total');
```

```
  writeln(MIN,tab10,'              (+1%)    cost   lost work  (-1%)   cost   lost work');
  writeln(MIN,tab10,'                       (SEK/yr)    (W)          (SEK/yr)    (W)');
  writeln;
  writeln(MIN,tab10,'Eff. compressor:',yadd[1]-y[1]:6:3,TCadd[1]:8:2,
   TLWadd[1]:10:2,ysub[1]-y[1]:8:3,TCsub[1]:8:2,TLWsub[1]:10:2);
  writeln(MIN,tab10,'Eff. condenser: ',yadd[2]-y[2]:6:3,TCadd[2]:8:2,
   TLWadd[2]:10:2,ysub[2]-y[2]:8:3,TCsub[2]:8:2,TLWsub[2]:10:2);
  writeln(MIN,tab10,'Eff. evaporator:',yadd[3]-y[3]:6:3,TCadd[3]:8:2,
   TLWadd[3]:10:2,ysub[3]-y[3]:8:3,TCsub[3]:8:2,TLWsub[3]:10:2);
  writeln(MIN,tab10,'Eff. el. engine:',yadd[4]-y[4]:6:3,TCadd[4]:8:2,
   TLWadd[4]:10:2,ysub[4]-y[4]:8:3,TCsub[4]:8:2,TLWsub[4]:10:2);
  writeln(MIN);
  writeln(MIN);
END;

{**************************************************************}
```

HPCHART.PAS

```
{PROCEDURE Chart}
{************************ Chart procedure *********************}

PROCEDURE Chart;

BEGIN
  write(CHARTFILE,pel*3.6E6:6:2);
{write(CHARTFILE,T[8]-273.15:7:1);}
{write(CHARTFILE,hrs:6:0);}
  write(CHARTFILE,pel*hrs*3600*El:10:2);
  write(CHARTFILE,Z[1]:10:2);
  write(CHARTFILE,Z[2]:10:2);
  write(CHARTFILE,Z[3]:10:2);
  write(CHARTFILE,Z[4]:10:2);
  write(CHARTFILE,Z[5]:10:2);
  writeln(CHARTFILE);
END;
```

Start values

```
Flow    Temperature  Pressure    Volume    Energy     Enthalpy    Exergy
 #:       Celsius:     bar:        l/s:      kW:        kW:         kW:

 1          2.86      3.384      2.395      9.464     10.275      0.043
 2         12.86      3.384      2.516      9.732     10.584      0.052
 3         96.80     16.727      0.587     11.103     12.609      1.619
 4         64.29     16.727      0.473     10.501     11.292      1.321
 5         64.29     16.727      0.041      6.109      6.109      0.333
 6         54.29     16.727      0.041      6.109      6.109      0.333
 7          2.86      3.384      1.011      6.883      6.109      0.000
 8         50.00      1.013      0.158     32.500     32.500      2.655
 9         60.00      1.013      0.158     39.000     39.000      3.744
10         10.00      1.013      0.214      8.949      8.949      0.160
11          5.00      1.013      0.214      4.475      4.475      0.040

  Flow of refrigerant: 0.0472 kg/s
  Waterflows:  0.156 kg/s in condenser and  0.214 kg/s in evaporator

                             Variable decision variables    Marginal price (SEK/yr/unit)

  Efficiency compressor:               0.7000                 -2918.407506
  Efficiency condenser:                0.7000                 -1009.627099
  Efficiency evaporator:               0.7000                  -214.819764
  Efficiency electric engine:          0.7000                 -4870.683036

                                      Condenser, hot side          Evaporator, cold side
 Number of H. T. Units:              1.2040                     1.2040
  Overall therm. conduct. [W/K]:   782.5823                  1077.4614
  Log. mean temp. diff. [K]:         8.3058                     4.1529

 Zone          Total      Costs      Lost        Ratio        Marginal
               costs                 Works       Costs         Costs
                SEK       SEK/yr       W         SEK/MJ        SEK/MJ

 Total:                   4220.9     1932.5     0.121343      0.059470
  Electricity:            3616.8     2893.4     0.069444      0.069444
 Compressor:    695.4      113.2      458.4     0.013715     -0.011225
 Condenser:    1187.7      156.1      196.5     0.044157     -0.038727
  Exp. valve:   236.1       31.0      333.3     0.005175     -0.003383
 Evaporator:   1635.2      215.0       76.3     0.156440     -0.362962
 El. engine:    675.1       88.8      868.0     0.005681     -0.001635
```

Optimal values

```
Flow   Temperature  Pressure   Volume   Energy    Enthalpy   Exergy
 #:     Celsius:      bar:      l/s:      kW:        kW:       kW:
 1        3.14       3.416     2.448     9.767     10.603     0.050
 2       13.14       3.416     2.572    10.044     10.923     0.060
 3       87.26      15.928     0.613    11.404     12.676     1.548
 4       62.00      15.928     0.516    10.799     11.621     1.323
 5       62.00      15.928     0.042     6.176      6.176     0.316
 6       52.00      15.928     0.042     6.176      6.176     0.316
 7        3.14       3.416     0.989     6.963      6.176     0.000
 8       50.00       1.013     0.158    32.500     32.500     2.655
 9       60.00       1.014     0.158    39.000     39.000     3.744
10       10.00       1.013     0.227     9.494      9.494     0.170
11        5.00       1.013     0.227     4.747      4.747     0.043


Flow of refrigerant: 0.0487 kg/s
Waterflows:  0.156 kg/s in condenser and  0.227 kg/s in evaporator

                  Variable decision variables        Marginal price (SEK/yr/unit)

  Efficiency compressor:    0.8035                     6.854373
  Efficiency condenser:     0.8335                     1.048093
  Efficiency evaporator:    0.7293                     2.489199
  Efficiency electric engine:0.9070                    4.063741

                                  Condenser, hot side                 Evaporator, cold side
 Number of H. T. Units:                1.7927                  1.3069
  Overall therm. conduct. [W/K]:    1165.2608               1240.7924
  Log. mean temp. diff. [K]:           5.5782                  3.8259

 Zone          Total      Costs       Lost        Ratio        Marginal
               costs                  Works       Costs         Costs
                SEK       SEK/yr        W         SEK/MJ        SEK/MJ

 Total:                   3387.5      979.4      0.192148      0.000473
  Electricity:            2415.6     1932.5      0.069444      0.069444
 Compressor:   1340.3      218.1      264.2      0.045869     -0.067795
 Condenser:    1739.6      228.7      143.6      0.088453     -0.129606
  Exp. valve:   243.5       32.0      315.6      0.005636     -0.003204
  Evaporator:  1864.3      245.1       76.3      0.178349     -0.388686
 El. engine:   1885.7      247.9      179.6      0.076678     -0.055508
```