Chapter 2

Energy analysis

The energy requirements of household consumption items and the spendings on these items are the building blocks of household energy requirements. So, answers on questions like How much energy is required to produce a bread? or What are the energy costs of a visit to the hairdresser? are needed in order to determine the energy requirements of households. These questions can be answered by energy analysis. This chapter gives a general introduction to energy analysis.

2.1 INTRODUCTION ON ENERGY ANALYSIS

A workshop on energy analysis, under the auspices of the International Federation of Institutes for Advanced Study (IFIAS, 1974), has defined energy analysis as:

"... the determination of the energy sequestered in the process of making a good or service within the framework of an agreed set of conventions or applying the information so obtained."

Energy analysis comprehends the determination of the energy that is required for the production of a material, for the manufacture of a product or for the supply of a service. So, energy analysis can answer the questions posed in the introduction of this chapter concerning the energy requirements of a bread and a visit to the hairdresser. However, there are different answers possible for these questions. In general, the energy requirement for a bread from bakery A will differ from the energy requirement for a bread sold by bakery B. Besides, the energy requirement of the bread depends on the country and the time of year. Within the framework of this study, it is not interesting to know the energy requirements of a bread produced in a particular bakery, but it is interesting to know the energy requirements of an average bread bought by an average household in the Netherlands. So, by carrying out an energy analysis, it is very important to start with a definition of the system that has to be analysed. In their handbook, Boustead and Hancock (1979) emphasize the importance of system boundaries in energy analysis. So, energy analysis is not restricted to a certain product, but it also concerns companies, economic sectors, countries, etc.
An energy analysis has to be carried out in a framework of an agreed set of conventions. The aforementioned IFIAS workshop elaborately discussed these conventions and methodological problems concerning energy analysis. Sections 2.3 and 2.4 go into some of these conventions. According to the definition given, energy analysis not only prescribes the way in which the energy requirements of goods and services have to be determined, but it also shows how the calculated results can be used. Although, at the workshop, the topic of applying the information obtained by energy analysis was underexposed, some applications were mentioned. Since the workshop, energy analysis has been applied by many researchers (cf. section 2.2).

Energy analysis examines the energy requirements in the whole production chain of a product. So, energy analysis concerns not only the direct energy use in manufacturing a product, but also the indirect energy requirements of the production process. These indirect energy requirements involve e.g. the energy requirements of production and transport of the material inputs or the energy requirements of capital goods. The consideration of the whole production chain may result in better decisions. The consideration of only the direct energy use in a process may result in wrong solutions which shift the energy use to other parts of the production chain. E.g. centralizing a production process at one place, generally, decreases the direct energy use per unit product. However, this gain can be cancelled out by increasing indirect energy requirements for transport, since the average distance to the consumer increases.

By comparing the energy requirements of different alternatives for a product or system, energy analysis offers the possibility to select the alternative with the lowest energy requirements. Such comparisons can be used to examine if investments in energy conservation are profitable in energy terms. E.g. insulation measures for buildings demand additional energy. An energy analysis over the whole lifetime of a building can answer the question whether of not this additional energy for isolation materials is regained by the savings in the direct energy use for heating. Other applications of comparing different alternatives are the feasibility of recycling of materials or the feasibility of renewable energy systems (wind, solar, etc.). An application more related to this study is the comparison of energy requirements of household products. For example, consumer organisations can use the results of such comparisons to inform households of the impact of their spendings on energy use.

The consideration of the whole production chain identifies stages which have a high energy use. These stages give starting points for energy conservation programs. It is recommended to compare the energy use in these stages with the theoretical minimum value based on thermodynamics. It is difficult to gain further savings in case the difference between the real value and the minimum value is small. Ross (1978) introduced an indicator for this second
law efficiency of a system as the ratio of the energy use in an ideal system and the actual energy performance of the system.

A further application of energy analysis is the forecasting of future energy use. E.g. total household energy requirements can be calculated on the basis of an estimate of the demand of consumption items.

Until now, energy analysis has been discussed according to the IFIAS conventions, which is aimed at the stocks of fossil fuels. However, there is another approach of energy analysis that also includes energy flows associated with labour and natural processes. Since the 70s, Odum (1971, 1978) has had a pioneering role in the development of this energy analysis approach in which energy is the ultimate valuation standard. In contrast with the IFIAS approach, which acts as a supplement to economic analysis, in the Odum approach, energy analysis is considered as an alternative for macro economic analysis. Since in the Odum approach all decisions are based on energy aspects only, this approach received quite a lot of criticism and it has not had many followers. Gilliland (1978) discusses the similarities and differences for both approaches, the IFIAS school and Odum school.

2.2 HISTORICAL BACKGROUND

Obviously, the concept of energy analysis did not appear overnight. As described in chapter 1, in the early 70s, the interest in energy increased strongly, as a result of both the hike in energy prices and a growing awareness of the negative impacts of energy use on the environment. Rising fuel prices, initially, caused an increasing interest in direct energy use. The depletion of fossil fuels and the impact of the use of fossil fuels on the environment enhanced the interest in indirect energy use.

Several engineers and researchers were engaged in the calculation of the energy requirements of materials, products and economic sectors. This paragraph lists some examples without having the illusion to be complete. Chapman (1974a, 1974b) calculated the energy costs of copper and aluminium. Berry et al. (1975) studied the energy requirements of some packaging materials by comparing polymers with some alternatives. The energy cost of automobiles was determined by Berry and Fels (1973). A special application of energy analysis is the analysis of energy industries, e.g. electric power plants and refineries. Chapman et al. (1974c) worked on this topic by calculating the energy cost of fuels. Another field of interest concerned the energy needed for

---

1 E.g. solar irradiation, hydrologic cycling of the oceans and cyclic exchange of carbon, hydrogen, oxygen and nitrogen.
food production (Leach, 1976). Wright (1974), and Bullard and Herendeen (1975) determined the energy cost of goods and services by using economic input-output analysis. Hannon (1974) compared energy intensities of economic sectors with labour intensities. Furthermore, he investigated the effects of changes in consumption on total employment and energy use in the U.S. (Bullard, 1978).

Since all researchers used their own methods, it was difficult to compare outcomes of different studies. In order to bring energy analysts together, the International Federation of Institutes for Advanced Study (IFIAS) organized the workshop already mentioned. At this workshop several procedural recommendations for executing energy analysis were formulated. At a second workshop (IFIAS, 1975), the central theme was the relationship between economics and energy analysis. In the Netherlands, the Landelijke Stuurgroep voor Energie Onderzoek (LSEO) took care of the coordination between the several researchers (Van Gool, 1975). In those days, a conference organized by TNO took place. At this conference, the results of energy analyses in several fields were presented (TNO, 1976). A more recent publication is the thesis of Nieuwlaar (1988) which gives an overview of the state of affairs of energy analysis at the end of the 80s and discusses some applications of energy analysis.

Since the first IFIAS workshop on energy analysis, several research groups have worked on the composition of databases of energy requirements of industrial processes (CCMS, 1978; Boustead and Hancock, 1979; van Heijningen et al., 1992a and 1992b). In the Netherlands, the energy analysis of agriculture has received special attention (Brascamp, 1983; Procé, 1986; Brand et al., 1993; Melman et al., 1994).

### 2.3 ENERGY ACCOUNTING

Energy analysis allocates energy to a good or service. This allocating is carried out with the so-called gross energy requirement (GER) which is defined by IFIAS (1974) as:

"... the amount of energy source which is sequestered by the process of making a good or service ...".

The GER of a product is the sum of all energy sources which are required for the making of the product. The GER is expressed in energy per physical unit of the good or service, e.g. MJ per kg steel, MJ per bread or MJ per visit to the hairdresser. In case of energy per financial unit, often the term energy intensity
is used. It is defined by IFIAS (1974) as:

"... the energy requirements in terms of energy per unit money value of product."

The term energy intensity is e.g. used for economic sectors. Since economic sectors, generally, produce several products, no single adequate physical unit is available.

Energy requirements are expressed in primary energy terms. Primary energy is energy in the form in which it appears in nature. Types of primary energy can be divided in renewables, e.g. solar energy and wind energy, and non-renewables, e.g. natural gas, coal, crude oil, uranium. Almost all energy used on earth originates from the sun\(^2\). This solar energy is available both in a direct way and in an indirect way via natural cycles. Furthermore, million years of solar energy are stored in fossil fuels. Some people, e.g. Odum (1971) and Costanza (1980), include all solar energy in their analyses. On the other hand, the IFIAS group regards the sun as a free good (Slessser, 1977). Since this study concerns the depletion of fossil fuels and the impacts of fossil fuel use on the environment, the IFIAS view is followed.

Since energy is expressed in primary energy terms, the GER of a product contains the energy which is required for the conversion from primary energy to secondary energy. Secondary energy is energy in a form in which it is available for use, e.g. coke, coal gas, petrol or electricity. To deal with the energy requirements for conversion from primary to secondary fuels, IFIAS (1974) defined the energy requirement for energy (ERE) as:

"... the ratio of energy sequestered to deliver a unit of energy divided by the unit of energy."

The ERE value is always greater than or equal to one, since both numerator and denominator contain the combustion value of the fuel under consideration. The inverse of the ERE value gives the efficiency of the energy conversion.

According to the first law of thermodynamics, energy is never lost. However, by using energy, the quality of the energy diminishes. E.g. the combustion of oil for driving an engine gives heat that cannot be used again directly for the same task. The amount of energy measured in heat units, the so-called enthalpy, is the same before and after combustion. In the light of studies

\(^2\) Exceptions are e.g. tidal energy, which is the result of gravitational forces in the solar system, and geothermal energy.
concerning the depletion of fossil fuels, it is more accurate to take into account
the quality factor of the fuels. This can be achieved by using the free energy
concept. Unfortunately, for many processes, it is difficult to compute the
amount of free energy. Since in most cases the difference between the free
energy and enthalpy is less than 10%, IFIAS recommends, for practical reasons,
to use enthalpy instead of free energy.

Some economic sectors, e.g. the fertilizer industry and the petrochemical
industry, use fuels as feedstock. In some situations, according to the aim of the
analysis, the calculation has to include this fuel use. The report of the first
IFIAS workshop (1974) mentions two such situations. The first situation in
which the feedstock fuel use has to be considered is the case in which the
calculations are done in consideration of the depletion of fossil fuels. The
second situation is when there is no possibility to use the energy embodied in
the product in the future. Only when the inputs have an alternative use as fuel,
the gross heat of combustion has to be included. So feedstock use of oil, coal,
natural gas, etc. has to be included in analyses. On the other hand, analyses do
not include use of wood, in the developed world, and uranium in granite as
building materials.

2.4 SYSTEM BOUNDARIES

In practice, a product will have different GER values, depending on technology
and moment in time. E.g. steel produced in the Netherlands will certainly have
another GER value than steel produced in the former Soviet Union. Furthermore, if technological innovation results in more energy efficient
production processes, this leads to lower GER values. In a process of
technological change, GER values are time-dependent. So, by presenting GER
values, it is recommended to specify additional information about the production
process, the country, the year, etc. This also holds for energy intensities and
ERE values. This implies that the first step in an energy analysis is the
definition of the system which has to be analysed. The system boundaries
determine what is taken into account in the analysis. The definition of the
system determines the GER value unequivocally.

IFIAS (1974) proposed a scheme which depicts the various levels in an
energy analysis. Figure 2.1 shows a revised version of the scheme, which
depicts the levels in energy analysis more clearly (IFIAS, 1975). The first level
of an analysis only contains the direct energy inputs of the process, e.g. fossil
fuels and electricity. The second level concerns the energy for the acquisition,
e.g. extraction, conversion and distribution, of the direct energy at the first level
of the scheme. The third level adds the energy requirements of the capital
Chapter 2

goods, e.g. machines, buildings, means of transport. The fourth level concerns
the machines to make capital equipment. All levels contain a contribution of
energy for transport.

A controversial topic in energy analysis concerns the energy
requirements of labour. These energy requirements can be considered in two
ways. First, manpower requires energy in the form of food. The recommended
daily intake of food amounts to 10 MJ per person. Moreover, workers have to
be fed, clothed, housed, etc. to do their jobs. Employees spend their salaries by
buying goods and services for their own life-support or that of their family. It
is very difficult to make a division in purchases for work or for private
consumption. Generally, system boundaries in energy analysis only concern
production and do not include consumption. In this study too, a strong
distinction is made between production and consumption. Since labour is part
of both production and consumption, energy for labour is not accounted for in
energy analysis. Only in the approach of Odum (1971) and Costanza (1980), in
which the system boundaries concern the whole earth, labour and government
are accounted for in energy analysis. A more practical argument for omitting
labour from energy analysis is that, in an industrial society, the contribution of
energy for labour, in the case of the calorific value of food, is very low in
comparison with the energy requirements of other inputs (Leach, 1976).
In the IFIAS-scheme, the second level refers to energy requirements of materials or other inputs used in the process under consideration. These inputs are produced in other processes for which analyses can be carried out in a similar way. So, the process can be seen as a link in a chain of processes, which constitutes the life cycle of a product. Upstream processes in the chain are processes in the direction of the raw materials. Downstream processes are processes in the direction of ’waste’. In case of recycling of materials, the chain contains feedback loops. The treatment of recycling in energy analysis is discussed by other authors, e.g. IFIAS (1974), Casper et al. (1974), and Boustead and Hancock (1979). The industrial economy can be seen as a dynamic network of matter and energy flows similar to the metabolism in the biosphere (Baccini and Brunner, 1991; Graedel and Allenby, 1994). A comparison of the industrial metabolism with the metabolism in the biosphere possibly leads to an increased efficiency in the material and energy flows in the economy (Ayres, 1989; Frosch and Gallopoulos, 1989).

In energy analysis, the choice of appropriate system boundaries is useful. The question arises at what level is the contribution of higher levels of less importance? Practice has shown that the first two levels already cover 90-95% of total energy requirements. After adding the third level, the energy requirements of the capital goods, almost 100% of total energy requirement is reached. When presenting the results of an energy analysis, IFIAS recommends to specify the system boundaries and the levels in accordance with the scheme. Only in this way, comparisons of different calculations are meaningful and useful.

2.5 ENERGY ANALYSIS IN PRACTICE

Once the system is defined, the energy requirements of the system can be determined. This section presents some ways to do this.

2.5.1 Methods of energy analysis
An energy analysis can be carried out from both a technical perspective and an economic perspective. An energy analysis from a technical perspective is called process analysis. An energy analysis from an economic perspective is called input-output energy analysis. Besides, it is possible to combine both perspectives in a hybrid analysis. This section gives an overview of these methods of analysis.

Process analysis has been developed by engineers and technicians. Process analysis uses a description in physical terms of the processes in the life cycle of the product. Next, the energy use in the different processes is
determined in a detailed way. Therefore, process analysis is an accurate, but also a laborious method. Process analysis is carried out in accordance with the IFIAS scheme (figure 2.1).

Input-output energy analysis has its origins in economics. An input-output table of an economy contains the transactions between economic sectors in financial units. With such an input-output table and data on the primary energy use of every sector, the energy intensity of each sector can be calculated. This energy intensity gives the total primary energy that a sector needs for the production of one financial unit of output. Since the data available from input-output tables are more aggregated than data received from process studies, input-output analysis is less accurate than process analysis. On the other hand, input-output analysis offers the possibility to consider all inputs in the whole life cycle of the product in the calculation. Chapter 3 describes input-output energy analysis thoroughly.

By combining both methods in a so-called hybrid method, the advantages of both methods can be used. Chapter 4 presents such a hybrid method.

2.5.2 Energy requirements of inputs

All levels in the IFIAS scheme use input data. In practice, inputs at the first level and the main inputs at the second level are determined with process analysis. Since the contributions of the third and higher levels are low, IFIAS recommends to determine the energy requirements at these levels with input-output analysis.

The direct energy requirements of a process are determined with process analysis. The energy requirements for the direct energy use, which is a second level contribution, are calculated by using ERE values of the fuels at the first level. The second level also contains the energy requirements of other process inputs, i.e. materials and services. Since a separate energy analysis for each input is very laborious, data from other studies are often used. These data mostly concern average values. For products which are imported it is assumed that they are produced in a similar way as domestic production. There are several other inputs with only a marginal contribution in total energy requirements of the process\(^3\). It is unfeasible to consider all ancillary inputs with process analysis, so the corresponding energy requirements are determined by input-output analysis. The energy requirements of all ancillary goods together may have a reasonable contribution in energy requirements of the

---

\(^3\) The hybrid approach, which is described in chapter 4, uses the concept of residual goods. Residual goods concern not only inputs with a small contribution in energy requirements, but also inputs for which energy requirements are unknown.
product under consideration.

The third level of an analysis adds the energy requirements of the capital goods. Capital goods are buildings, machines, means of transport, etc. which are applied in the production process. Usually, the energy requirements for the capital goods took place in the past. So, the total energy requirements for production and maintenance of a capital good has to be attributed to all products produced in the lifespan of that capital good. For practical reasons, energy analysts use the economic lifespan instead of the technical lifespan. The energy requirements are based on the annual depreciation of the capital good. This depreciation is calculated on the basis of the historical cost price of the capital good. The energy requirement of the capital good based on depreciation is calculated using an energy intensity of depreciation which is determined by input-output analysis. The energy intensity of depreciation is based on input-output data of the year under consideration. It is more accurate to use the energy intensity of depreciation from the years that the capital goods were made, but these figures often are not available. Since energy efficiency has increased over the last decades, the present energy intensity is too low for calculating the energy requirements of capital in the past. A drawback of the method chosen is that the same energy intensity of depreciation is used for all capital goods irrespective of the composition of the capital goods.

2.5.3 Energy requirements of outputs
In cases that a process produces several outputs, the energy requirements of that process have to be divided over the outputs. E.g. at the production of cheese, a byproduct is buttermilk. IFIAS mentions several methods for this partitioning, but recommends a partition based on some physical parameter, e.g. weight, volume, distance, or heat of combustion, characteristic for the products under consideration. If there does not exist an appropriate physical parameter, a financial parameter should be used. In this case, usually the values of the outputs are used for the partition.

When the system under consideration is a factory or economic sector, the partitioning of the energy requirements over the outputs is more complicated, especially when some of the inputs are not used for all outputs. In such situations ad-hoc assumptions should be made.

---

4 Another way to calculate the energy requirements of capital goods in a certain year is by using the energy requirements of the new investments in that year (Casper et al., 1974).