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Units in Energy Accounting; how are they defined, how are they measured

Dr. Malcolm Slesser
Director Energy Studies Unit
University of Strathclyde
Glasgow
Scotland

Introduction

By late 1973 accounting for production in terms of energy use as well as money had become a widespread activity. However, the various workers in the field had adopted no consistent basis for their accounting procedures and some divergent results were propagated in the literature. About the same time the International Federation of Institutes of Advanced Study, meeting in Copenhagen, decided to sponsor a number of international interdisciplinary energy studies one of which was to set up a workshop to examine the methodology of energy accounting, as it was then popularly referred to. In August 1974 an international group of twenty people from nine countries, reflecting academic, government and industrial interests, with backgrounds ranging from econometrics to physics, assembled for one week at Guldmedshytten in southern Sweden to thrash out a firm methodology. The workshop soon revealed, contrary to what many hopefuls had thought, that accounting in energy terms in not absolute. One still has to adopt conventions, just as, for example, one must adopt a convention in stating the standard state for thermodynamic properties, in spite of thermodynamics being a remarkably absolute science.

The following notes summerise the conventions proposed by the workshop. They represent a near unanimous agreement by the group, and differences centred around peripheral matters rather than basic principles. For example some people saw no value in the definition of Process Energy Requirement (PER) and others were indifferent to the concept of Energy Requirement for Energy (ENE).

Title of the field

After examining a very wide range of terms, Energy Analysis was adopted and taken to imply "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". (1)

Unit of account

Like money, the unit of energy account us not as simple a concept as might seem at first sight. It is common place to see national energy budgets expressed in trillions of BTU's or millions of Kwht. But this raises the question, a BTU of what? There is a precise relationship between BTU, joules and kilowatt hours, but no rigorous method of defining an energy resource in terms of heat units. A popular basis for definition is the calorific value of combustion, but this has dangers, since one can show that there is almost certainly more heat in the Atlantic Ocean than in the potential heat of combustion of the whole of the Middle East oilfields. Moreover, all of us instinctively appreciate that once a fuel is burnt it is of no further use, yet the first law of thermodynamics states unequivocally that heat is neither lost nor gained, but is conserved. Clearly what the energy analyst is seeking is some other property of fuels than their ability to release heat on combustion, fission of fusion.

The quality sought is called Available Energy and measures the amount of work a quantity of heat can perform. It is defined as $A = (E - E_f) + P_o(V - V_f) - T_o(S - S_o)$ (1)

Where quotes are shown, these refer to the actual text of original IFIAS Report No. 6.

where these terms have the meaning expressed in figure 1.
A close analogue to Available Work is Gibbs Free Energy, which is readily calculable for chemical systems, and since combustion is a chemical process, G is an attractive property to work with. It can be defined as

$$G = H - T\Delta S \qquad (2)$$

where T is absolute temperature, S entropy and H being enthalpy. However assessing either A or G for most real systems is a well nigh impossible task without an inordinate amount of experimental data. Fortunately for most of the fuels in use, such as oil, gas, coal, or nuclear, the temperature of combustion or fission is such that the error in taking the enthalpy rather than Gibbs Free Energy is of the order of 10%. Table 1, taken from the American Physical Society (2) reveals the differences, which are less than 10% for natural fuels, and 18% for hydrogen, which, however, is a secondary fuel.
The adopted convention was: "Where energy analysis is concerned with depletion of resource base all figures should be expressed in terms of Free Energy. However, recognising that in many cases it is impossible to compute the Free Energy of actual processes, it is sufficiently accurate in the case of intensive fuels to express figures in terms of gross enthalpy, if clearly stated in the report as such."
The workshop was most emphatic that the energy unit used in expressing all energy analytic studies be the Joule. In general a convenient form of expression is to describe the GER as so many MJ/kg of output or GJ/tonne of output.
Both the Enthalpy and Free Energy are to be calculated for the state one bar pressure and 273.15 K with the products of combustion fuels or fission restored to the same state. Combustion is by air, not oxygen.

Gross Energy Requirement - GER

The value arrived at by these means is referred to as Gross Energy Requirement (GER), and is defined as "the amount of energy source (in terms of enthalpy) which is sequestered by the process of making a good or service". In the case of Free Energy, it is referred to as GFER, Gross Free Energy Requirement.
Since GER assesses the amount of resource sequestered, the GER of a product tends to increase as it moves through the economic system.

Process Energy Requirement - PER

Since the GER of GFER definition embraces all the energy resource sequestered to make a good or service available at a given point in the system, it is necessary to define a unit to deal with those situations where the analysis seeks only to examine the energy consumed in promoting a particular part of a process. This is known as the Process Energy Requirement (PER).

System boundary

To calculate GER the system boundary must embrace all resources at the point they were still in the ground, oceans or air. In other words one must network back all the inputs, assessing the energy required to make them available at each stage, till each is traced to the energy resource in its native state. This aspect of energy analysis differs from that of money accounting, where at each stage of the network a profit may be taken so that the money value of the input reflects material, capital costs, profit and the value set by the market mechanism.
Figure 2 depicts some hypothetical process for making a good, y. which requires feed stocks of natural gas, silicon dioxide and hydrogen. It also requires an input of direct energy to make the process function. Let us suppose that this direct energy is furnished by coal.
Three system boundaries are shown. The inner one (-. -. -) is that most immediately apparent to the person concerned with operating the process. The necessary inputs are coal, silicon dioxide, natural gas and hydrogen. The energy requirement of the process

might be calculated by considering, at standard reference state, the gross enthalpies of combustion of the hydrogen, natural gas and coal. However one may readily see from Fig. 2 that this is not really the true energy requirement of the process. Hydrogen is not a naturally available substance, and has to be made by a process further back in the system. Such a process consumes more energy than is available in the hydrogen product. There is an energy requirement for making hydrogen. For the sake of example, let us assume that the hydrogen is made from natural gas. Is natural gas a free and infinite good ? It is not. It has to be won by the process of exploration, production platforms, pipeline investment and separation plants. In order to make the energy of natural gas available to the processes within the middle system boundary (-----) some energy must be expended on the supply system. Similarly, Silicon dioxide rarely occurs as a pure substance. It has to be mined, purified and transported. There is a necessary supply system. Equally, coal has to be minded, prepared and transported. There is a coal supply system requiring energy. These supply systems take operational energy from various sources, each of which in turn requires a supply system and energy source. Gross Energy Requirement (GER) is the sum of all the energy sources that must be sequestered in order to make product, y, available. It therefore includes everything passing through the outer system boundary (-----).

Conventions on Energy Requirement for Fuels

So long as the GER of a fuel is expressed in terms of MJ/kg of delivered fuel, fuels can be treated in exactly the same way as any other input to a system. It is tempting, and indeed often useful, to express the GER of a fuel as being so many MJ fuel resource per MJ of fuel delivered. This produces a dimensionless number and can and has lead to misinterpretation. IFIAS designated the following conventions.

Gross Energy Requirement of a Fuel - GER Fuel

This parameter is of special use when considering depletion of energy sources. It is defined as the total amount of fuel resource of all species sequestered from the global stock in order to produce one unit of delivered energy. In this definition all energy resources inputs are counted: the principle resource under study plus the other resources used to build and or operate the plant used to obtain the principle resource. An energy transformation system will have products in addition to energy of the type sought. Where these by-products are wasted with no realisable energy content, then they are not counted as an energy product. For example one does not count the enthalpy of the hot water emanating from a power station, unless it is carrying out some function in which it is replacing another source of energy. When that hot water is at too low a temperature to serve any function, it has no value. No credit is given for useless transformation. For example combustion might generate soot, but this has no value as an energy product. On the other hand some systems do generate potentially energetic by-products. A nuclear reactor, particularly a breeder generates plutonium, which has an enormous energy potential. That energy potential cannot be released without the application of technology, in its turn energy consuming. The credit that would be ascribed to the plutonium would be its fission energy at standard state (ibid) less any energy required to carry out the fission process, including capital requirements, and preparation.

These points are illustrated in a hypothetical nuclear reactor system depicted in figure 3. Uranium is the reactor fuel but in the construction process and for making fuel elements some coal and oil has been used. The output is heat, but this is quickly turned into electricity, which is the final output of interest.

The electrical inputs to the system may be treated as recycle from the output, and since this recycle lies within the total system boundary, the quantities are not counted as inputs but reduce the output.

Figure 3 shows that for each y kwh of electricity and z kg of plutonium jointly produced, a units of coal, b units of oil and x units of uranium were used. a, b and x are each expressed as their enthalpy of combustion or fission under standard conditions. The oil and coal preparation systems each require some electricity, q and p, while a further amount of electricity, r, is used to build the reactor and operate it, and s to operate the uranium fuel reprocessing plant. The electricity produced by the nuclear reactor is thus:

$$y + s + q + r + p,$$

but the amount of electricity yielded by the system is only y kwh, which is the basis of the calculations. Reactor efficiency statements often fail to record such quantities as p, q, r, or s.

The plutonium output cannot release energy until it too has been put into some reactor; an energy transformation somewhat similar to the one shown for uranium in figure 3. The credit to be attributed to the plutonium is the not amount of energy that could be released by the plutonium energy system.

Thus the GER of uranium to electricity may be computed as:

$$\text{GER}_{\text{nuclear electricity}} = [\text{a+b+x-(net enthalpy release from z units plutonium)}]\ /\text{y}$$

expressed as MJ/kwh of electricity.

IFIAS convention discourages the conversion of 1 kwh electricity into its strict thermal equivalent of 3.6 MJ in order to arrive at a dimensionless GER because electricity is a secondary fuel of high quality, and its expression in purely thermal terms is misleading. The question of what value to ascribe to the electrical output was unresolved by the workshop, though several suggestions have since been put forward (3)(4)(5).

If, however, the output is simply a refined version of the input, such as fuel oil from crude, then the convention allows one to put a thermal value on the output equal to its gross enthalpy of combustion at the standard state, and so arrive at a GER which is MJ/MJ. This quantity is referred to the ENERGY REQUIREMENT FOR ENERGY - ERE. It is always $\gg 1$.

Net Energy Requirement - NER

This parameter applies only to fuels or to goods which have a potential use as a fuel at some future time, such as waste paper or as plastic products. The definition arises out of the need to distinguish between the use of an energy resource as an energy or heat source on the one hand and as feed-stock on the other. NER, therefore, represents the amount of energy resource required to make the good, but not the energy resource tied up in the good. However it is considered desirable in making a NER calculation to add a further amount for the energy that would be required to make the product available for combustion. If the product was timber, or paper, this might be trivial or even zero. If the product was plastic fitments on an auto, this quantity might be significant. Thus NER is defined:

NER = GER of all resources used to make the good (whether fuel or object)
- gross enthalpy of combustion of the good
+ any energy required to usefully combust the object at some future time.

NER can be expressed in two ways. The recommended manner is to express it as MJ/unit of product, but where the product is a fuel, it may be expressed as MJ/MJ, which can be misleading.

Waste

A production process is essentially a process in which components are assembled into something larger or more ordered. Thermodynamicists and information scientists call this a reduction in the system entropy. An example of such process of entropy reduction is the series of processes in which iron ore is turned into iron, then into steel, then into sheet steel, and then into an automobile. There is a precise relationship between this 'order' and the heat required to make it possible, which yields a property known as Gibbs Free Energy (G). Thus $G = H - T\Delta S$ where H is the enthalpy and ΔS the change in system entropy. Thermodynamics enables one to compute the entropy change when some order is introduced into a system, and thus to compute the associated enthalpy change required to effect that change. The reader should refer to the seminal study by Berry and Fels on the US automobile (6) for a further insight into this sort of calculation.

However the essential point is that though the above equation can tell one the minimum amount of energy required to effect the transformation, that transformation is occurring reversibly - that is to say, at zero rate. In the real world where transformations have to occur at finite rates, the difference between the actual free energy changes and the theoretical represent a measure of the 'energy waste'. Table 2 lists some figures on waste.

IFIAS defined a waste factor thus:

$$\frac{\text{Actual } \Delta G \text{ required to effect transformation - ideal } \Delta G \text{ transformation}}{\text{actual } \Delta G \text{ required to effect transformation}}$$

Thus an ideal situation is one in which the waste factor is zero. Normally it is much greater. The actual ΔG is ibtained by computing the Free Energy of the fuels used in the real process.

Partitioning

When a given process yields two or more products, each of which has worth to society, how are the energy inputs to be partitioned between them? The workshop examined a number of possible conventions, and agreed that the partitioning should be done on the basis of some physical quantity, not on economic value. Thus if the products were fuels or potential fuels, then partitioning would be upon their gross enthalpy of combustion (or fission). If they were chemicals, as in the electrolysis of brine, then since the one cannot produced without the other, partitioning should be in proportion to the weight of the products.

This is clearly a difficult area. For example, in the electrolysis case, a physical chemist might argue that partition should be in proportion to mol ratio of the products, while an economist would argue that it should be in proportion to the relative market value of the products.

Methods of Calculation

The method of calculation is sensitive to the object of the exercise: for example, upon whether one wishes to compare plastic bottles made by one process with that made by another. Where industry aggregates are appropriate, one may use the input-output tables, though the work of Heredeen and others (7) has shown the dangers and care that must be taken in such work. Input/output tables give only average values and tend to be several years out of date. In order to compare between processes, a real life process analysis is called for. Even here, however, input/output tables can be useful for estimating the energy inputs of second order elements like capital or transport. One can visualise the process of energy amalyses as embracing four levels of precision and of importance. These are depicted in figure 4. At each level there are direct energy inputs, and indirect. All must be summed, though by the time one reaches level 4, the influence of the inputs is probably less than 1%, which in a calculation that can rarely hope to be more than 5% accurate, suggests irrelevancy.

List of participants

Dr Frank Alessio,
Director,
Energy Modelling Programme,
Electrical Power Research Institute,
3412 Hillview Avenue,
P.O. Box 10412,
PALO ALTO, California 9703, U.S.A.

Professor R. Stephen Berry,
University of Chicago,
Department of Chemistry,
5735 S. Ellis Avenue,
CHICAGO, Illinois 60637, U.S.A.

Dr Peter Chapman,
Open University,
Walton Hall, Walton,
BLETCHLEY, Buckinghamshire, U.K.

Dr Leslie Cook,
Planning & Programme Analysis,
EXXON,
P.O. Box 45,
IJNDEN, N.Y. 07036, U.S.A.

Dr. Paul Graig,
National Science Foundation,
WASHINGTON, D.C. 20550, U.S.A.

Professor Bent Elbek,
Niels Bohr Institute,
Blegdamsvej 17,
2100 COPENHAGEN, Denmark.

Dr Bertil Eneroth,
Skandinaviska-Enskilda Banken,
STOCKHOLM, Sweden.

Dr Robert Herendeen,
Centre for Advanced Computation,
University of Champaign-Urbana,
CHAMPAIGN-URBANA, Illinois 61801,
U.S.A.

Professor Takao Hoshi,
Seikei University,
TOKYO, Japan.

Professor Ingvar Jung,
Royal Institute of Technology,
STOCKHOLM, Sweden.

Dr Rurik Krymm,
I.A.E.A.,
VIENNA, Austria.

Professor Thomas Long,
University of Chicago,
Department of Chemistry,
208 Kent Laboratory,
5727 S. Ellis Avenue,
CHICAGO, Illinois 60637, U.S.A.

Dr Caesar Marchetti,
I.I.A.S.A.,
2361 LAXEMBURG, Austria.

Dr William Mebane,
Montedison,
MILAN, Italy.

Dr Sam Nilsson,
I.F.I.A.S.,
The Nobel House,
Sturegatan 14,
STOCKHOLM, Sweden.

Dr Peter Roberts,
Systems Analysis Research Unit,
Department of the Environment,
2 Marsham Street,
LONDON, SWIP 3EB, U.K.

Mr Joel Schatz,
Office of the Governor,
SALEM, Oregon 97310, U.S.A.

Dr Malcolm Slesser,
Director, Energy Analysis Unit,
University of Strathclyde,
100 Montrose Street,
GLASGOW G1 1X1, Scotland.

Dr Gerald Stanhill,
Agricultural Research Organization,
The Volcani Centre,
P.O. Box 6,
BET DAGAN, Israel.

Professor Carroll L. Wilson,
Massachusetts Institute of Technology,
CAMBRIDGE, Massachusetts 02139,
U.S.A.

I.F.I.A.S. Secretariat:

Eva Bengtsson
Irene Holmgren

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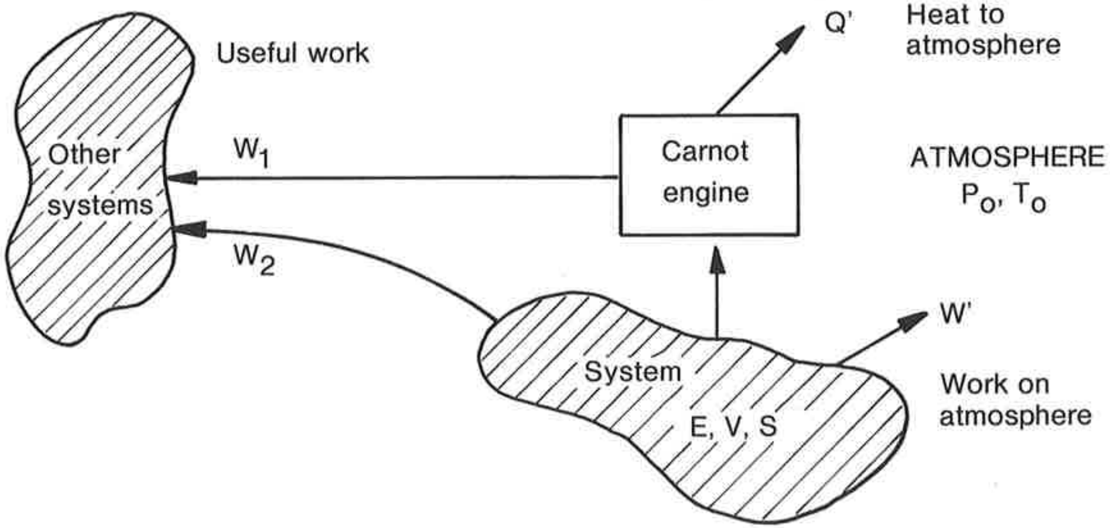
Useful work
Q'
Heat to atmosphere
Other systems
W1
Carnot engine
ATMOSPHERE
P0, T0
W2
W'
System
E, V, S
Work on atmosphere

Figure 1.

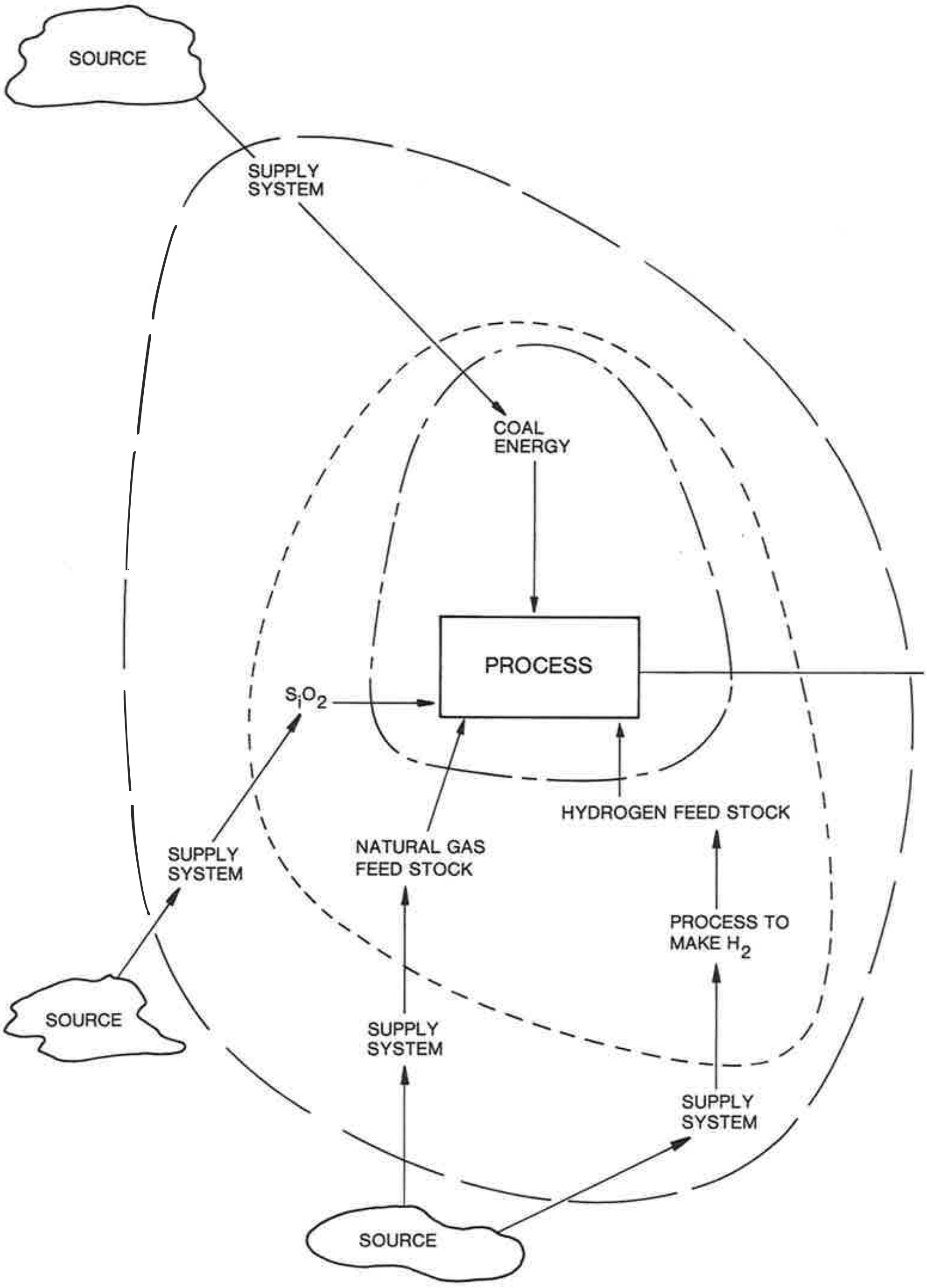

Figure 2. System boundaries to estimate G.E.R.

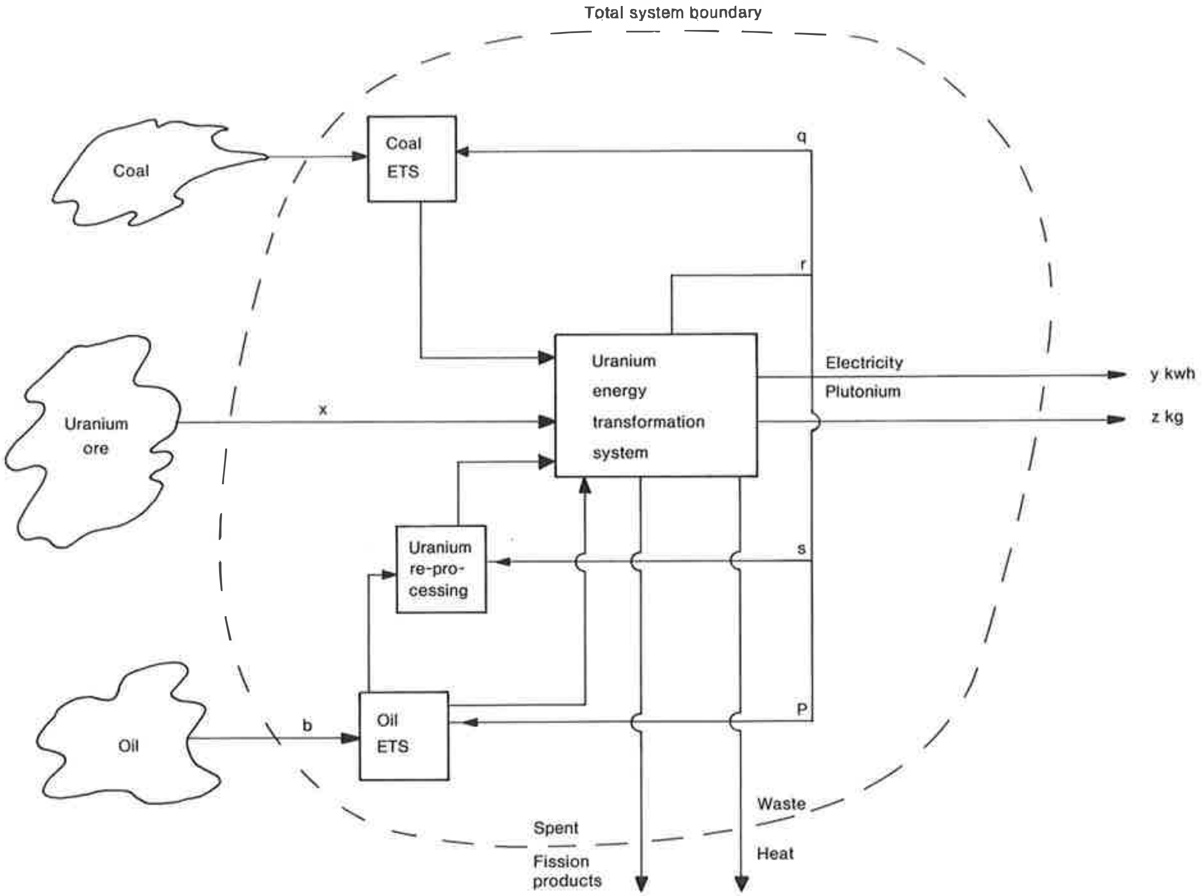

Figure 3. Uranium energy transformation system.

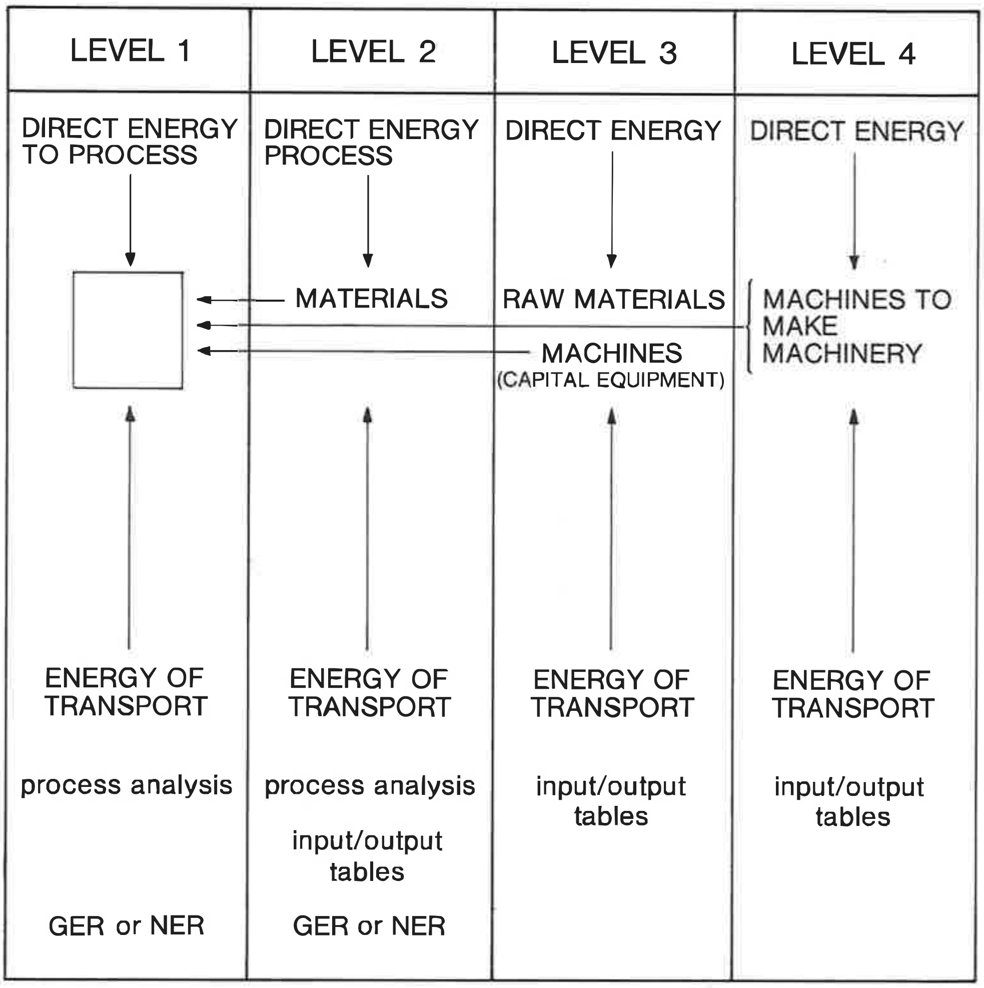

Figure 4. Energy analysis procedure: four levels of information.

Source: Energy Conservation Study, American Physical Society, Princeton, 1974. (Calculations are for combustion in air yielding a liquid H_2O product (gross enthalpy of combustion) at 1 bar pressure and 273.15K. Energies in the upper part of the table are in kJ per mole of fuel. Available work is given in other units in the lower part of the table).

Energy terms	Hydrogen H_2	Carbon C (to CO_2)	Carbon Monoxide CO	Methane CH_4	Ethane C_2H_6	Propane C_3H_8	Ethylene C_2H_4	Liquid Octane C_8H_{18}
Heat of combustion — Δ H	285.2	393.6	282.7	890.1	1559.4	2219.4	1410.5	5467.2
Available work without diffusion A	233.8	394.4	256.8	813.2	1460.3	2099	1326.8	5274.8
Percentago change from Δ H to A	-18%	+0.2%	-9.2%	-8.6%	-6.4%	-5.4%	-5.9%	-3.5%
Available work in MJ/kg	116	32.9	9.17	50.7	48.6	47.6	47.3	46.2

Table 1 **ENERGIES ASSOCIATED WITH COMBUSTION OF VARIOUS FUELS**

Free Energy use, actual and ideal.
(Sources: (1) Gyftopolous et al, Thermo-Electron, Waltham Mass, 1974).
(2) Berry and Fels - ibid.

		G actual for industry in US in 1968 Mj joules/kg	Product	Waste Factor
Coking of coal	(2)			1.13
Iron	(1)	25	6	.76
Gasoline	(1)	4.2	.4	.9
Paper	(1)	38	.2	1.005
Aluminium	(1)	190	25	.87
Cement	(1)	7.8	.8	.9
Steel from Fe	(2)			1.19
Bauxite - Ai_2O_3	(2)			1.0
Zinc smelting	(2)			1.02

Table 2

Economics and Energy Analysis

Dr. Thomas Veach Long II
Department of Chemistry
University of Chicago
Chicago
U.S.A.

Acknowledgment

Many of the topics discussed herein are also included in the Report of the International Federation of Institutes for Advanced Study Workshop on Energy Analysis and Economics, which I prepared as rapporteur.
However, in this presentation I offer a more personal view of the interface between these fields. The considerable intellectual debt that I owe to the distinguished participants in that Workshop will be obvious to those who wish to compare the two discussions. Professor R. Stephen Berry of the University of Chicago must be singled out for particular thanks. In innumerable conversations he has served as a constructive critic and as an invaluable source of stimulation and support. The aid of Ms. Sandra Hebenstreit in the analysis of the coal industry is also gratefully acknowledged.

As is fitting for a new endeavor, the objectives of energy analysis are being continually critically evaluated, sharpened and revised. Although no list of these would be accepted by all practitioners, many would agree that there are at least five aims that should be included.

1) Precise physical description of real-world processes.
2) Evaluation of "energy conservation" measures and technology assessment.
3) Examination of substitution possibilities between materials and energy over total life cycle and recycle of commodity.
4) Calculation of near-term fuel price elasticities and medium-term disaggregated demand forecasting.
5) Determination of physical bounds on economic activity.

The impact that energy analysis has had on prescriptive social policy has been somewhat surprising. Undoubtedly, this has been a product of the desire to respond to a perceived constraint on fossil fuel supplies over the past two and a half years. One of the promises of energy analysis is that it aids in the evaluation of the effectiveness of suboptimization "energy conservation" alternatives. Additionally, it provides the data from which we can calculate the average and marginal physical products of energy inputs and the corresponding output elasticities. Presumably, efficient pricing hypotheses could be tested using this information, and it could be incorporated into economic projection models.

This discussion will focus on The Real World and principally on the first three objectives. It is perhaps true that the heavy demand for energy analysis for use in prescriptive policy has obscured its origins in an desire by early workers to formulate more complete and precise physical descriptions of real-world economic processes. Their use of an energy parameter in these descriptions was probably more a product of their training in thermodynamics than a recognition of the imminence of an energy crisis. It is my contention that energy analysis can exert the greatest long-run impact by returning to this descriptive orientation and by concentrating on the means by which the physical information generated can be incorporated more fully into economic description and the associated valuation procedure.

Descriptive Energy Analysis

The first lesson that an energy analyst would give to a young protoge would be that in a sense all materials are "fuels", because when combined with certain other materials they can react to yield a flow of thermodynamic potential that can be used to do work or to furnish heat. Thermodynamic potential changes for some selected reactions are shown in Figure 1. This distinction between coal as a fuel and sulfur as a material is clearly arbitrary. Indeed, some high-sulfur fuel oils have larger enthalpies of combustions than the corresponding sulfur-free oils, because of the enthalpy of combustion of sulfur!

There is an important point that will be obvious to a scientist, but may be hard for an economist to swallow. The possible technical substituations between fuels and materials is completely determined by their respective thermodynamic potential. Moreover, the rate of technical substitution between an energy good and a material will be directly proportional to the relative thermodynamic potential changes associated with their use. This must be interpreted carefully. It does not say that it is possible to completely substitute natural gas for copper in making a copper teapot. What it does say is that the extent to which any physical tradeoff between the use of copper and natural gas exists depends solely on the degree to which the copper acts as a source of thermodynamic potential at any point in the manufacturing process.

Let us trace through a process-type energy analysis to emphasize this point. We will also see that the data required is identical to that utilized in economic process analyses, although the economic analyses have thus far explored a richer variety of questions.[1] Symbols that have become widely accepted for presentation of flow-chart energy analysis data are shown in Figure 2.[2] The detail that has been attempted is shown in Figure 3 for the case of iron and steel production.[3] Figures 4-7 illustrate the construction of a flow chart for the production of aluminum.[4] The first step is the determination of all material flows in the process as shown in Figure 4 for the Hall-Héroult electrolytic reduction of alumina to aluminum. Second, the energy requirements for the transformation process and transportation are determined by evaluating all fuel and electricity inputs, as shown in Figure 5. Although the energy use for a process is aggregated in the inverted triangle on the basis of enthalpies of combustion for the fuels and the thermal equivalent of electricity, the raw data would generally be provided elsewhere in the report, including the assumed electrical generation efficiency. Observe that 1 tonne of carbon anode is oxidized for every tonne of aluminum produced, and it must be considered to be a material input rather than a unit of fixed capital. Figure 6 traces the production process back a step further, showing that while only a small amount of energy is required to produce the 0.04 tonnes of cryolite, 25.2 GJ (gigajoules) of energy are needed in anode preparation. Moreover, the upper-half semicircle tells us that the enthalpy of combustion of the carbon in the electrode is 50.4 GJ. In the electrolysis, the carbon electrode reacts to form carbon dioxide, with the release of 50.4 GJ of energy in the oxidation step. Were it technologically possible to substitute a chemically inert electrode for the carbon anode, at the same overall efficiency, this additional amount of energy would have to be furnished to help sustain the molten production process. This illustrates the type possibility of technical substitution between energy goods and materials and its dependence on thermodynamic potentials, but makes no statement about its desirability. That is an economic question. Finally, in Figure 7, we see the electrolytic step embedded in the total flow process, tracing back to extraction of the raw materials. We could simply sum all energy requirements to find that production of one tonne of aluminum requires a total of 303 GJ of process energy and 353 GJ if the enthalpy of combustion of the carbon electrode is included. A flow chart presentation draws our attention to substitutional possibilities for energy husbandry that transcend usual establishment boundaries. Also, we see that an attempt at an energy saving at one point in the totally integrated process may lead to increased use of fuel or materials at another stage. A complete analysis of the impacts on energy use of a technological change would begin with raw material extraction and beneficiation, trace through article manufacture and use, with eventual assessment of recycling and disposal options. Figure 8 illustrates this for the case of the automobile.[3] Again, we should be aware that the result of our analysis will show us only what is technologically possible, and the data must be incorporated along with information about scarce factors such as capital and labor in a valuation step that determines the desirability of the change.

Physical efficiency and economic efficiency

The participants at The International Federation of Institutes for Advanced Study Workshop on Energy Analysis and Economics were unanimous in their rejection of an "energy theory of value." In the language of that report the rejection is based on:

> "the simple observation, applicable across a wide range of institutional forms and degrees of technical development, that besides energy resources there are often indispensable primary inputs - labor, land, capital, non-energy minerals - with equal claim to having their scarcities expressed in the valuation system that guides allocation."[5]

A clear understanding of the concepts of thermodynamic and economic efficiency shows that a concentration on decreasing the input of only a single factor of production, such as energy, could lead to a sub-optimal societal choice. In Figure 9, the physical scientist's concept of second-law efficiency or effectiveness[6] is defined and several illustrations are provided. The activities are apparently quite inefficient, and there is probably substantial room for improvement through better husbandry. However, we must also recognize that there are two other reasons for the low effectiveness of the processes. One contributing factor lies in the definition of the idealized reversible process that would yield the maximum work. Conceptually, the process could achieve maximum effectiveness, equal to one, only if allowed an infinite amount of time to evolve.[6] Energy is required to drive the activity at a finite rate, and, in practice, the maximum effectiveness limit is probably closer to 0.5.[7] The second reason for the low thermodynamic efficiency is found in the economic tradeoffs discussed more fully below. The market assigned low prices to material and particularly energy inputs, relative to capital and labor, over an extended period. As a consequence, technologies developed that are capital and labor saving, with increased energy and material use.

The energy analyst maintains that his efficiency criterion is appropriate for assessing a trade-off in the physical world, that there is a natural valuation system operating in that world, but that it is only part of the larger realm of human activity. What it does not permit - and this is where economics enters - is an examination of how systems that require human labor and an investment in capital can efficiently combine these resources with those of the physical system.

Economic efficiency is attained if given resources (including capital, labor and natural resources) are combined in such a manner that a higher output of any desired good could be obtained only at the cost of a lesser output of some other desired good.

Let us investigate this concept in greater detail by analyzing Figure 10.[8] The economy represented in this figure consists of two industries, one engaged in the production of electrical energy and the other in the production of equipment. Each industry makes only one homogeneous product, and quantities of production are represented by coordinates y_1 and y_2, respectively. Both industries utilize labor. For simplicity, but without loss of generality, we can assume that one unit of labor input is required for one unit of output of electricity or of equipment. Thus, we will omit the third coordinate corresponding to labor and utilize a two-dimensional diagram.

Each point in the plot corresponds to a production technology available to the industry. A positive value for a coordinate indicates that the commodity is an output of the industry, while a negative value signifies that the industry utilizes the commodity as an input. The electrical power generation industry requires equipment and labor inputs and furnishes a net output of electrical energy, while the equipment industry requires electricity and labor to produce a net output of machinery. The electrical power generation industry can adopt methods A_1, B_1, C_1, and others indicated by points in the upper left-hand quadrant. The equipment industry has techniques represented by points A_2, B_2, C_2, . . . available to it. There is no joint production. The possibility that some labor will not be utilized can be handled by admitting a point at the origin O of the coordinate system, for which one unit of labor is expended without production of outputs. The polygon created by connecting the points A_1, C_1, O, C_2, B_2 bounds the production possibilities, and every point on the boundary or inside can be achieved by the proper combination of techniques. If there are no exogenous sources of supply of either commodity, the only attainable points utilizing one unit of labor will lie within the triangle

$L_1 OL_2$. A point in the set of attainable points is efficient if there exists no attainable point that is superior in providing greater output of one commodity without diminishing the output of the other. The line segment $L_1 L_2$ is the efficient set. Point α is not efficient because the output of both electricity and equipment can be increased within the attainable set, but point β is clearly on the efficient boundary. Consequently, for a two industry input-output model, we have arrived at the set of possible combinations of techniques that represent efficient use of labor in production. These are combinations of only two methods, A_1 and B_2.

Observe that it would have been feasible to produce equipment using technique A_2 with a decrease in electrical energy requirements (per worker) and that electricity production could employ method C_1, with a higher net energy output (per worker).

But the set of attainable points along $A_2 D_1$ correspond to a set of technique combinations that is everywhere inferior to those of $L_1 L_2$. One function energy analysis can serve is to aid in the development of a technique for equipment production that utilizes one unit of labor but less energy per unit produced, as would be represented by point D_2. The efficient set would then fall along a line connecting A_1 and D_2.

One difficulty that the economist and energy analyst encounter in seeking a level of discussion is that, in loose terms, the economist concerns himself with fuels as intermediate goods and does not recognize energy in the abstract as a good. The energy analyst treats energy as an aggregate quantity that is a primary factor of production. More precisely, the economist deals only with specific forms of energy considered at points in the chain of extraction or interception and processing at which an option in the extraction, conversion or utilization exists and may be exercised. This concern therefore encompasses a number of scarce primary energy sources such as uranium, oil, coal in the crust of the earth or elevated water. This disagreement is meaningful to the degree that sources of thermodynamic potential other than those ordinarily regarded as fuels are utilized by economic society for their ability to deliver this potential. For example, materials whose marketplace values are primarily determined by their structural properties or by their ability to provide other services desired by society are also sources of thermodynamic potential. The energy analyst is arguing that he is providing the information that society requires to make a knowledgable choice between use of a material for the energy it naturally embodies and its use based on some other characteristic. Through careful empirical evaluations, he is showing society the full range of options that it confronts.

Consequently, let us consider a two-industry economy in which there are two primary factors, energy (thermodynamic potential) and labor, each available in a given amount. The industries will be taken to be metal mining and equipment production. Each requires both primary factors. This economy can be analyzed with the aid of Figure 11. First, we will ignore any restriction on labor and make the assumptions utilized in discussing Figure 10. The attainable point set is defined by the two processes A_1 and A_2 and is $L_1 OL_2$. Similarly, the attainable point set resulting from ignoring the restriction on energy, $M_1 OM_2$, is defined by the pair of techniques B_1 and B_2. Taking both restrictions into account, the attainable point set consists of the quadrilateral $OL_1 DM_2$, and the efficient production set lies along the two line segments $L_1 D$ and DM_2. Thus either of the two pairs of methods can be utilized in efficient production, and the efficient choice between the pairs depends on whether labor or energy is the limiting primary factor. Energy analysis can be employed in determining the points A_1 and A_2.

Applications of energy analysis

There are several practical applications of energy analysis that have economic ramifications. These are:

- international comparisons of energy conserving technologies;
- assessment of the impacts of technological change;
- utilization as an information tool in maximizing return on investment.

International Comparisons

In the discussion above I have argued that an analysis based on flows of thermodynamic potential highlights the possibilities for fuel-material substitution and that it provides an accurate picture of real-world processes. In comparing technologies between countries, it is clearly advantageous to use a method that is based on physical rather than financial data, obviating the need to worry about rates of exchange and other features peculiar to international financial comparisons. Several groups have turned to energy analysis as the method of choice for such assessments, including the Industrial International Data Base project of the Committee on the Challenges of a Modern Society that holds its fifth meeting in The Netherlands in the first week of March.

Figure 12, taken from one of the first published comparisons of this kind, contrasts the energy requirements for aluminum in the U.S., the U.K. and the Netherlands.[9] Interestingly, although the total process energy requirements are approximately equal, those of the individual process steps vary widely. The energy requirements for the mining and beneficiation steps are lower in the United States because of better ore quality. Although the electrolysis is identical in all three countries, the British data are based on the best available equipment, the Dutch data is industry-wide data but all cells are efficient, while the U.S. is saddled with older, less energy-efficient capital.

In Figure 13, a similar comparison is made for the energy use in polyethylene production.[9] Feedstock energies are not included. United States industry has primarily utilized natural gas to produce ethylene, although this is rapidly being converted to the naphtha cracking technology used in European countries. The large apparent energy requirement for the U.S. polymerization step probably arises from treating process steam as a single rather than a joint product in the data available to us. More recent U.S. studies have determined a value closer to the U.K. and Netherlands figures for this step, and a considerably lower value (22 GJ/tonne) for the natural gas-ethylene conversion.[10] Our data was obtained at a time when proprietary considerations may have taken precedence over concerns of national energy demand and probably should be reevaluated in the light of these later results.

Even though international comparisons may disclose technological innovations that could be energy saving, technology transfer may not be a realistic option. Closer investigation may show real economic barriers, such as geographic or demographic factors, market structure, or competitive pressures that limit the return on investment to levels at which financing of new capital facilities is difficult.

Technology Assessment

Energy analysis can also be used to project the requirements associated with the introduction of new technologies. This implies that the analyses are sensitive to probes of technological change. The coal industry is a nice choice for which to investigate this claim, because the financial costs of fuels and electricity and the recovery percentage are practically the sole discretionary variables under management control. Capital costs are locked in over extended periods, as are labor costs that are fixed by long-term agreements.

Figure 14 schematically displays coal extraction and preparation through electrical generation for both surface and underground mining. Attention should be given to the low (50%) underground mining recovery percentage in the U.S.A. This nationwide average could probably be improved 20% by technological changes that are economically feasible. Also, note that the tradeoffs in the possible technologies and associated energy requirements for cleaning up high-sulfur coal begin in extraction (reduce percentage of ash), and are found in preparation (proper washing and drying), combustion (fluidized beds) and post-combustion scrubbing.

The sensitivity of energy analysis data to technological change is illustrated in Figure 15, in which the effects on the per-tonne energy requirements of an underground mine from technological changes and the enforcement of a new mine safety law that forced modified work patterns are clearly evident. Figure 16 evaluates the energy needed for various surface-mine reclamation options. Although the reclamation requirements could be large in comparison to the extraction-beneficiation energies, they are but a small part of the combustion enthalpy of the coal. Capital and labor costs will determine feasibility.

Maximization of Return on Investment

Improvements in company profitability is a central concern of all industrial managers. Can energy analysis be helpful in achieving this goal? If the experience of a major U.S. corporation can be used as a guide, the answer is yes.

Dow Chemical U.S.A. over five years ago began a no-nonsense program of energy and material husbandry. They recognized that the chemical industry is especially resource-intensive, and that the key to increased return on investment lay in developing a workable system of material and fuel management control. Working independently and unaware of academic interests along similar lines, Dr. J.M. Leathers, an Executive Vice President, and Irving Snyder designed a system of management supervision based on an energy analysis method identical to that proposed at the first IFIAS Workshop.[1]

Energy accounts are kept alongside financial accounts for each of the over 600 plants, with the notable difference that the energy accounts are always up-to-date while there is a lag-time for the financial books. The material and energy accounts allow Dow to immediately and accurately calculate the effect of a price change of an input on the costs of each of their products.

Comparing actual and theoretical energy requirements using a second-law "effectiveness" criterion modified for finite time losses has led them to realize further savings in energy, materials and dollar costs. Two examples of energy savings juxtaposed to the payback periods for the new capital facilities required are found in Figure 17. Such far-sightedness has turned Dow currently into the most profitable U.S. chemical company.

Although particularly useful for the chemical industry, this control system could probably be used to advantage in numerous other industries. An example of the form that Dow uses in calculating the energy content of a product is given in Figure 18. The form emphasizes that all material flows carry with them "embodied" energy, and that material loss is entirely equivalent to lax energy husbandry. Significantly, we see that when one considers the energy required for waste disposal and effluent cleanup under new environmental legislation, water is an energy-intensive solvent. We had made the same observation, but on a national scale, in studying the energy requirements for the provision of water of suitable quality. Although the per gallon energy requirements are low (Figure 19), the per capita national average use of ca. 800 gallons/day results in energy use for water equal to more than 2.5% of the total national energy budget.

Substitution in Production

The traditional neoclassical macroeconomic formulation treats material and energy inputs as "ingredient" inputs that are fixed by specification of the output good.[11] In contrast, streams of capital and labor services are treated as substitutable inputs that are the productive agents in the economy in a value-added motif. Thus, gross domestic product calculated as value-added is ascribed a functional dependence on capital and labor flows in the usual production function framework: $Y = F\ (K, L)$. This implies that investment decisions are made independently of information regarding the prices of the ingredient inputs or substitutional possibilities for these inputs with capital and labor. The energy analyst would challenge this formulation based on his examination of the substitutional possibilities whose existence he directly observes. In recent years economists have likewise questioned the reality of the traditional specification and have attempted to develop aggregate production and cost function formulations that incorporate multifactor substitution.[12] Although there may be a number of valid and serious criticisms of the specific functional forms that have been proposed, the basic proposition of disaggregation along non-traditional lines is appealing in its realism and presents some interesting results.

For example, Berndt and Wood[12] have concentrated their attention on possible substitutions between energy and non-energy inputs. They utilize a translog cost function with functional dependence on four input factor prices and output as shown in Figure 20, where K, L, E and M represent capital, labor, energy and materials, respectively, and Y is output. Within this specification, they find the cost share behavior represented in Figure 20, and conclude from their time-series regression that energy and labor are substitutes while energy and capital inputs are complementary. Further, they contend that United States manufacturing data does not support the Leontief aggregation condition.[12] This condition assumes that the quantity ratios E/Y and M/Y are perfectly correlated either because E and M are technologically nonsubstitutable or because of accidental correlation of shifts in supply and demand. Finally, note the magnitudes of cost shares of M and E.

The energy analyst recognizes that E and M have a limited substitutability based on the thermodynamic potentials. The optimization of a physical efficiency criterion function would lead to a condition within a given technology in which further substitution between ingredient inputs is not desirable. Having achieved this physical efficiency, I assert that the proper aggregation variable for the physical inputs would be based on the individual thermodynamic potentials. Equivalently, this says that the possibilities for physical substitution between inputs of capital and labor services, on the one hand, with aggregated physical inputs on the other, will be in relation to the thermodynamic potentials of the ingredient goods.

My formulation suggests that the decomposition should be in terms of three aggregate variables, capital K, labor L, and thermodynamic potential T. The KLT production space so defined is shown in Figure 21. In effect, premaximization efficiency in the physical inputs under the constraints of constant technology, capital and labor is assumed.

Physical Bounds

The use of energy analysis in setting the limits on what is feasible for the economic system was discussed at length in the Workshop Report.[5] It is evident that a number of energy analysts are concerned with determining the levels at which intensive energy use is compatible with continued maintenance of normal local and global climatic conditions, in addition to energy husbandry interests. Economists were surprised to learn that it is also possible to define precise lower (ideal) limits for thermodynamic potential changes in processes. Some of the economists were intrigued to learn that energy use per unit output is a function of the rate at which a process is driven, because this implies that under conditions of capital saturation, energy use per unit output can be reduced.

In closing, the informational function of energy analysis in a production setting should be stressed. While economists often represent the production possibilities frontier as a single bounding line, the actual knowledge of the frontier contains the uncertainty implied in the fuzzy frontier of Figure 22. The band is a real-world effect that arises from individual producers making imperfect assessments of the most efficient use of scarce resources within the given technology. They have less than complete information about their production possibilities, but must act on the basis of it. The information from technological analyses such as energy analysis permits one to gain a firmer definition of the frontier, pushing back the uncertainty to move closer to the postulated efficient economic production set. This should be separated from the argument that the macro production possibility frontier has finite width because of the use of a mix of capital vintages. This, too, is a question that can be more precisely defined by careful process analyses.

When considered within the KLT formulation, this informational expansion of the production frontier leaves the output elasticities of both capital and labor unchanged, and thus mimics a neutral growth process. However, a modification in the actual physical capital stock (with maintenance of a constant flow of capital services), which is often implied by the association of the term "invention" with technological change,[11] is not required. Of course, there is a very thin line between this process and what the economist would regard as a housekeeping change. The only clear differentiation is the energy analyst's proposition that some changes could be quite large and transcend establishment boundaries. Further, it is not that they are known and tacitly ignored, but that they lie outside the information set presently available to the entrepreneur.

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11. C.E. Ferguson, The Neoclassical Theory of Production and Distribution, Cambridge Univ. Press, Cambridge, England (1969).
12. E.R. Berndt and D.O. Wood, "Technology, Prices and the Derived Demand for Energy," The Review of Economics and Statistics, 57, 259 (1975), and references therein.

Reaction	ΔG^o ($\frac{\text{kcal}}{\text{mole}}$ at 298^oK)
$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$	-191.38
$H_2 + 1/2\ O_2 \longrightarrow H_2O$	$-\ 54.64$
$C + O_2 \longrightarrow CO_2$	$-\ 94.26$
$S + O_2 \longrightarrow SO_2$	$-\ 71.79$
$2Al + 3/2\ O_2 \longrightarrow Al_2O_3(S)$	-376.8
$BaO + SO_3 \longrightarrow BaSO_4$	-135.4

Figure 1 **FREE ENERGIES**

Thermodynamic potential changes in selected reactions.

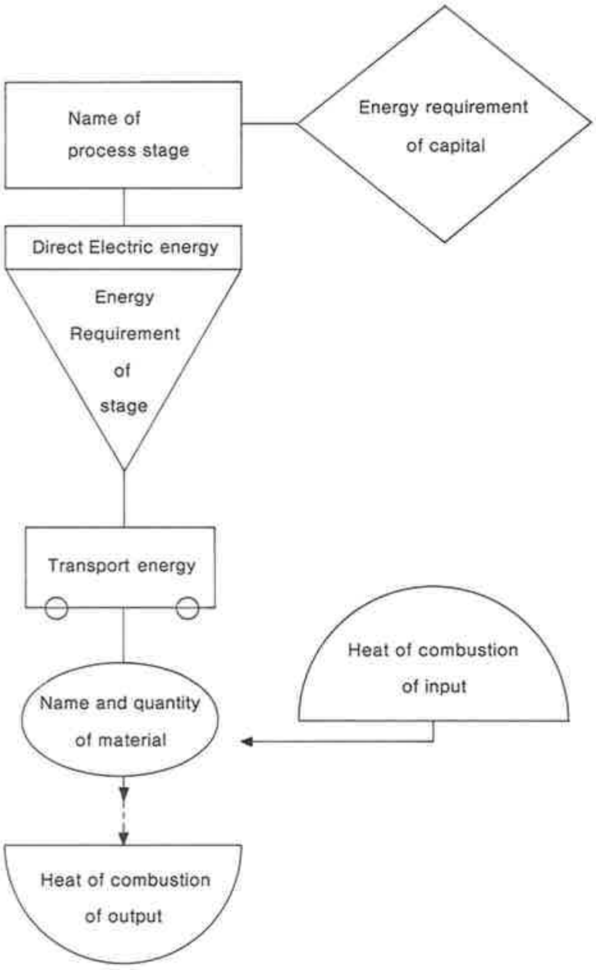


Figure 2. Energy analysis flow chart symbols.

IRON AND STEEL

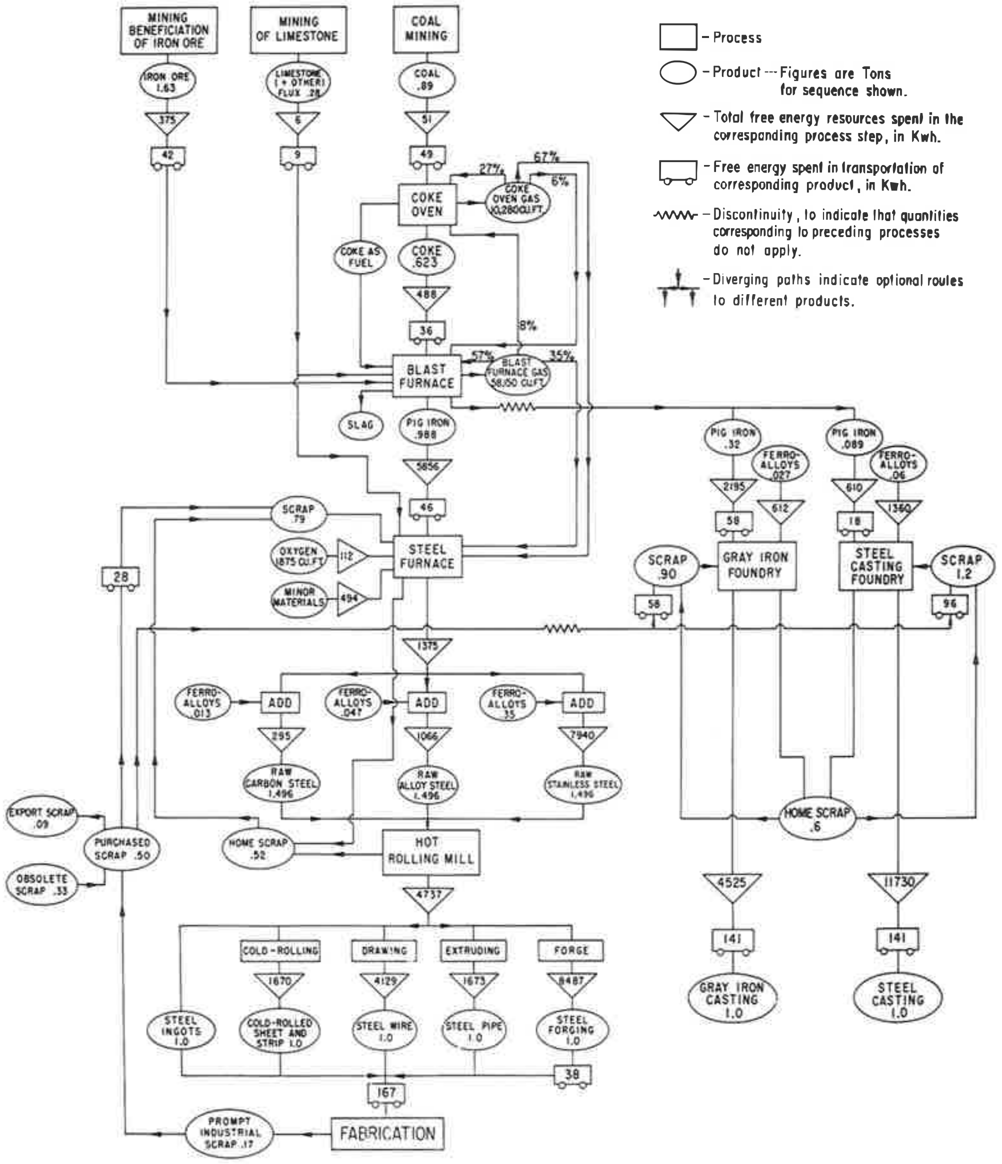
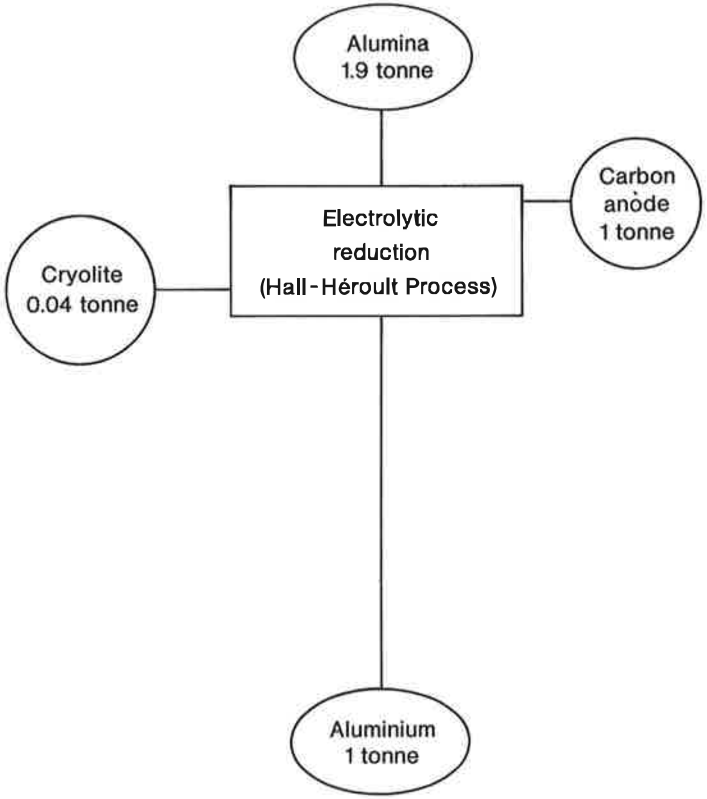
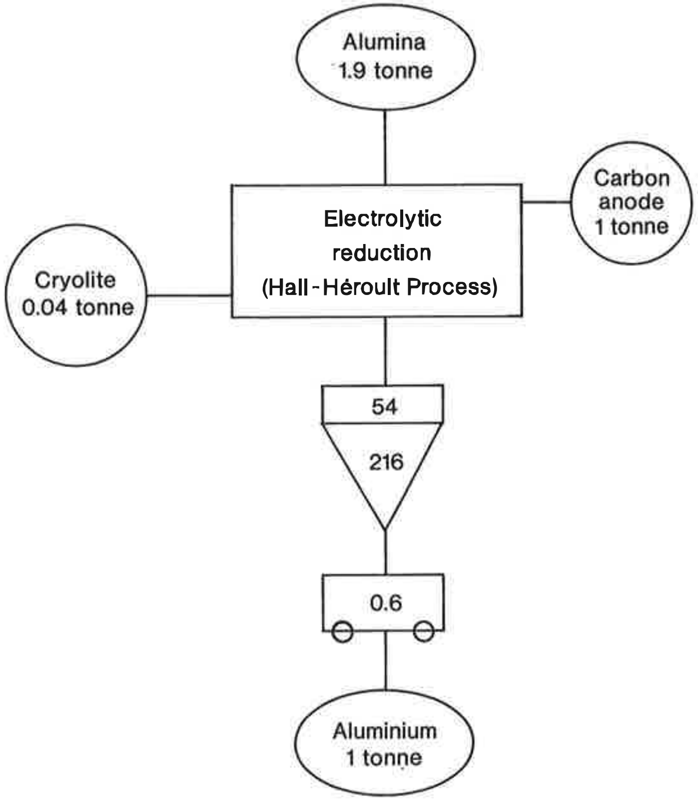


Figure 3. Process analysis of iron and steel production.





Construction of a process analysis flow chart for aluminum production. Energy in gigajoules(GJ).

Figure 4.

Figure 5.

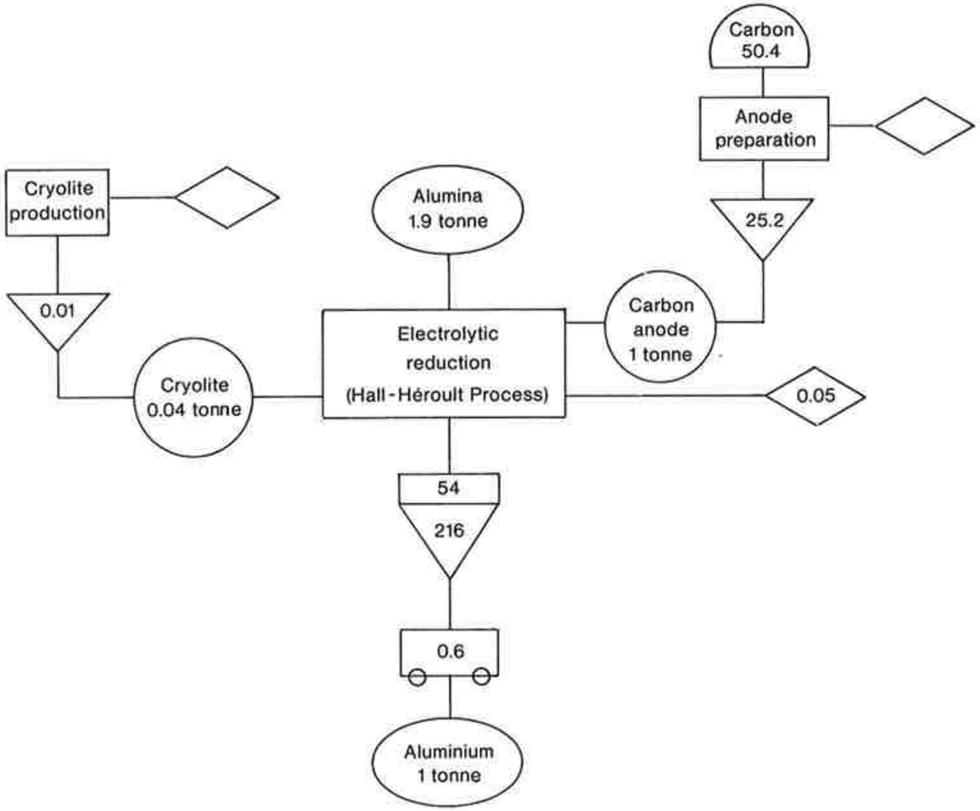
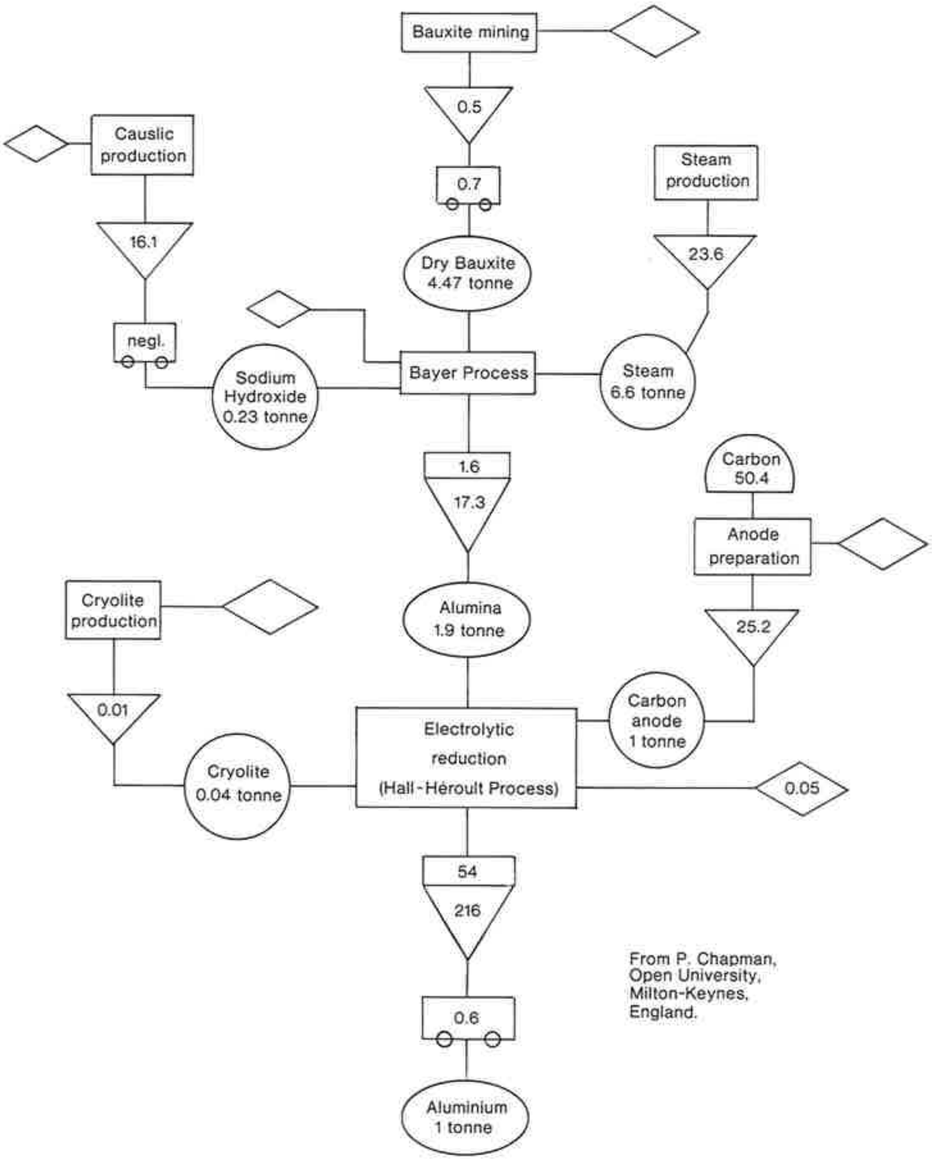

Carbon
50.4
Anode
preparation
Cryolite
production
Alumina
1.9 tonne
25.2
0.01
Carbon
anode
1 tonne
Electrolytic
reduction
(Hall-Héroult Process)
Cryolite
0.04 tonne
0.05
54
216
0.6
Aluminium
1 tonne

Figure 6.



From P. Chapman,
Open University,
Milton-Keynes,
England.

Figure 7.

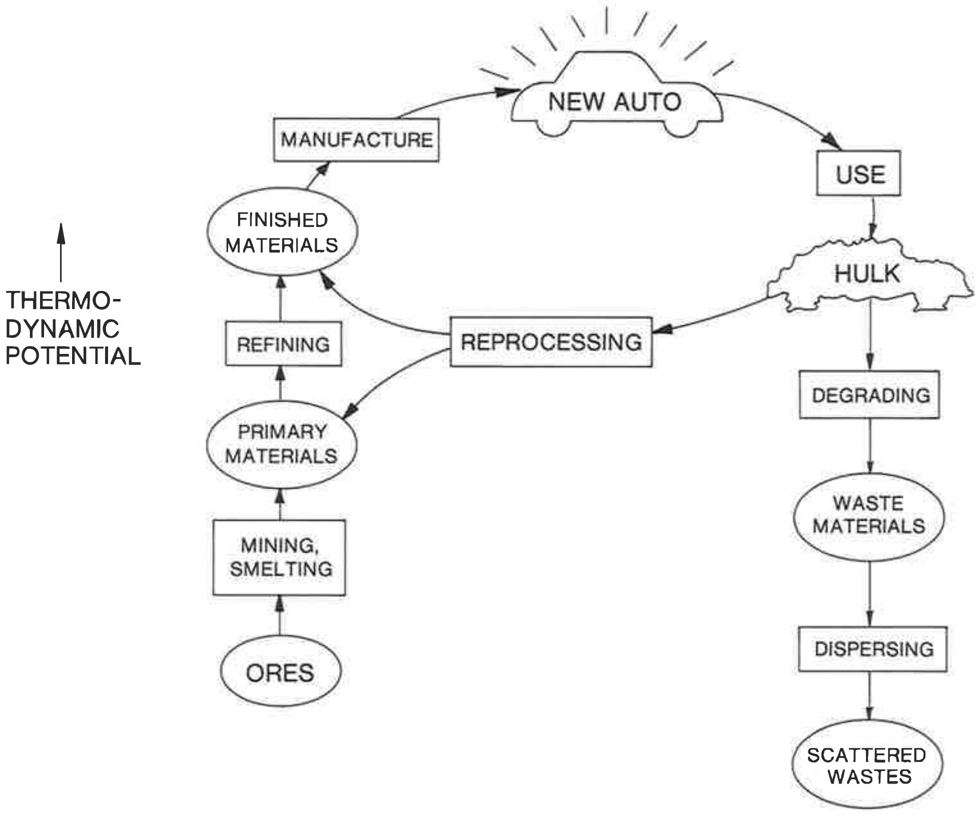


Figure 8. Manufacture-disposal-recycle of an automobile.

"Second-law efficiency" or "effectiveness" is the ratio of the actual work to the maximum work, for a fixed fuel input $\mathcal{E} \equiv \frac{W_{act}}{W_{max}}$

Process (1970 Technology)	$\mathcal{E}$	**Ref.**
Driving 3600 lb. auto	0.12	6
Heating house on a cold day	0.10	6
Joint production of steam and electricity	0.44	6
Blast Furnace	0.09	3
Smelting aluminum	0.07	3

Figure 9 **PHYSICAL EFFICIENCY**

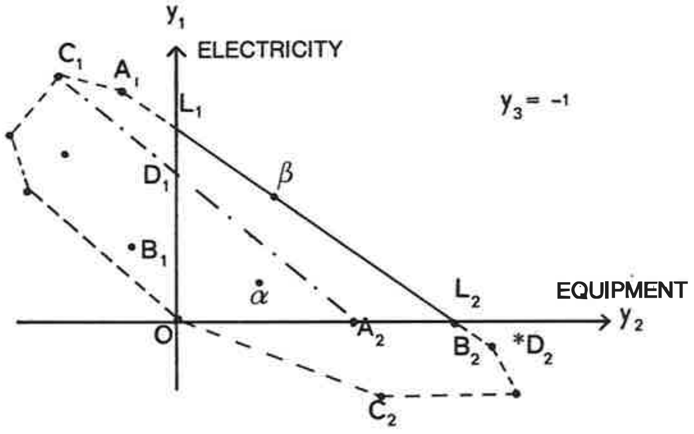


Figure 10. The convex hull for the production of electrical energy and equipment (arbitrary units) with labor as a primary input ($y_3 = -1$).

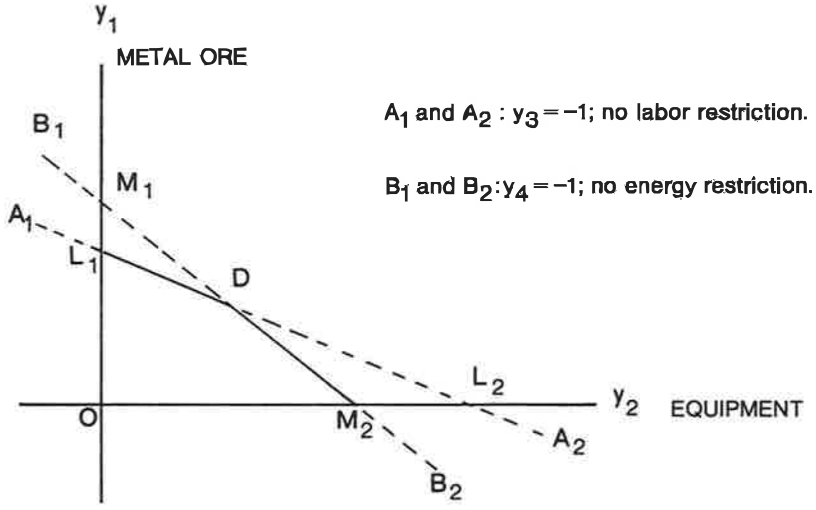


Figure 11. Production with two primary factors, energy (y_3) and labor (y_4).

Process	UK[8]	The Netherlands[3]	USA[4]
Ore-extraction	5 (GJ/t)	5 (GJ/t)	3 (GJ/t)
Alumina production from ore	56	31	13
Aluminium production from alumina	192	196	242
Total	253	232	258

Figure 12 **ENERGY COSTS OF PRIMARY ALUMINIUM PRODUCTION**
(Transportation energy is neglected)

Energy use in the production of polyethylene (GJ/tonne ethylene)

	The Netherlands	UK[13]	USA[6, 7]
Production of crude oil or nat. gas	0.3	0.3	0.4
Crude oil → naphta	1.4	5.7	—
Naphta → ethylene	25.8	20.5	—
Natural gas → ethylene[3]	—	—	62.2
Ethylene → polyethylene[b]	18.3	18.2	43[c]
Subtotal, for polymer production	*45.8*	*44.7*	*105.6*
Polyethylene → film	3.4[3]	13.7	10.9
Total	49.2	58.4	116.5

Figure 13 **AN INTERNATIONAL COMPARISON OF POLYMERS AND THEIR ALTERNATIVES**

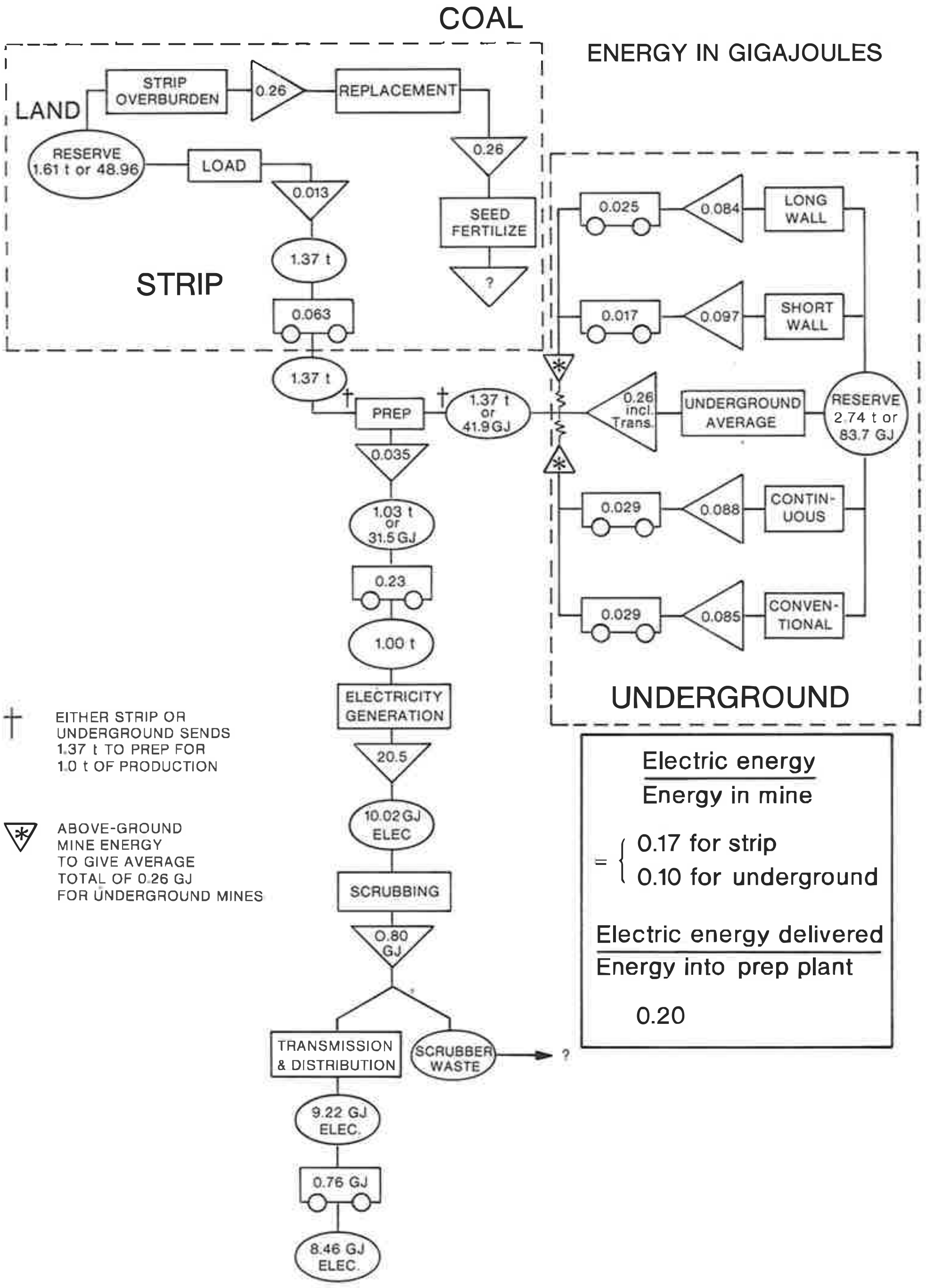


Figure 14. Underground and surface coal mining.

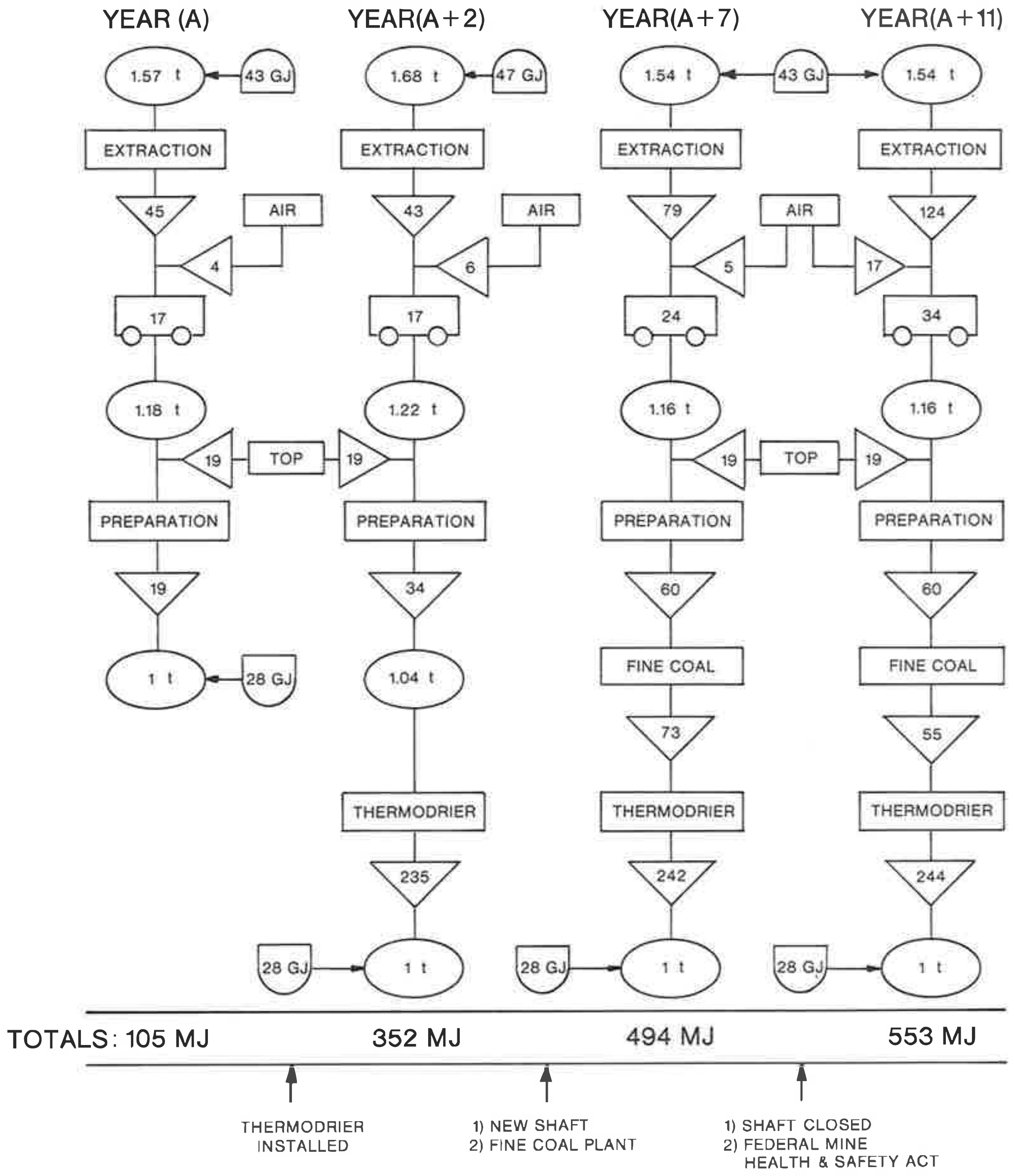


Figure 15. ENERGY REQUIREMENTS FOR UNDERGROUND MINE

Units: MJ/tonne 6500 tonnes/acre	Maximum grade 33 1/3%	 25%	 8%
Spoil reclamation	17	27	41
Tipple refuse disposal	3	4	9
Sub-total	*20*	*31*	*50*
Highwall	38	45	62
Total	58	76	112

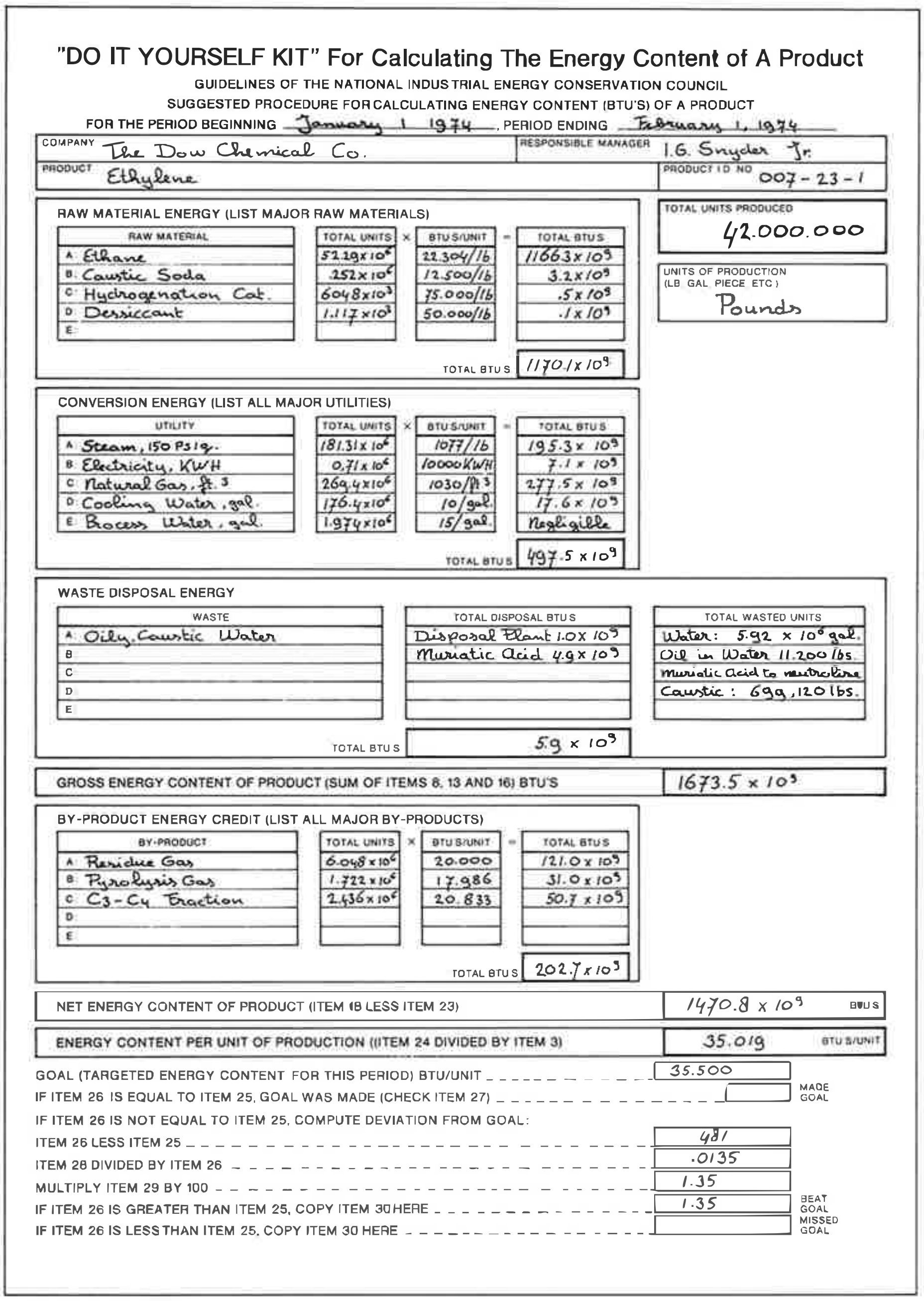
Error limit ±50%

Figure 16 **ENERGY REQUIREMENTS FOR RECLAMATION**

Process change	Energy savings	Capital payback period
1) Ethylene glycol-water heat-transfer media substituted for steam in tracing systems	40%	ca. 1 yr.
2) Aromatic byproduct recovery redesign	85%	less than 2 yr's

Figure 17 **DOW U.S.A. DOLLAR SAVINGS FROM EFFICIENT USE OF ENERGY**

EXAMPLE



"DO IT YOURSELF KIT" For Calculating The Energy Content of A Product

GUIDELINES OF THE NATIONAL INDUSTRIAL ENERGY CONSERVATION COUNCIL
SUGGESTED PROCEDURE FOR CALCULATING ENERGY CONTENT (BTU'S) OF A PRODUCT

FOR THE PERIOD BEGINNING January 1 1974, PERIOD ENDING February 1, 1974

COMPANY The Dow Chemical Co.	RESPONSIBLE MANAGER I.G. Snyder Jr.
PRODUCT Ethylene	PRODUCT I D NO 007-23-1

TOTAL UNITS PRODUCED 42.000.000

UNITS OF PRODUCTION (LB GAL PIECE ETC) Pounds

RAW MATERIAL ENERGY (LIST MAJOR RAW MATERIALS)

RAW MATERIAL	TOTAL UNITS	×	BTU'S/UNIT	=	TOTAL BTU'S
A Ethane	52.19×10^6		22.304/lb		11663×10^9
B Caustic Soda	$.252 \times 10^6$		12.500/lb		3.2×10^9
C Hydrogenation Cat.	6048×10^3		75.000/lb		$.5 \times 10^9$
D Dessiccant	1.117×10^3		50.000/lb		$.1 \times 10^9$
E					

TOTAL BTU'S 1170.1×10^9

CONVERSION ENERGY (LIST ALL MAJOR UTILITIES)

UTILITY	TOTAL UNITS	×	BTU'S/UNIT	=	TOTAL BTU'S
A Steam, 150 Psig.	181.31×10^6		1077/lb		195.3×10^9
B Electricity, KWH	0.71×10^6		10000 KWH		7.1×10^9
C Natural Gas, ft.^{3}	269.4×10^6		1030/ft^3		277.5×10^9
D Cooling Water, gal.	176.4×10^6		10/gal.		17.6×10^9
E Process Water, gal.	1.974×10^6		15/gal.		Negligible

TOTAL BTU'S 497.5×10^9

WASTE DISPOSAL ENERGY

WASTE	TOTAL DISPOSAL BTU'S	TOTAL WASTED UNITS
A Oily, Caustic Water	Disposal Plant 1.0×10^9	Water: 5.92×10^6 gal.
B	Muriatic Acid 4.9×10^9	Oil in Water 11.200 lbs.
C		Muriatic Acid to neutralize
D		Caustic: 699,120 lbs.
E		

TOTAL BTU'S 5.9×10^9

GROSS ENERGY CONTENT OF PRODUCT (SUM OF ITEMS 8, 13 AND 16) BTU'S 1673.5×10^9

BY-PRODUCT ENERGY CREDIT (LIST ALL MAJOR BY-PRODUCTS)

BY-PRODUCT	TOTAL UNITS	×	BTU'S/UNIT	=	TOTAL BTU'S
A Residue Gas	6.048×10^6		20.000		121.0×10^9
B Pyrolysis Gas	1.722×10^6		17.986		31.0×10^9
C C_3-C_4 Fraction	2.436×10^6		20.833		50.7×10^9
D					
E					

TOTAL BTU'S 202.7×10^9

NET ENERGY CONTENT OF PRODUCT (ITEM 18 LESS ITEM 23) 1470.8×10^9 BTU'S

ENERGY CONTENT PER UNIT OF PRODUCTION ((ITEM 24 DIVIDED BY ITEM 3) 35.019 BTU'S/UNIT

GOAL (TARGETED ENERGY CONTENT FOR THIS PERIOD) BTU/UNIT ______________ 35.500

IF ITEM 26 IS EQUAL TO ITEM 25, GOAL WAS MADE (CHECK ITEM 27) ______________ ☐ MADE GOAL

IF ITEM 26 IS NOT EQUAL TO ITEM 25, COMPUTE DEVIATION FROM GOAL:

ITEM 26 LESS ITEM 25 ______________ 481

ITEM 28 DIVIDED BY ITEM 26 ______________ .0135

MULTIPLY ITEM 29 BY 100 ______________ 1.35

IF ITEM 26 IS GREATER THAN ITEM 25, COPY ITEM 30 HERE ______________ 1.35 BEAT GOAL

IF ITEM 26 IS LESS THAN ITEM 25, COPY ITEM 30 HERE ______________ ☐ MISSED GOAL

Figure 18. Sample form. Energy content of a product. From "How to Profit by Conserving Energy," published by the Subcouncil on Technology of The National Industrial Energy Conservation Council.

Category of use[a]	Withdrawals[b, c]		Energy for Acquisition and Delivery[c]		Energy for Post-use Treatment[c]	
	10^9 gal/day	10^9 tonne/yr	MJ_T/tonne	10^9MJ/yr.	MJ_T/tonne	$10^9 MJ_T$/yr.
Public Supplies:						
surface	18.0	25	4[d]	100	5[e]	125
ground	9.4	13	8[f]	104	5[e]	65
Rural Domestic:[g]						
surface	0.9	1.2	0.5[h]	0.6	0[i]	0
ground	3.6	5.0	5[l]	2.5	0[i]	0
Irrigation:						
surface	81	112	4[k]	448	0[i]	0
ground	45	62	8[k]	496	0[i]	0
Thermoelectric:						
surface	170	230	0.5[h]	120	0[i]	0
ground	1.4	1.9	4[l]	7.6	0[i]	0
Other Industrial:						
surface	38.0	52	0.5[h]	26	0[i]	0
ground	9.0	12	4[l]	48	0[i]	0
Totals	370	510		1350		190

Figure 19 **DIRECT ENERGY EXPENDED FOR WATER IN THE UNITED STATES IN 1970**

$G = G(Y, P_K, P_L, P_E, P_M)$

Total Cost and Cost Shares of Capital, Labor, Energy, and Other Intermediate Materials

U.S. Manufacturing 1947-1971

Year	Total Input Cost*	Cost Shares K	L	E	M
1947	182.373	.05107	.24727	.04253	.65913
1957	338.633	.05033	.27184	.04820	.62962
1967	540.941	.05443	.28646	.04074	.61837
1971	658.235	.04675	.28905	.04479	.61940

*Billions of current dollars

Figure 20 **BERNDT-WOOD TRANSLOG COST FUNCTION**

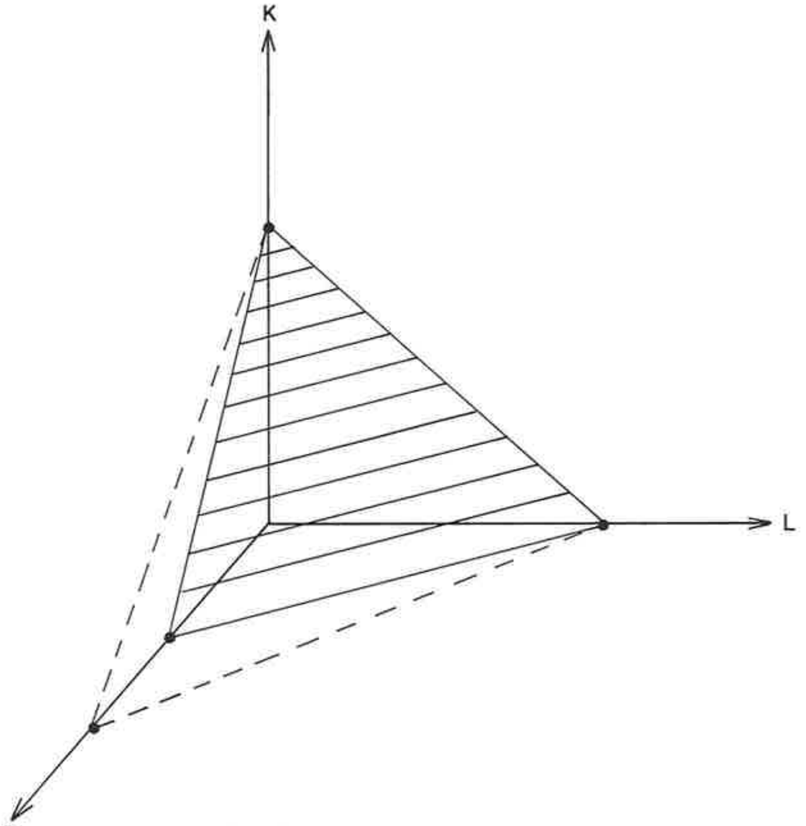


Figure 21. KLT production space.

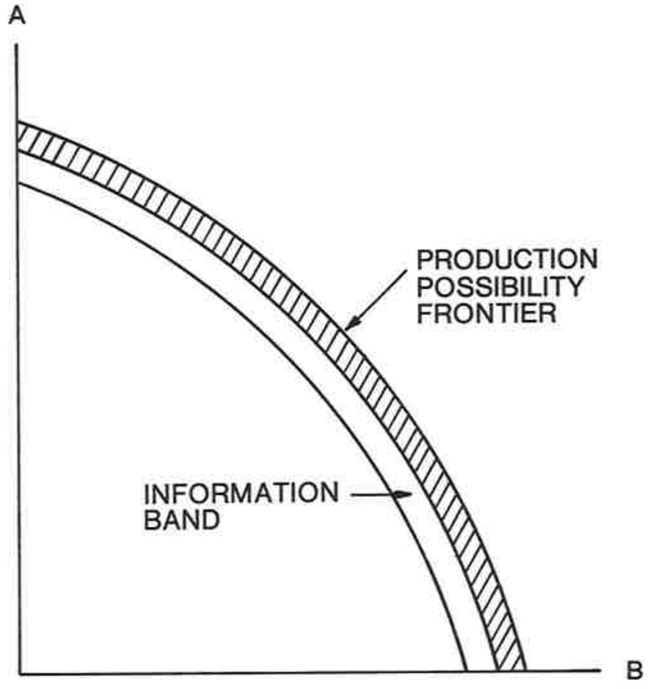


Figure 22. Defining the boundary of the production possibility frontier.

Energy considerations in synthetic and natural fibres

Mr. A.H. Woodhead
Imperial Chemical Industries (ICI)
Londen
U.K.

The subject is treated in five parts:

First	- the history, size and shape of the world of fibres.
Second	- fibres as users of energy, now and in the future.
Third	- how the energy goes into different fibres.
Fourth	- saving energy and using the preferred fibres.
Fifth	- what we are doing about the problem presented.

1. The world of fibres

Natural fibres - wool, cotton, silk, etc. - have been known and used for thousands of years. The first man-made fibre, however, was discovered only 85 years ago, and was not made in significant quantities until 50 years ago. (Table 1).

Yet today one-third of all fibres are man-made, and this is expected to rise to one half by 1990. (Figures 1 and 2). Fibre usages are a bell-wether of standards of living, the per capita usage going up with the gross domestic product. (figure 3). Fibres are used predominantly for clothes and home furnishings, but more than a quarter of fibres now go into industrial and other end uses. (Figure 4).

We now turn to the main aspect of this paper, energy usage.

2. Fibre usage of energy in the world

As we shall see, fibres are substantial users of energy. Nevertheless, factors such as fashion, style, fitness for purpose, standard of living, cost and availability of capital are also important determining factors in all but energy crisis or siege economy conditions.

Throughout this paper I shall use only two units of energy - the gigacalorie, and the oil equivalent in tonnes per tonne of fibre. Heat and oil are, after all, the main forms in which energy is used in the textile industry. (Table 2).

Although one third of all fibres are synthetic, they account for 60% of all the energy used. The total energy used to make fibre-based products including raw materials, is now running at more than 80 million tonnes of oil per year. (Table 3). This is to be compared with 70 million tonnes per year for the total consumption of oil energy in the Netherlands, 200 million tonnes in the United Kingdom, and 6,000 million tonnes in the world. We shall be seeing how these figures are arrived at in the next section.

Growth over the next 15 years is going to be predominantly in the synthetic field, so that by 1988 there will be about equal quantities of synthetic and natural fibres produced, and the total energy requirement at 150 million tonnes of oil a year almost double what it is today. (Table 4).

These estimates are based on population, standard of living and pattern of living changes, and fitness for purpose of the fibre products.

But the determining factors could well be the availability of energy or capital for fibre purposes, and we have to ask ourselves if world economy can justify a rate of increase of 5 million tonnes of oil per year, and $ 1,500 million of capital per year on fibre expansion over the next 15 years. (Table 5). These estimates assume that it can.

3. Energy usage for fibre variants

The energy required to make man-made fibres differs markedly according to the fibre type. As regards raw materials and monomer making, polyamides are the most profligate, as their intermediates involve the greatest number of stages in the chemical process. Polyolefines, of the wholly man-made fibres, use least energy as they involve the least number of stages. But cellulosics, using non accountable solar energy and a relatively small amount of fuel energy in the form of wood, are the most sparing in energy usage up to the polymer stage. The energy used at fibre making, however, is least for the melt spinning processes of polyesters, polyamides and polyolefines, and very large for the solution or solvent spinning processes employed for acrylics and cellulosics. In round figures, however, and considering the pattern of usage, we can conclude that it takes about 5 tonnes of oil to make 1 tonne of man-made fibre. (Table 6).

The energy to make natural fibres, such as cotton or wool, is only about 1 tonne of oil per tonne of fibre, a fifth of that required for the synthetics, because of the large content of non accountable solar energy, both at the raw material and fibre forming stages, and the nil practical value of the raw materials as fuels. (Table 7).

All the above figures relate to staple fibre in the raw condition, and more work has to be done to put them into usable form for fabric. For example, if the synthetic fibres are required in the more sophisticated forms of continuous filament or bulked continuous filament, energy of the same order as that used to produce the unmodified staple fibre has to be expended. (Table 8).

Further substantial expenditure of energy is needed to prepare raw fibres for making into cloth, and to weave or knit the yarns into fabric. Added together, these additional expenditures of effort add about 20% to the total energy needed to make synthetics and double the amount needed to produce raw natural fibres. (Table 9).

We conclude, therefore, that synthetic fibres require about 6 tonnes of oil, natural fibres 2 tonnes of oil per tonne of fabric.

4. Energy economics in fibre production

Opportunities for energy conservation in fibres operations arise through
(a) reduced numbers of processes,
(b) integration or improvement of processes,
(c) recycling of high energy content raw materials,
(d) better use of fibres in end products,
(e) replacement of fossil resources by renewable resources for synthetic fibres.

The effect of a smaller number of processes is exemplified by a comparison of polyamides, polyesters and polyolefines, which all use basically the same carbon source but diminishing number of processes. (Table 6).

The effect of process integration is demonstrated by combining the polymerisation and spinning operations in polyester manufacture. Other examples of process integration are combining spinning with drawing, texturising with spinning or drawing, replacing knitting or weaving by lower energy fabric forming processes linked to polymer making or fibre forming. In the textile processing field an example is the development of differentially dyeable fibres, which permits multi-coloured fabrics to be produced by mixing several dyes in a single dye bath. (Table 10).

Recycling is practised widely in synthetic fibres production by regenerating in-house arisings at the various stages of manufacture, and an example is the glycolysis of polyester polymer arisings, which takes only one third of the energy compared with making virgin polymer from oil. (Table 11). Similar savings, though even greater, are achieved through the hydrolysis of nylon waste. There is considerable scope for developing the recycling operation, however, to include the re-working of made up garments and fabrics, though collection and segration are major constraints.

There are several ways in which fibres can be used more efficiently, by chosing the correct fabric structure and using the right fibre. For example, there are certain end uses which, while demanding a fully synthetic fibre on the grounds of abrasion resistance, tenacity, or drip dry properties, could be served equally well by polyamide, polyester or polypropylene, and in these instances, considerable savings of energy could be made by switching to the lowest energy user.

The durability factor of man-made synthetics, combined with the general rule that smaller weights are needed to produce the same affects as natural fibres, militate against the higher energy content per tonne of fibre. (Table 12). In situations where haute couture and fashion are not overriding, and durability and fitness of purpose are predominant, about one quarter the weight of synthetic fibres has the same usefulness as natural fibre.

5. Ultimate resources for fibres

In the ultimate, when all fossil resources are exhausted, the starting point for synthetic fibres, like cellulosic and natural fibres, will move to renewable resources. Nylon 66, it is interesting to record, was initially made on the commercial scale from corn husks (via furfural) and Nylons 9, 10 and 11 are still made commercially from soyabean, sperm and castor oils.

Chemically speaking there is no reason why polyesters, polyolefines and acrylics should not be made from renewable cellulose sources, by hydrolysis to sugars and fermentation to alcohol, from which ethylene can be made, and used as a precursor for synthetics. Already, in India, molasses are converted to polyethylene by this route on the commercial scale. (Table 13).

year introduced	fibre (monomer or polymer)
1891	rayon
1918	cellulose acetate
1930	rubber; glass; nylon; vinyl chloride
1940	vinylldane chloride; metal; polyester; acrylic
1959	urethane
1961	olefin

Source: American Chemical Society. Chemistry in the Economy. 1973

Table 1 **HISTORY OF MAN MADE FIBRES**

A heat unit (gigacalorie) is used, as most energy is used in this form and all the electrical energy is made from heat, which is included in calculating the energy content of the electricity.

1 G.Cal = 10^9Cal = 40 therms = 4.2 GJ = 1.17 MWH

11 G.Cal = 1 Tonne oil equivalent

Table 2 **ENERGY UNITS**

	Fossil energy used		
	10^6 Tonne	10^6 G.Cal	Oil equivalent 10^6Te.
Synthetic fibres (60% non cellulosic, 40% cellulosic)	8	528	48
Natural fibres (60% cotton, 20% jute, 10% wool, 10% others)	17	374	34
All fibres	25	902	82

Table 3 **WORLD USE OF ENERGY FOR FIBRES IN 1973**

	World output 1973 (10^6 Te)	Annual growth rate (10^6 Te)	World output 1988 (10^6 Te)
Synthetic fibres	8	0.7	18.5
Natural fibres	17	0.1	18.5
All fibres	25	0.8	37.0

Energy consumption by 1988 will be 1628 G.Cal OR 148×10^6 Te oil or nearly double that of 1973.

Table 4 **GROWTH OF WORLD CONSUMPTION OF FIBRES 1973-88**

1. **Energy needs**

Extra 5×10^6 oil per year each year.

2. **Capital needs**

Extra $\$1500 \times 10^6$ per year each year.

Synthetic fibres are more energy and capital intensive than natural fibres.

Table 5 **CONSTRAINTS TO SYNTHETIC FIBRE GROWTH**

	Polyester	Polyamide	Acrylic	Cellulosic
Monomer making	29.6	51.5	40.0	—
Polymer making	6.8	4.5	36.0	3.1
Fibre forming	6.8	4.9		26.4
Total (G.Cal/Tonne)	43.2	60.9	76.0	29.5
Oil equivalent (Tonne oil/tonne)	3.9	5.5	6.9	2.7

Table 6 **FOSSIL ENERGY USED TO MAKE MAN-MADE FIBRES** (G.Cal per Tonne)

	Cotton	**Wool**
Polymer growing (feeding, pesticides)	0.4	1.0
Fibre making	7.5	8.4
Total (G.Cal/Tonne)	7.9	9.4
Oil equivalent (Tonne oil/tonne)	0.7	0.9

Table 7 **FOSSIL ENERGY TO MAKE NATURAL FIBRES** (G.Cal per Tonne)

Example 1	To make continuous filament yarn of high uniformity and quality from polymer takes three times as much energy as to make staple fibre.
Example 2	To impart bulk (texturise) in nylon takes as much energy as polymerisation and fibre forming.

Table 8 **ENERGY TO MAKE FIBRE IN DIFFERENT FORMS**

	Wool	Polyester
Scouring	5.7	–
Conversion to top	0.6	0.4
Worsted spinning	2.5	2.5
Weaving	2.6	2.6
Dyeing and finishing	3.0	4.2
Total processing energy	14.4	9.7
Energy to make fibre	9.4	13.6

Table 9 **ENERGY NEEDED TO PROCESS FIBRES** (G.Cal/Tonne)

To convert raw fibre to fabric can take more energy than to make the fibre itself.

Batch polymerisation of polyester	6.8
Batch fibre forming	6.8
Total	13.6
Integrated polymerisation/fibre forming	11.5
Saving	2.1 (15%)

Other examples
Spin/draw, producer texturising, non wovens, differential dyeing

Table 10 **ENERGY SAVING BY PROCESS INTEGRATION** (G. Cal/Tonne)

Example: Glycolysis of polyester

	G.Cal/Tonne
To regenerate good polymer from waste	11.0
To make good polymer from virgin monomer	6.8
To make virgin monomer	29.6
Hence expenditure of 11 G.Cal. Saves 36.4 G.Cal/Tonne.	

Table 11 **ENERGY SAVING BY RECYCLING**

Men's socks	(Nylon: wool, cotton)	12
Work suits, uniforms	(P.E./cotton: cotton)	5
Upholstery	(Nylon: wool, cotton)	5
Woven trousers	(Polyester: wool)	4
Shirts	(P.E./cotton: cotton)	3
Carpets	(Nylon: wool)	3
Tyres, belts, slings	(Nylon, P.E.: rayon, cotton)	1½

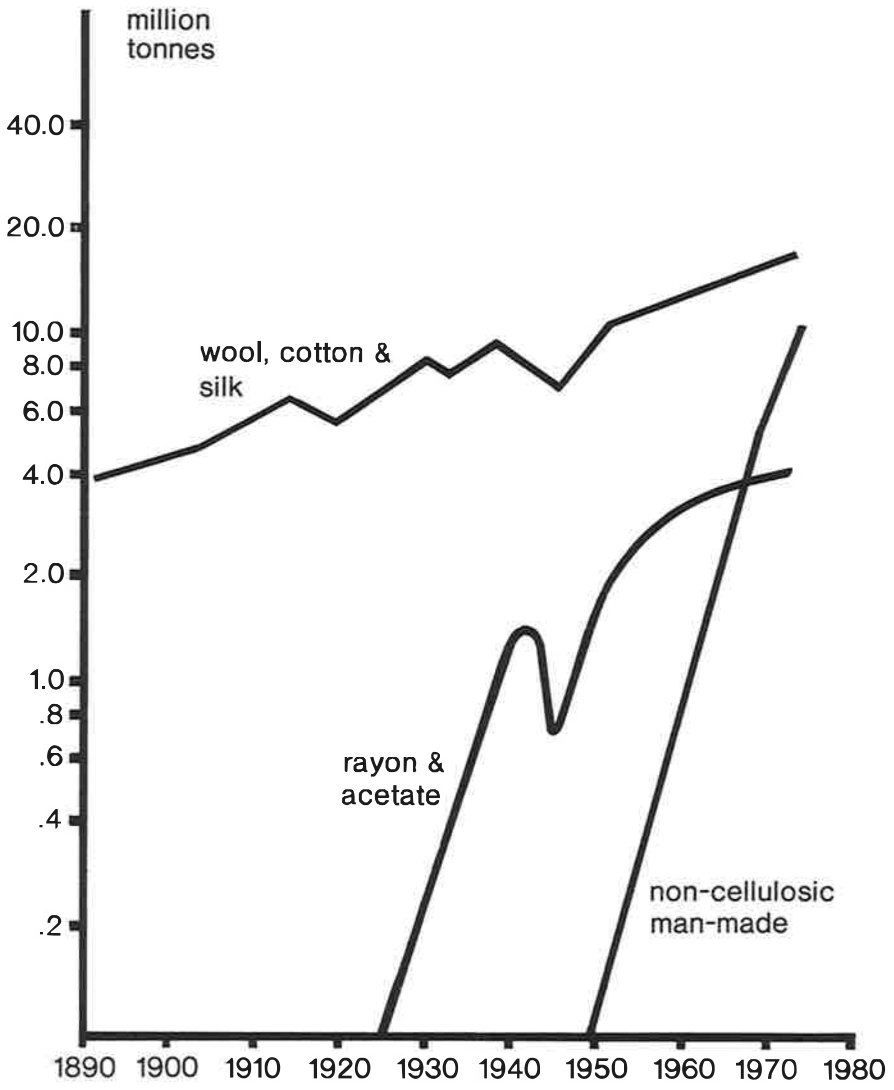
Table 12 **DURABILITY FACTORS OF MAN-MADE OVER NATURAL FIBRES**

Nylon 6.6	Corn husks → Furfural
Nylon 9	Soyabean, sperm oil → Nonanoic acid
Nylon 10,11	Castor oil → Sebacic, undecanoic acids

Speculative routes for nylons, polyester, acrylics

Cellulose → Sugars → Ethylene

Table 13 **MAN-MADE FIBRES FROM RENEWABLE RESOURCES**
COMMERCIAL ROUTES FOR NYLONS



sourse: Textile Organon

Figure 1. World Fibres Production

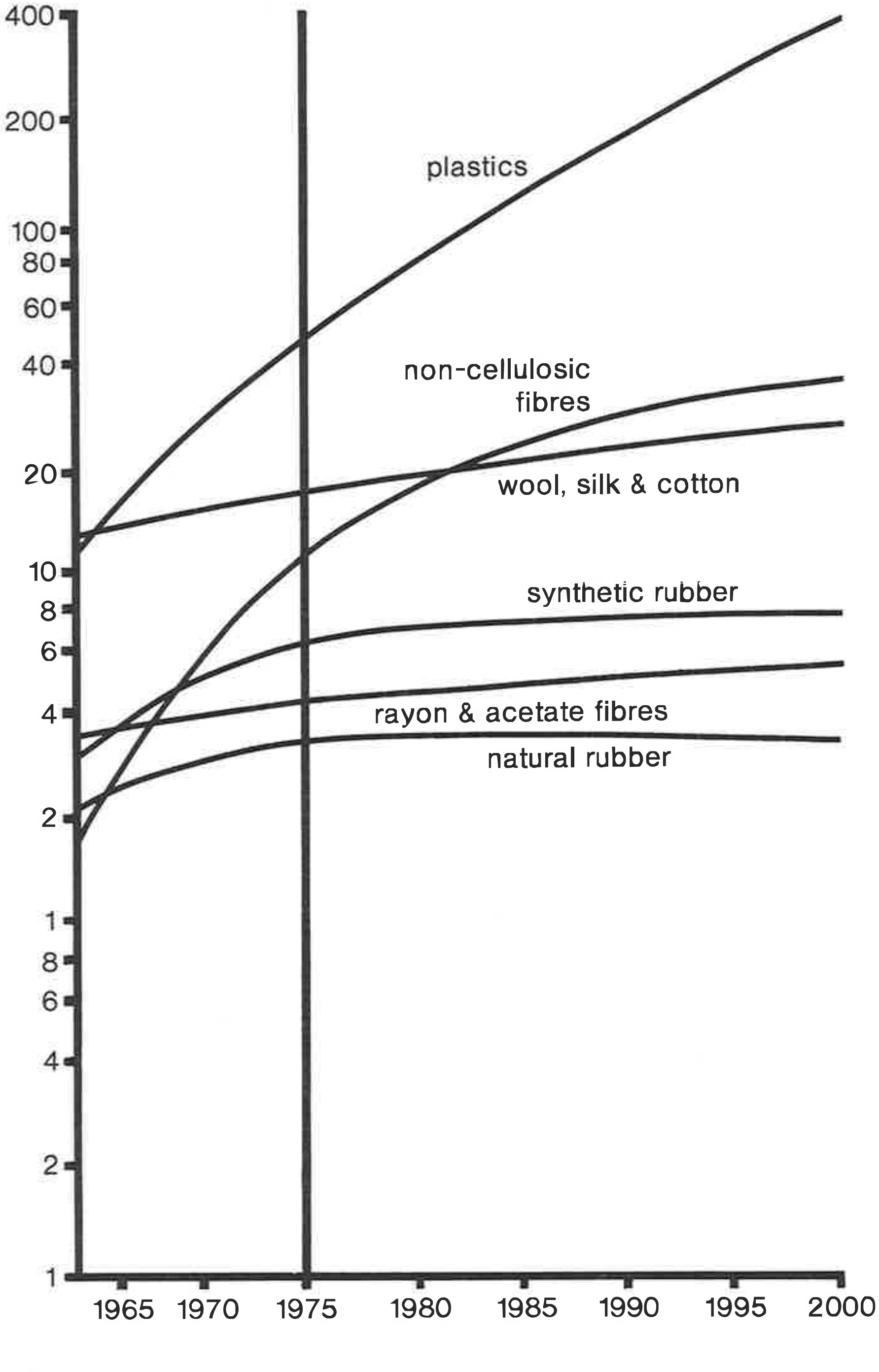


Figure 2. Future of World Polymers Production.

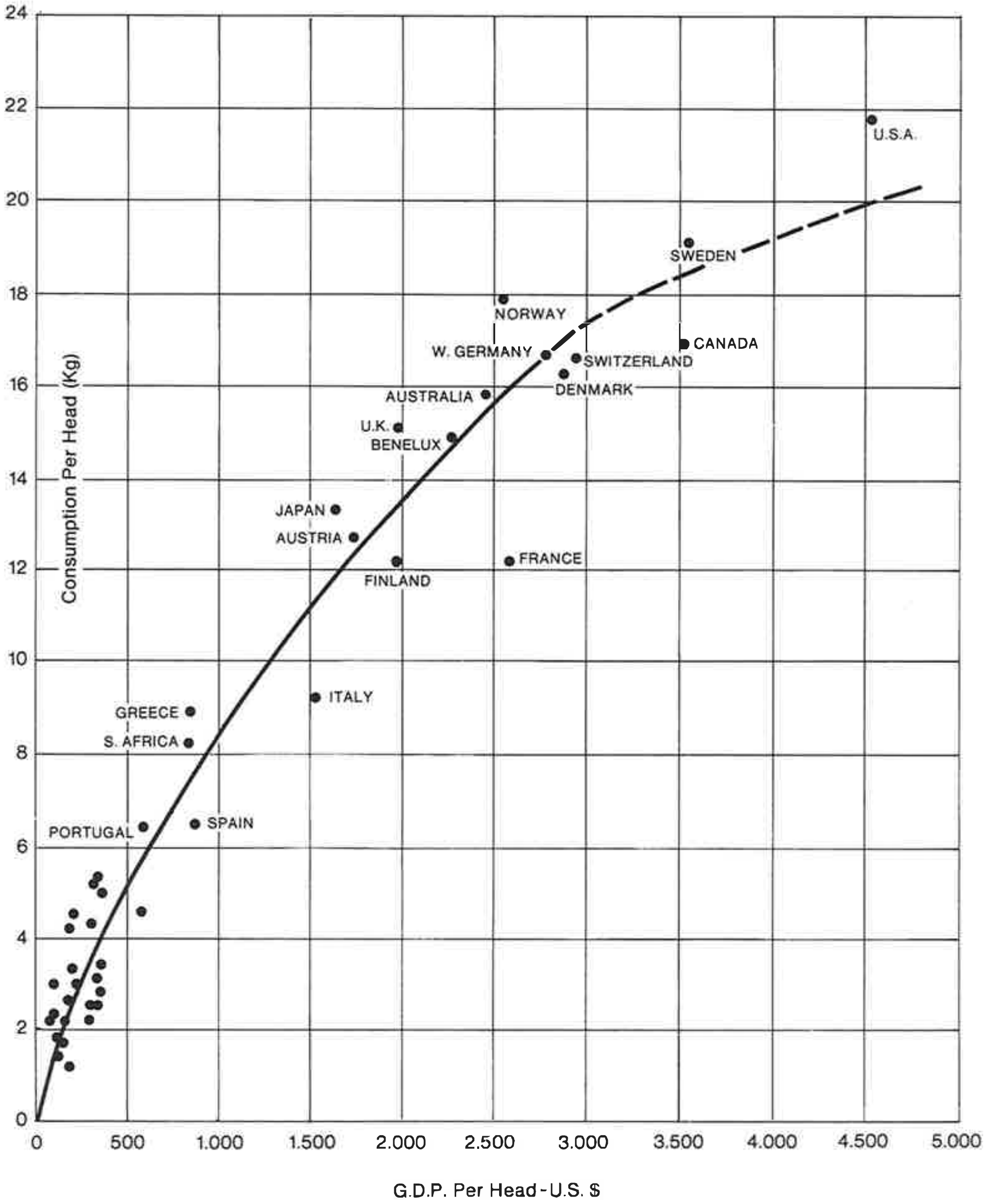
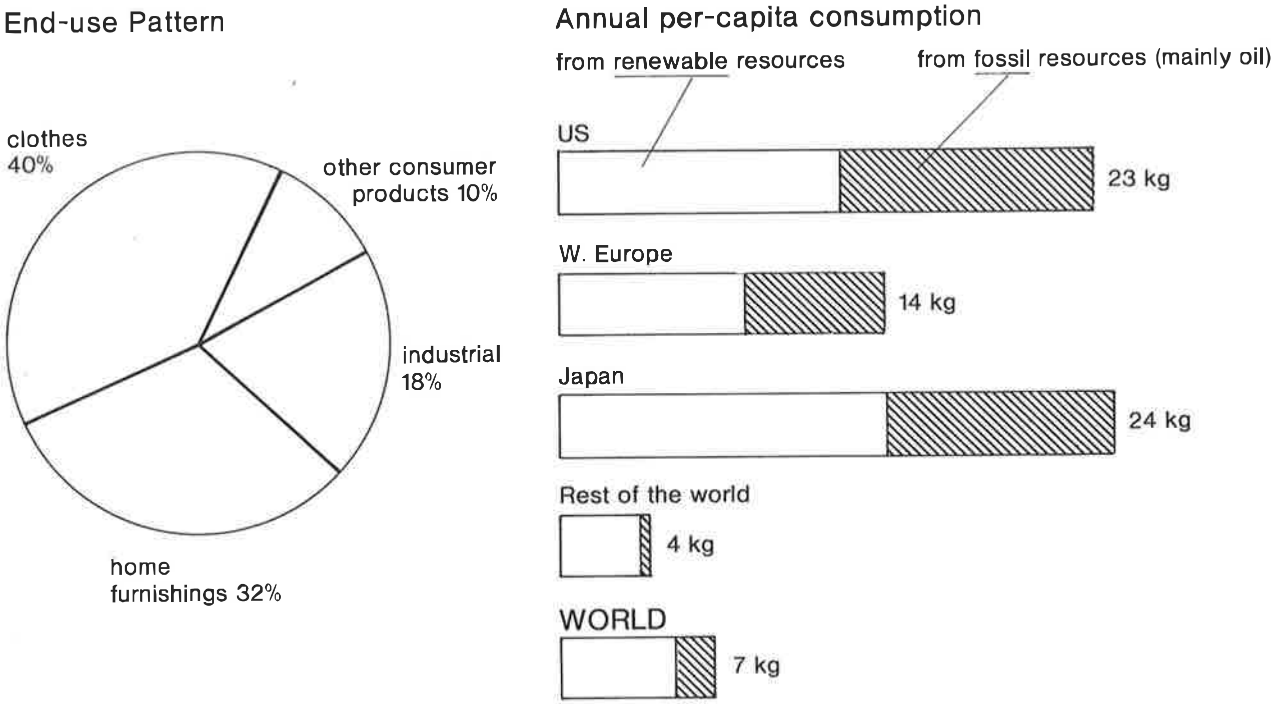


Figure 3. Comparison of gross domestic product per head with fibre consumption per head - 1969.



End-use Pattern

Annual per-capita consumption

Source: Textile Organon

Figure 4. Fibres use.

Energy accounting in food products

Mr. Gerald Leach
Fellow, International Institute for Environment and Development
London
U.K.

Food production in the industrialised countries is heavily dependent on inputs of energy from fossil fuels. Most developed societies now use about 3 units of fossil fuel energy for each food energy unit produced by the farmer but up to 7 or 8 units when one counts in the processing, packaging, transportation, retailing, storage and cooking of food. This energy for the whole food production-delivery-cooking system equals about 0.8 tonnes of oil equivalent per capita per year, while the weight of food consumed is only about 0.5 tonnes per person. One result of these large energy inputs is that the food system takes a substantial slice of national energy budgets: for example, 22% in the United Kingdom.

These figures indicate that food production is clearly an important topic for energy analysis. By mapping the total energy flows through the system - one major purpose of e.a. - one can detect the most energy intensive process steps and products and thus contribute both to energy demand forecasting and conservation efforts. Equally important, the use of energy can be related to other crucial inputs to production, such as land and labour. Obviously the large energy inputs of Western food production have not emerged without reason. Fuels have been cheap, and their use in the form of mechanisation, fertilisation, packaging, etc., has helped raise yields, reduce manpower needs and provided higher quality diets with round-the year availability. But now that fuels are not cheap, and may become scarce, we need to know more about these energy-land-labour-'quality' relationships in order to strike new and more sensible balances or trade-offs. We also need to know whether the Western food production model is a possible one, even on energy grounds alone, for the less developed world to copy; and if not, what energy-food strategies are needed instead.

These are the broad themes of this paper. I shall start by examining the energetics of farming and the whole food system in the UK and the way it has developed over the past 25 years as, like most Western countries, it rapidly industrialised its food sector. I shall then look at the world's farming systems and compare them with the UK and other industrialised countries for the energy, land and labour used to grow food. We shall find that the industrialised, energy-intensive Western food system has not made the giant strides in saving land and labour usually credited to it. Finally, I shall look briefly at the food energetics of the less developed world and suggest where the imperatives for energy development lie.

The UK farm system

Fifty years ago energy inputs to UK farming were low. There were only 10,000 tractors compared to 410,000 today. Only 6% of farms had an electricity supply and their combined consumption was less than 1% of present levels. In all, fossil fuel inputs were about 100-150 MJ/hectare/year compared to 9000 MJ in 1970*.

Industrialisation with its associated energy inputs occured very rapidly and mostly after World War 2. From 1940-72 the number of farm horses fell from about 500,000 to almost zero, to be replaced by tractors which are now more numerous that full-time farm workers, whose numbers dropped from 700,000 to 260,000 in the 50 years to 1972. At the same time, while crop yields roughly doubled their 1900 level, fertiliser consumption soared, with a 4-fold rise in nitrogen use and a 15-fold rise in potash and phosphorus from 1940-72.

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* All data in this paper are from (Leach, 1975a) and (Leach, 1975b) unless ontherwise stated.

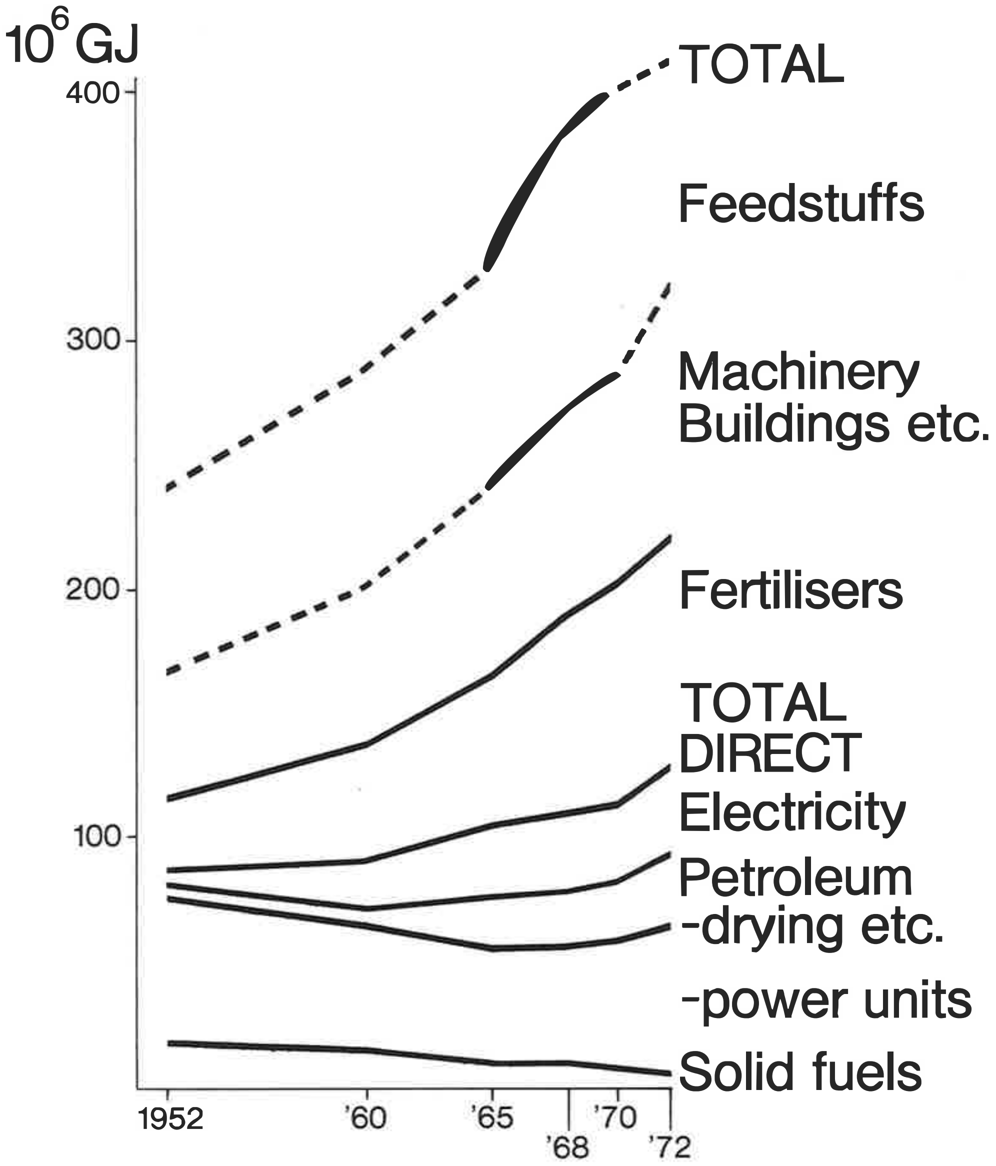


Figure 1. Gross energy input to U.K. Agriculture, 1952-'72.

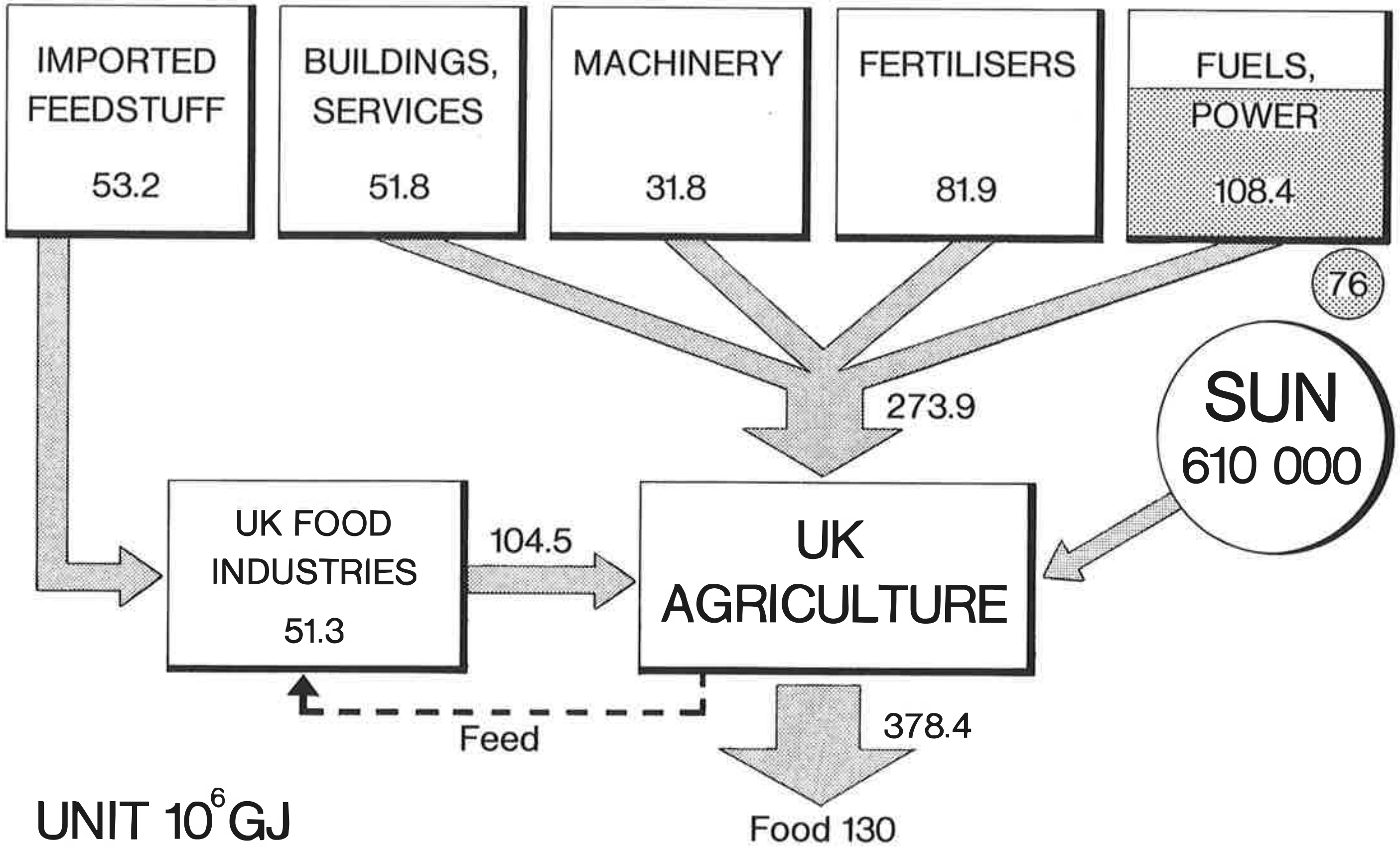


Figure 2. Energy flow in U.K. Agriculture, 1968.

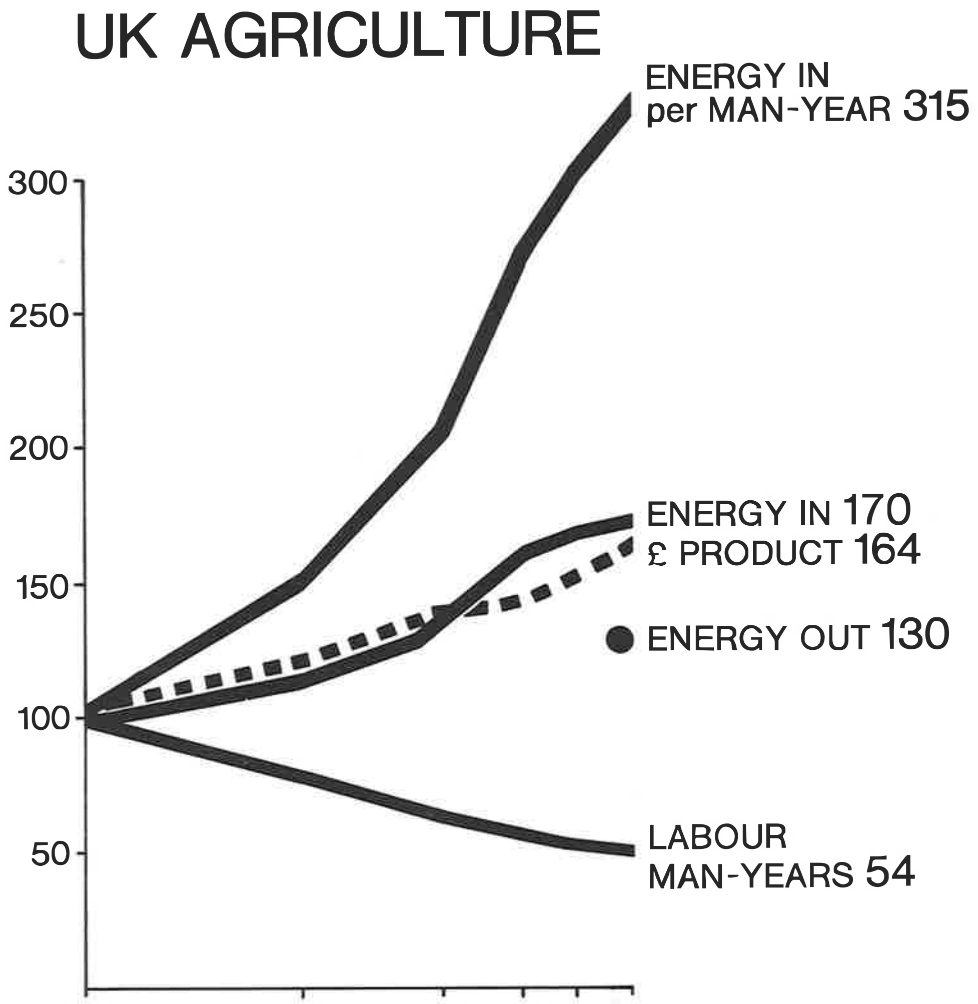


Figure 3. Energy, manpower and £ product in U.K. Agriculture, 1952-1972.

The effects on energy consumption are shown in Figure 1, while Figure 2 gives a breakdown of the gross energy inputs to UK farming in 1968, the latest year for which sufficient data for detailed energy accounting is available. By 1968 energy use in agriculture had risen to 378 million GJ or 8.76 million tonnes of oil equivalent, equal to 4.6% of UK primary energy consumption in that year. Interestingly, only 20.0% of this energy - the quantity of fuels and electricity delivered to farms, equal to 76 million GJ - is recorded in the UK energy statistics. All the remainder is indirect consumption occurring off the farm in tractor manufacture, mining, fertiliser manufacture, transport, the provision of fuels and electricity, etc. - and thus recorded only by energy accounting methods.

For this energy investment, among others, UK farming delivered 130 million GJ of food energy and 1.16 million tonnes of protein for human consumption, enough to feed exactly half the population in energy terms and 62% in terms of protein. The Energy Ratio measuring output divided by input was 0.34 while it took 325 MJ or 7.5 kg oil equivalent to provide each kg of protein.

How did the increase of energy relate to other factors of production? Figure 3 provides some answers. The financial product (value added) rose in real terms in close step with the energy input so that energy consumption per unit of output hardly altered. Since the cost of fuels and electricity declined in real terms, it became more and more profitable for farmers to substitute energy for other basic inputs, such as labour (through mechanisation) and land (through fertilisation, but also some mechanisation aimed at increasing yields through higher rates of work in tilling, harvesting, etc.). However, much of the increase in financial product was due to a shift towards costly animal products with the result that nutritional food outputs did not rise so rapidly: during the period energy output rose by only 30% and protein outputs only 35%. Consequently the Energy Ratio declined from 0.46 to 0.34 while the energy to produce a kg of protein rose from 251 to 325 MJ. All this took place on a farmed area that altered by only a fraction of 1%, with losses to forestry and building land almost exactly equalling the gain in farmland from the removal of horses.

By far the most notable changes were in the substitution of energy for manpower. By 1972 each full-time farm worker was backed by a direct energy input of 502 GJ or 11.6 tonnes oil equivalent per year. Counting all part-times workers, wives who do some farm work, directors, etc., reduces this to about 180 GJ per man year. Even this lower figure puts agriculture, on this measure, well into the category of heavy industries: in the UK the direct energy per man year is about 130-140 GJ in engineering industries and 310 GJ in motor vehicle production. Equally significant, the marginal energy cost of replacing labour has soared. In the early days of farm mechanisation it often took only 10-20 MJ of energy to save one hour of labour - for example, in going from hand to mechanical milking, chaff cutting, or cheese making - but by 1965-70 this had risen to around 230 MJ.

The UK food system

When one considers the entire food system of the UK the energy consumption of farming plays a fairly minor role. Table 1 gives a much condensed breakdown of the energy inputs for the whole UK food sector, including (rough) estimate for imports, and shows that the total was 1,847 million GJ or 22.5% of primary energy consumption. This works out at 33.6 GJ or 0.78 tonnes oil equivalent per capita per year, with an Energy Ratio of only 0.14. As much as 1100 MJ or 25 kg oil equivalent are needed to provide each kg of protein for human consumption.

As shown in Table 2, these figures are very similar to those of other industrialised countries such as the USA, Holland and Australia. They do not suggest that such food systems are very 'efficient' in energy terms.

This low energetic efficiency would matter less, perhaps, if other important resource efficienciencies were very high as a consequence. But this is not the case, at least in the UK. Considering land use, the overall conversion efficiency from solar input to final food energy outputs is only about 0.02%. This is far lower than that achieved by most subsistence agriculturalists who use no fossil fuel inputs at all, though there are

	10^6GJ	% UK energy
Imports of fish	13	
Imports of food	260	
UK fisheries	33	
UK agriculture	378	
Total for primary sector	684	8.3
Food and drink industries (less work for agriculture)	476	
Food shops, etc, including transport	139	
Total for secondary sector	615	
Cooking, refrigeration	438	
Equipment, consumer transport	110 approx.	
Total for tertiary sector	548	6.7
Overall total (33.6 GJ per capita)	1847	22.5

Table 1 **ENERGY INPUTS TO THE UK FOOD SYSTEM, 1968**

important differences of climate and food quality and reliability to allow for.

Nor is the UK system all that efficient by comparison in its use of labour. Counting up the direct and indirect manpower requirements of UK agriculture, the food industries and retail distribution gives a total close to 3 million workers, with perhaps a further 1 million to provide imported feed and food. Since these workers provide 261 million GJ of final food output for humans, their resource productivity is only about 30-35 MJ per hour of working time. This performance is little better than for subsistence farmers in the tropics (see Figure 5). Alternatively, 4 million workers represent 19% of the total UK workforce and 7.3% of the population. This means that each person in food-related employment, in the UK or abroad, feeds 'only' 13 to 14 people rather than the 60-70 usually quoted on the basis of full-time farm workers alone. Again, this performance is little better than many subsistence communities, who often work surprisingly short hours in providing food.

Energy and land: the world

Figure 4 compares energy inputs and outputs per unit of land area for a wide range of farming systems across the world. The areal unit is the hectare-year averaged over a long period so that fallow periods as well as double or triple cropping are allowed for: for example, where land is used only one year in 10, as in many slash and burn systems, the inputs and outputs are given as one tenth those during the cropping year. Soil and climatic differences have not been corrected for.

On this broad view a number of important relationships are apparent. The first, demonstrated by the subsistence crops (open squares), in which virtually all energy inputs are in the form of human and animal muscular work, is that hard work can provide large yields. The highest point of this group, topping all Western crop systems, is for traditional Chinese small-holdings of 230 m^2 with labour inputs of 7064 hours per hectare-year and outputs as rice and beans of nearly two tonnes of protein and 280 GJ per hectare-year. Much of the labour is for collecting dung for use as fertiliser, while the small-scale allows intensive weeding, double cropping, inter-cropping and application of the TLC (Tender Loving Care) factor.

The second relationship is the more familiar one between high output yields and large energy inputs in the form of fertilisers and mechanisation, represented by the Western crop systems (black squares). These crops (cereals, rice, potatoes and sugar beet) have energy yields of 30-80 GJ per hectare-year, or roughly three times higher than for most subsistence crop systems. Yet energy inputs, now over 98% from fossil fuels - are very much higher while there appears to be a marked tendency to diminishing returns.

The third important relationship is between the crop and animal systems. The UK farm and animal products (black circles) with their low energy yields but high inputs are the principle cause of the poor energetic performance of the UK agricultural sector, in which 85% of farmland acreage produces feedstuff for animals and only 13% provides food directly to people.

Table 2 exapnds these points by comparing the Energy Ratios for different food products and systems. As one goes from subsistence crop producers through industrialised crops, industrialised animal products and whole food systems, to the most energy intensive products such as winter-grown glass house lettuce, the energy ratio changes by a factor of over 30,000.

Energy and labour - the world

An important consequence of the high Energy Ratios of 'primitive' farming systems is that labour requirements for food supply are not abnormally high, despite popular mythology. What is often high is the number of people living on the land and dependent on agriculture, so that seasonal or year round unemployment and underemployment are high. For example, with a typical Energy Ratio of 25 a subsistence farmer need spend only two hours per day on average in order to feed a family of four having a combined food energy intake of 40 MJ per day. This figure is comparable to Western societies

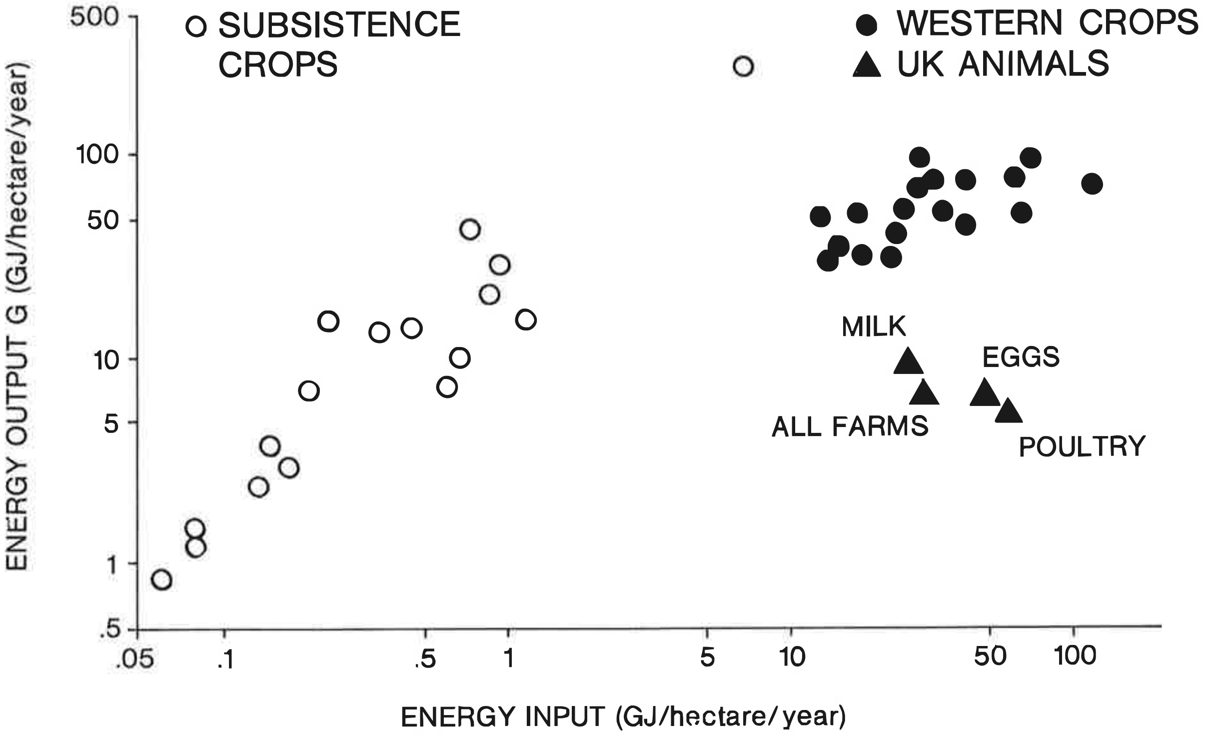


Figure 4. Energy inputs and outputs per unit of land – world farming systems.

To farm gate or dockside	$\frac{\text{Energy out}}{\text{Energy in}}$	Source
Chinese small holdings	41	
Tropical crops, no fuel inputs	13-38	
Tropical crops, some fuel inputs	5-10	
Cereals, UK and USA 1970	1.3-3.4	
Milk UK 1970	0.37	
Eggs UK 1970	0.14	
Poultry UK 1970	0.10	
Fishing fleets UK 1969	0.05	
Fishing, Adriatic 1970-71	0.01	
Prawn fishing, Mexico 1974	0.006	
Winter tomatoes, Denmark (134 MJ/kg)	0.004	Elbeck, 1975
Winter lettuce, UK (230 MJ/kg)	0.002	
All agriculture UK 1952	0.46	
1968	0.34	
1972	0.35	
USA 1963	0.87	Hirst, 1974
Holland 1950	0.91	Lange, 1974
1960	0.53	
1970	0.30	
Food system to shop door UK 1968	0.20	
USA 1970	0.15	Steinhart, 1974
Australia 1965-69	0.14-0.20	Gifford, 1973

Table 2 **ENERGY RATIOS (OUTPUT/INPUT) FOR WORLD FOOD SYSTEMS**

where roughly 25-30% of household incomes is spent on food and drink.

With fully industrialised crop systems the substitution of fossil energy for labour sends manpower productivity to very high levels of around 3-4,000 MJ of food energy produced at the farm gate for each man hour of direct farm labour. This is a remarkable figure: a typical hectare of cereals, yielding a net 4 tonnes of grain, can be ploughed, harrowed, sown, fertilised, sprayed and harvested for a mere 15-20 hours of direct labour. Yet equally remarkable is the way this huge gain is then dissipated in two ways. The first is by feeding much of the crop to animals and by concentrating directly on animal production. On average UK farms in which livestock accounts for more than 10% of the energy output the labour productivity is down to 50-170 MJ of food output per direct man hour. The second loss occurs in all the other sectors of the food system, which have largely arisen because high labour productivity has driven people from the country into the cities. As we have already seen, for the total UK food system the productivity is a mere 30-35 MJ/man hour, little more than the 25 MJ per hour at which we started.

This hint that 'progress' has closed the circle is underlined in Figure 5, which plots the man hours and energy input required to produce 1 GJ of food energy - enough to feed one average Westerner for about three months. The enormous drop in labour requirements as one advances through stages of civilisation from the Kalahari bushmen to the European or American cereal farmer with his massive tractors and combines and the consequent increase in energy input is most evident. So too is the climb back to higher labour inputs and even greater energy consumption as one passes up through the typical UK cereal farm (with some animal production), the bulk of UK farms with substantial animal outputs, ending with the entire UK food system.

The food-energy challenge

Figure 5 also raises the question 'where next' for the energetics of food production. Supposing that energy must be saved, how in broad terms might it be done ? The dotted arrows suggest several directions of change. One is to stress the route towards personal self-sufficiency and 'small is beautiful', exemplified by the home garden. But this appears to take us right back to the labour productivity of the Kalahari bushmen - though with the interesting difference that energy outputs per hectare are 20,000 times greater (Bushmen, 2.9 MJ; UK garden, 60 GJ).

My own guess is that a large number of relatively minor energy conservation measures are being and will be made that reduce energy use with only slight effects on labour requirements. These are suggested by the two arrows pointing to the left from the UK food system point. The changes include greater care in applying correct fertiliser quantities; a shift towards mixed farming with greater use of manures instead of (expensive) artificial fertilisers; a shift towards minimum tillage systems in which herbicide applications replace much tractor work; the reduction of extremely energy intensive products such as winter glasshouse vegetables (an EEC directive has requested this change); and better 'housekeeping' all the way along the line, especially in food processing, transport and storage. It is too early to say how rapidly these changes are being made or what effect they are having on the energy requirements of food production.

Nor is it obvious how useful energy analysis can be in effecting such changes. My own conviction is that energy analysis can be a powerful tool for studying macro systems, for looking at averages and broad swings and trends. It is of little use in studying the micro scale, Francis Bacon's 'minute particulars' on which most actual decisions are made. This is particularly true of farming, where variability of soils, terrain, management skills, markets and the like are so enormous that each individual farm is its own microcosm. Farmer A and farmer B, living only two kilometres apart, might benefit from a full energy analysis of their production systems and how they differ and how they might be altered to save energy. But they would benefit far more by a proper economic analysis which accounted for all factors of production, including energy. And it is on economic judgements that they decide how to act.

Because of this, in my opinion the most important role for energy analysis in the food

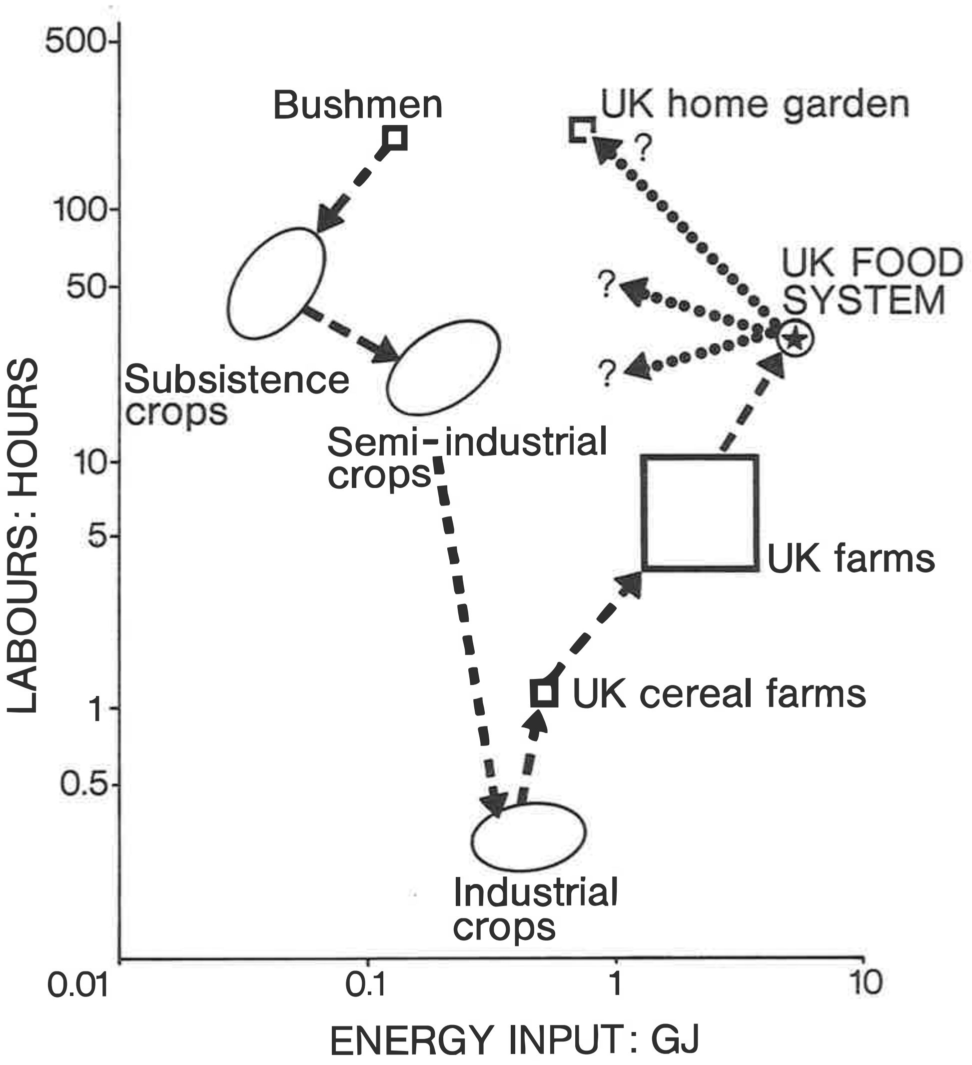


Figure 5. Energy and manpower to grow 1 GJ of food energy.

sector does not lie in making further and more refined studies of Western systems, where economic judgements dominate, but in searching out and testing entirely new ways of doing things: in looking at new types of food-energy system. And here the needs of the less developed world, with its two billion villagers, dominate all else.

To conclude, I shall give two simple examples of where energy analysis offers important insights for these regions.

Consider Table 3, which shows how energy is used for food-related activities, including cooking, in six typical Third World villages (Makhijani, 1975). Several striking points are apparent. Total energy use is comparable to that in the West but (Mexico excepted) almost none of it is derived from commercial fuels. This of course makes a nonsense of all those graphs comparing countries by their (commercial) energy consumption and GNP per capita. Most of the fuels consumed are precious biological resources - dung as fertiliser, crop wastes as manures or animal feeds, wood as ecological capital - whose over-exploitation has, literally, brought civilisations to their knees in the past and in many regions today is causing alarming environmental threats. Thirdly, the biological energy sources are used with extremely low overall efficiencies. With draught animals the conversion of fuel to useful work is about 3-5% compared to 25-30% for a tractor; similarly with cooking, where wood and dung stoves have a useful efficiency around 5% compared to 20-25% for a gas or electric stove.

What these villages need is more useful energy in the form of work to till the fields or pump irrigations water and heat for cooking and lighting. Normally this is not available because the efficiencies of energy conversion are so low, the local biological sources are limited, and imported commercial fuels and electricity are too expensive. A prime need, therefore, is to find cheap and socially acceptable ways of harnessing the energy that is locally available by using it with higher efficiencies. In turn this means providing (storable) energy which can be used efficiently - for example, gas or liquid hydrocarbons, or electricity - by converting local materials.

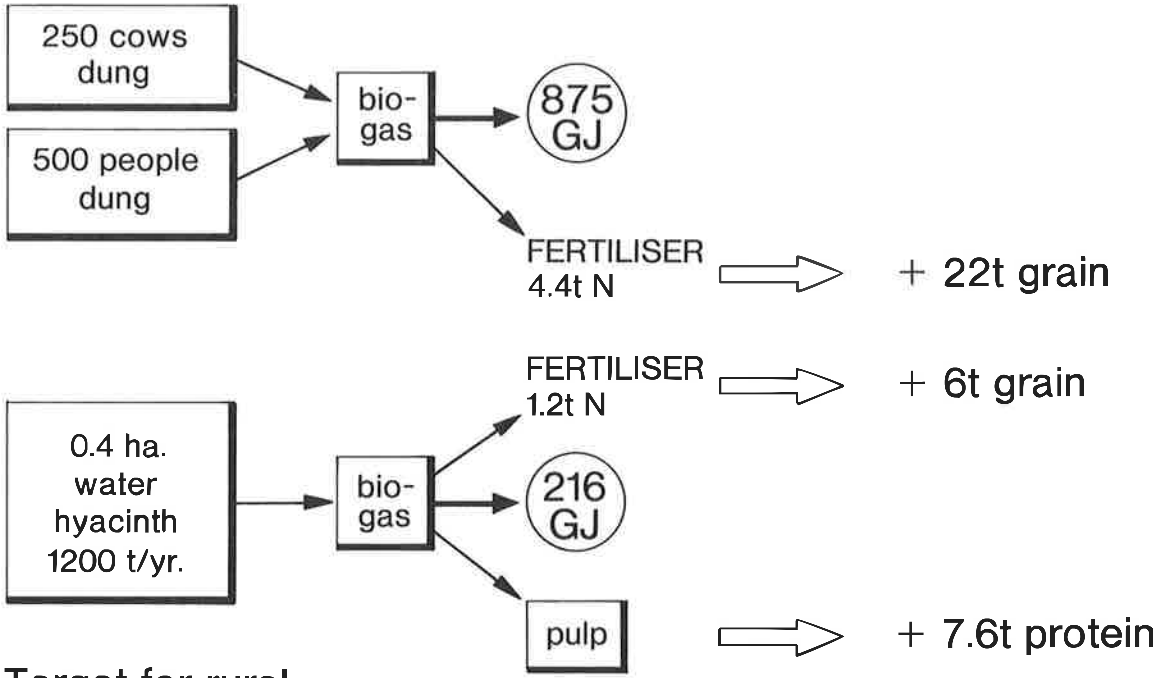
My second example, illustrated in Figure 6, shows one of many schemes now being examined in India for doing just this (Prasad, 1974). The system is for a 500-person village and assumes the all-India average of 0.5 cattle per person. Apart from providing fertiliser and vegetable protein equivalent to an extra 28 tonnes of grain plus 7.6 tonnes of protein per year for the village, and improving health through an effective sewerage system, the bio-gas plants provide a total 1091 GJ of gas, or nearly eight times as much energy as is now targetted for by rural electrification schemes for villages of this size. While this energy amounts to only 2 GJ per person it should allow a much greater end point efficiency of use and thus does approach the figures for wood and dung shown in Table 3.

Where energy accounting is needed in schemes of this kind is to establish the energy inputs to secure the outputs: for instance, in harvesting, transporting and perhaps fertilising water hyacinth. It is also needed in a more positive role to look at the increases in agricultural production that could come from having more available energy to spend in the fields. There is an exciting prospect here of stepping on to an upward-moving food-energy escalator, as more energy produces greater biomass outputs and greater biomass outputs are converted to still more useful energy.

However, once again one must stress that energy accounting help only one aspect of the problem, just as energy provision is only one aspect of the whole development process. The village which takes advice from an energy analyst who recommends the most energy efficient system and then finds that it is the one most easily controlled by the local landlord or moneylender would not be grateful.

	Gross GJ per capita			
	Wood, dung	Men, oxen	Commercial fuels	Total
India	4.2	11.1	0.2	15.5
China	21.1	8.5	3.6	33.2
Tanzania	23.2	3.2	–	26.4
Nigeria	15.7	3.8	–	19.5
Bolivia	35.4	14.1	–	49.5
Mexico	15.1	11.4	38.9	65.4
(UK food system			33.6	33.6)

Table 3 **ENERGY USE FOR FOOD NEEDS IN SIX THIRD WORLD VILLAGES**



Target for rural electrification 137 GJ

Figure 6. Renewable energy system for 500-person village in India.

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Energy analysis of transportation systems

Ir. E.J. Tuininga
Special Studies Group TNO
Apeldoorn
The Netherlands

Ladies and Gentlemen, I guess Gerald Leach could not have given a better introduction to me, as I must admit that I feel somewhat on the wrong place here. My own work is in a field of analysis that goes much wider than energy alone.
Harvey Brooks has written, about a year ago, in "Science" an article on the question "are scientists obsolete?". Nowadays there is discussion all over the world about the influence of policy on science, called 'science policy', but what we are talking about today is the influence of science on policy, called 'policy sciences' or 'policy analysis'. I am engaged in social assessment of technology, which is a scientific tool for policy analysis. Now I have been asked by TNO to talk about energy analysis, which can be considered as another tool for policy analysis, so I fear I may be not as objective as you would like me to be. Many of these policy analysis tools came up in the last ten years; to name a few, system analysis, then cost benefit analysis, PPBS and some others. A couple of years ago technology assessment appeared and these days we talk more about energy analysis. As Harvey Brooks has said, one of the fundamental questions on the role of science is: "what use does science have for policy decisions?". We are together here to discuss a scientific tool for policy analysis called energy analysis. I will try to convince you that energy analysis is useful, but especially when it is part of a framework of broad assessment of the impact of technological developments. That is why I said I could not have had a better introduction than that last sentence of Gerald Leach and of course the best thing for me was that he said it at the end of his talk just before I started mine.
I hope you do not expect me to go into the remark of Mr. Woodhead: driving one thousand kilometers takes the energy equivalent to 1250 panties, 9 shirts or 25 cubic meter of carpet. No, I am not going to give you that. What I would like to do is to have a short look at the energy required for present transportation systems and then to ask the question "how useful" (that is the question they alsways ask in Technology Assessment), "how useful is your tool?".
Actually, I will ask myself: "how useful are my own data?". Especially, going back to what our chairman Mr. Stuyt has said "are not these data too static, can we make them more dynamic?". We have looked at many sources for information on energy requirements of transportation systems and I must admit that the data are static. We did do some studies at TNO and most of the other data have been collected from the literature by Mr. Smit of the Centre of Energy Studies of TNO. So I am going to discuss:

1) Some background information.
2) Energy required for present transportation systems.
3) Can we make these data more useful.
4) Energy analysis as a tool for policy decisions in transportation.

1) Background information

The energy consumption of transportations systems has recently become a major issue. This sector is considered to be the one where energy conservation can be implemented with the least disruption. Conservation in this sector can have a significant impact as 28% of the EEC oil consumption (1972) goes to direct energy use in transportation, which is 16% of the total primary energy consumption of the community (in the USA the figure is 25%). (Table 1).
Although these figures may have changed somewhat in the last years they do indicate that transportations's share in energy consumption is considerable and that an energy analysis of this sector is important.

Generally the aim of energy analysis is to calculate how much energy is required to

produce a good or a service. This means for the transportation sector that we are interested in the energy requirement per passengerkm or per freight tonnekm. The energy requirements should comprise direct energy consumption as well as indirect energy consumption. The direct energy consumption is the fuel consumption of the vehicle, and indirect energy consumption is the energy sequestered in vehicles, infra structure and complementary services. So the energy requirement of a means of conveyance has the following components:
- vehicle construction
- vehicle fuel consumption
- vehicle maintenance
- infra structure used by the vehicle.

2) Energy requirement for present transportation systems

Since the oil crisis the amount of information on the energy consumption (direct energy use) of transportation systems has grown considerably. Even our own comparative survey for the EEC dated June 1974 (1) can be considered as outdated. But lagging very much is research into the total energy requirement (including indirect energy use or energy investment) of transportation systems. Two men have done most work in this field: E. Hirst of the Oak Ridge National Laboratory (U.S.A.) and N.D. Mortimer of the Open University (U.K.).
The following transportation systems have been studied by them:
- automobiles and trucks
- trains
- boats and planes.

As expected most information has been collected on automobiles and trucks. Information regarding the energy requirement of automobiles in the United States has been published by Eric Hirst (2); for the United Kingdom N.D. Mortimer investigated other means of conveyance (3, 4, 5). The conclusions of Eric Hirst have been summarized in Table 2.

In Table 2 the figures for production, retail dealers and maintenance are based on estimates of total expenditure. Total expenditures are converted into energy requirements by means of the energy requirement/sales ratios, that are known different components. Hirst gives no separate data about the infra structure and the construction of highways is represented by the vehicle tax that supports highway construction. Fuel consumption has the greatest share of all components as it accounts for about 60%. It is followed by maintenance etc. accounting for about 25%. Production and retail dealers are minor components from an energy point of view. The energy requirements for road and railway freight transport, marine transport and air transport that have been published by N.D. Mortimer also indicate that the direct energy consumption of the vehicle is the most important component. Infra structure accounts only for a relatively small part of the energy requirement (Table 3).

According to Mortimer there may be errors in his figures as a consequence of inaccuracy in the primary data used and the necessity to estimate some figures. However, as an indication of the order of magnitude of the various energy components in the transportation sector the presented figures will be helpful.
The main energy component in road freight transport is fuel consumption, taking about 60% of the energy requirement. The second component in size is vehicle production, about 25% of the total requirement, and infra structure and maintenance have each a share of about 10%.
The capital movements of railway companies can vary greatly from year to year. For British Railroad investment was low in 1968. So the energy requirement for capital will be underestimated in the 1968 figures. The main energy component is again fuel consumption, followed by maintenance. Data on the main component of energy consumption are given by the Association of the 9 railway companies of the EEC who in response to our comparative survey (1) give the following breakdown (1972).

Passenger trains:	
- express trains	0.50 - 0.73 MJ/passengerkm
- omnibus trains	0.98 - 1.21 MJ/passengerkm
- suburb trains	0.71 - 1.15 MJ/passengerkm
Freight trains	0.52 - 1.19 MJ/tonnekm

The figures refer to actual operative circumstances, but no indication is given about the exact load factors that were used to compute them. From other sources we gather that the load factor for passenger trains will be between 15 to 25% and at least 80% for freight trains.

Table 4 shows that the fuel consumption of the vessel is the main energy component in marine transport of passengers and freight. Construction is the second energy component in size if the typical voyage is long. When the typical voyage is relatively short, port facilities take the second place.

Table 5 summarizes U.K. data on planes. Fuel consumption is again the main component, 85-95% of the total energy requirement. Maintenance takes 2-5%. The infra structure component becomes higher when the flight shortens: the use of airport facilities is the same for short flights as for long flights as in both cases freight or passenger handling is needed twice while in the case of a long flight over a great distance these handling requirements are distributed over a greater number of miles.

In Table 6 all data mentioned on fuel consumption of various means of transportation are regrouped and compared with results from other studies (1).

The results of Hirst and Mortimer and the results of other studies (1) are roughly in agreement for road and railway transport. Mortimer's fuel consumption of aeroplanes seems rather low.

Table 7 gives the energy requirements for the several means of transportation as computed by Eric Hirst and N.D. Mortimer.

Note that an automobile in the USA requires more energy per passengerkm than an aeroplane does. Presumably fuel consumption per passengerkm of aeroplanes has been set too low in the computations and should be higher than the fuel consumption of US automobiles. As a result the energy requirement of aeroplanes rises, but would still be smaller than the specific energy requirement of automobiles. The reason for this is the relatively high energy components going into highway construction and into production, retailing and maintenance of automobiles.
It will be clear that several aspects might influence the data on energy requirement given here:

a) on the fuel consumption side:
   - load factor, e.g. if the load factor of automobiles drops from 40% to 30% the energy requirement rises from 5.10 to 6.80 MJ/passengerkm.
   - caloric value used in the study

b) on the other components of energy requirements, like vehicle production, maintenance, infra structure, etc.
   - conventions used to partition energy costs, as was mentioned in Dr. M. Slesser's talk. Most of the studies used here were completed before the IFIAS workshops.
   - system boundaries, what has been included in one study compared to the other, e.g. are the energy costs of labor included?

3) Can we make these data more useful?
As we have seen there is a wide range of conflicting data on the energy consumption, but the same can be said about the data on energy investment.

- Energy requirement of passenger car production in the USA:

Hirst (2)	125×10^9 J (1968)
Bullard and Heerendeen (6)	148×10^9 J (1967)
Berry and Fels (7)	133×10^9 J* (1967)
Tienway and others (8)	105×10^9 J* (1965-70)

* when using recycled metals this figure would be about one third part lower.

We checked these figures by recalculating the energy requirement for production and consumption, both for the European and the American situation, this has been done only for transportation systems.

a) European car (weight about 900 kg)

(1) production energy requirement, imported goods and capital goods excluded, of a car of Dfl 12,000 (prices of 1972): $12{,}000 \times 5.44 \times 10^6$ J = 65×10^9 J over a lifetime of 150,000 km — 0.43 MJ/km = 10%

(2) fuel consumption 10 km/liter petrol. 1 liter petrol requires 41.12×10^6 J so the energy requirement of fuel consumption = — 4.11 MJ/km = 90%

(3) production + fuel consumption — 4.54 MJ/km = 100%

Remarks:
- 5.44×10^6 J/Dfl 1.00 is the ratio for the transport vehicles industry in the Netherlands 1972 (9).
- According to Roberts (10) the production energy requirement for a passenger car is 64×10^3 MJ (UK 1968).
- 41.12×10^6 J/liter petrol = 48.0×10^6 J/kg x 0.745 kg/liter x 1.15 (= 1/estimated efficiency of the fuel industry) (9).

- (1) is made up of the primary energy sources oil, coal and gas,
  (2) will consist principally of oil.

b) American car (weight about 1600 kg)

(1) energy requirement of vehicle production = 125 x 10^3 MJ over a lifetime of 150,000 km = — 0.83 MJ/km = 11%

(2) fuel consumption 14 miles/gallon = 5.95 km/liter 1 liter petrol requires 41.12 MJ* so the energy requirement of fuel consumption = — 6.91 MJ/km = 89%

(3) production + fuel consumption = — 7.74 MJ/km = 100%

* Hirst used a higher energy requirement for petrol production (45.67 MJ/liter) than customary in Holland (9).

c) Trucks

Mortimer (3)

(1) energy requirement of vehicle production — 0.61 MJ/tonnekm = 29%

(2) energy requirement of fuel consumption — 1.45 MJ/tonnekm = 71%

(3) production + fuel consumption 2.06 MJ/tonnekm = 100%

Truck, price Dfl 100,000 (1972)

(1) production energy requirement, imported goods and capital goods excluded, of a truck of Dfl 100,000 (prices of 1972):
100,000 x 5.33 MJ = 544 x 10^3 MJ over a lifetime of 400,000 (200,000) km 1.36 (2.72) MJ/km = 11(20)%

(2) fuel consumption 4 km/liter diesel fuel
1 liter diesel fuel requires 42.48 MJ
so the energy requirement of fuel consumption = 10.62 MJ/km = 89 (80)%

(3) production + fuel consumption 11.98 (13.34) MJ/km = 100%

Remarks:
- 42.48 MJ/liter diesel fuel = 44.5 MJ/kg x 0.830 kg/liter x 1.15 (= 1/estimated efficiency of the fuel industry) (9).
- the relative importance of production and fuel consumption is strongly dependent on the total distance the vehicle covers during its lifetime.
- the relative importance of production, computed by Mortimer seems, too high.

Two interesting conclusions can now be drawn:

1) The greatest component of the total energy requirement of a transportation system is fuel consumption:
   - for cars close to 60%
   - for trucks at least 50 - 60%

   For railways there are only a few reliable figures, but fuel consumption will not be lower than 50 - 60%. For boats and planes this is between 80 and 90%.

2) For road transportation the principal fuel source is oil products, the same goes for boats and planes.
   Railway systems are often fueled with oil products (diesel engines) but also by other primary sources (through electrical traction).
   The production of these systems can be based on different primary energy sources like oil, coal or gas.
   This makes comparison of the energy used for production and consumption difficult and loweres the possibilities of energy analysis as a tool for energy policy.

4) Energy analysis as a tool for transportation policy decisions
As we have seen in table 6, the literature on energy consumption of present transportation systems in general and of cars in particular contains widely conflicting data.

The range of uncertainty is far larger than the 15% shown before for energy investment in the production of these systems.
One can question the usefulness of an energy analysis of policy changes regarding present transportation systems. To substantiate this statement we have analysed the energy impact of several trends in the production and development of automobiles in Europe. We did look at the possibilities of using energy analysis in determining the energy input of a change from the petrol/otto engine combinations to new fuel/engine combinations. Some information is also given on the energy impact of some trends in the development of passenger cars.

a) European passenger car: shift from petrol to diesel.
   (1) Let the price of the diesel car be Dfl 3,000 (prices of 1972) higher than the price of

the petrol car, the production energy requirement should be then 3,000 x 5.44 MJ = 16 x 10^3 MJ greater.

(2) the energy requirement of fuel consumption of a European car is 4.11 MJ/km
the diesel car has a 15%* lower fuel consumption 3.50 MJ/km

0.61 MJ/km

(* dependent on chosen calarific values of petrol and diesel fuel)

The extra energy investment in the diesel car is payed back in energy terms after $\frac{16 \times 10^3}{0.61}$ = 26,230 km, after 1 3/4 years (15,000 km/year).
Advantage over a car lifetime of 150,000 km = (150,000 - 26,230) x 0.61 MJ = 75 x 10^3 MJ, 25% greater than fuel consumption per car per year (= 15,000 x 4.11 MJ = 62 x 10^3 MJ).

b) European passenger car: shift from petrol to petrol-methanol fuel
petrol (for data, section 3, sub a):
(1) production 0.43 MJ/km

(2) fuel 4.11 MJ/km

Petrol methanol:
(1) production (same car and engine) 0.43 MJ/km

(2) fuel consumption 9.5 km/liter
1 liter requires: 0.85 x 41.1 MJ + 0.15 x 34.7 MJ = 40.14 MJ
So the energy requirement of fuel consumption = 4.23 MJ/km

Remarks:
- in this example methanol is made from coal which is an alternative policy option if oil is scarce. Natural gas is not likely to be used to make methanol as the policy of the Dutch government is to preserve gas for high grade applications.
- 34.7 MJ/liter of methanol = 19.7 MJ/kg x 0.80 kg/liter x 2.20 (= 1/estimated efficiency of methanol production). For methanol made of oil or natural gas this energy requirement per liter methanol may be lower.
- in the case of petrol methanol fuel, the energy requirement for fuel consumption is higher than for the petrol fueled car, but the oil component is lower (3.68 MJ/km) as the remainder is based on coal.

c) European passenger car: replacing steel and iron by primary aluminium.
(1) Let 200 kg iron and steel be replaced by 100 kg primary aluminium. The production energy requirement should be then
100 x 92 x 3.6 MJ + 200 x 13.2 x 3.6 MJ = 24 x 10^3 MJ greater.

(2) The conventional car has a fuel consumption of 10 km/liter
so the energy requirement of fuel consumption is 4.11 MJ/km

The equivalent aluminium car has a fuel consumption of 10.7 km/liter (estimated) so the energy requirement of fuel consumption is 3.84 MJ/km

0.27 MJ/km

The extra energy investment in the aluminium car is payed back in energy terms after $\frac{24 \times 10^3}{0.27}$ km = 88,888 km = 6 years.
The advantage over a car lifetime of 150,000 km =

(150,000 - 88,888) x 0.27 MJ = 17 x 10^3 MJ,
which is the equivalent of about one quarter of fuel consumption per car per year.

Remarks:
- the ratio of the specific gravities of steel/iron and aluminium is 7.8 : 2.7 = 2.9 : 1, but replacing should be done in a ratio 2 : 1 to realize sufficient strength.
- specific energy requirements of steel and aluminium are based on P.F. Chapman: The energy costs of materials (Energy Policy, March 1975).
- replacing steel and iron by recycled aluminium will lower the production energy requirement because of the relative very low energy requirement of recycled aluminium; even a shift from recycled iron and steel to recycled aluminium will lower the energy requirement of production (-5 x 10^3 MJ).
- Mr. Altenpohl from Alusuisse mentioned a more dramatic advantage in replacing steel by aluminium in the Parisian metro (subway) cars. As a result the energy use decreased by something like 40%, probably due to the fact that these heavy vehicles have to accelerate and decelerate very often.

d) Petrol, methanol and diesel:

Petrol/stratified charge engine (Honda CVCC):

(1) Let the price of the stratified charge engine be Dfl 2,750 (prices of 1972, price of the conventional engine is Dfl 2,500). Then the price of the car with stratified charge engine will be Dfl 12,250 (price of the conventional car is Dfl 12,000).
Energy requirement of vehicle production =
12,250 x 5.44 MJ = 67 x 10^3 MJ over a lifetime of 150,000 km = 0.45 MJ/km

(2) Fuel consumption of stratified charge engine is 5% lower than fuel consumption of conventional engine = 0.95 x 4.11 MJ/km = 3.90 MJ/km

LPG/adapted conventional engine:

(1) Let the price of the engine be Dfl. 3,500 (prices of 1972). Then the energy requirement of vehicle production =
13,000 x 5.44 MJ = 71 x 10^3 MJ over a lifetime of 150,000 km = 0.47 MJ/km

(2) Fuel consumption is 5%* lower = 3.90 MJ/km

(* dependent on chosen calorific values)

- The LPG fueled car has a 4% lower power/weight ratio.
- Assumed is that 1/estimated efficiency = 1.15 holds for the whole oil industry.

Methanol (pure)/adapted conventional engine (methanol from coal):

(1) Let the price of the adapted engine be Dfl 2,750, then the energy requirement of vehicle production = 0.45 MJ/km

(2) Fuel consumption is 5.5 km/liter
1 liter methanol requires 34.7 x 10^6 J so the energy requirement of fuel consumption = 6.31 MJ/km

Above we summed the energy requirements of (1) vehicle production and (2) vehicle fuel consumption and we computed pay back periods in energy terms. We assumed in fact that the energy used in (1) and (2) is exactly the same. This is a first approach that does not give more than a rough insight. In a second and more refined approach one should consider that there are three categories of differences between (1) and (2):

- differences in the primary energy sources used (oil, coal, gas nuclear, hydro or a mixture)

- differences in the geographical origin of the energy
- differences in the period during which the supply of the energy is required (the energy requirement of production).

This shows one of the major problems of using energy analysis for policy decisions: one Mega Joule can be quite different from the other! Dr. Slesser has called this somewhat different when he said we should define Time, Place and Technology. We would like to add the quality of the energy to this list, which is especially related to the primary source the energy is made from.

e) New developments in design and production of cars

Production technology
In the mass production of a technology one can distinguish two criteria: economic and energetic. The difference between energy analysis and economic analysis is one of time scale. Berry (1973) has calculated the energy required to make an automobile in Detroit. Automobiles are made as fast as possible on the assembly line as this is the cheapest in terms of money or profit. Berry calculated that it takes 133×10^3 MJ to make a Detroit automobile of which only 20% is theoretically necessary. 80% of the energy expended was wasted because of the haste with which the production was carried out. Nowadays (especially in Europe) some of this haste is replaced by more socially acceptable group technology approaches. But the energy impact of these are not yet known.

New materials
The use of plastics in passenger car production will lower the weight of the vehicle and diminish the fuel consumption. For instance the weight of a glass reinforced polyester panel compared with an equivalent stiff steel panel is about 30 per cent less overall. Also in the interior of the car plastics can be used (dashboard, ceiling). Since the energy requirement of plastics is about 2-3 times the energy requirement of steel (48×10^6 J/kg) the replacement will not always lower the energy requirement of input materials. Fabricational power could be lower for plastics.

Safety
Stronger bodies will result in a better protection of the passengers and can be realised by using more materials or by using stronger materials. More materials: greater fuel consumption, greater energy requirement of production.
Stronger materials: greater energy requirement of production.

Automatic control and adjustment apparatus and safety-belts will only make the energy requirement of production slightly greater.

Emission
CO and CH emission can be diminished by a fuller combustion. This requires adaption of the conventional petrol engine, for instance the introduction of a stratified charge engine. This engine can use petrol without lead as fuel, so the lead emission is zero.
The NO_x emission will also be smaller, say one third part lower. The stratified charge engine will have a somewhat greater energy requirement of production and a somewhat smaller fuel consumption than conventional petrol engines have. Extreme reduction of NO_x emissions requires presumably lower pressures in the combustion chamber by which also fuel efficiency will be deminished.
Another low emission engine is the diesel engine which can meet roughly the same standards as the stratified charge engine does. The addition of 10-20% methanol reduces CO emission about 50% and reduces CO emission about 50% and reduces lead emission.
The noise emission could be reduced by placing the engine in a sound proof box.

This would make the energy requirement of production greater and would also lead to a greater vehicle weight and greater fuel consumption.

Other trends

The construction of a passenger car that can easily be recycled when its lifetime is over will require more energy in the beginning. But in the long run, when easily recycled materials are available, the energy requirement of production will become lower.

Better aerodynamics (drag coefficient) and infinitely variable transmissions need not cost much in terms of energy requirement of production and can yield a better fuel efficiency.

5) Energy Analysis of new transportation technologies

In many countries new technologies in transportation are being developed. They range from the electrical moped going 25 km/h to supersonic aircraft going 2800 km/h. Most of the developments in the new transportation systems are aimed at increasing speed. This has considerable impact on the energy efficiency as shown in Figure 1. These data refer to fuel consumption only. Amazingly little is known about the expected fuel consumption of such sophisticated new technologies as high speed trains, tracked air cushion vehicles (TACV), STOL-airplanes, etc. as manufacturers give scarce information. Data on the energy requirement for production of such future systems are, of course, completely unknown. A major part of the energy requirement for production will no doubt go into the propulsion systems, which e.g. for high speed trains up to 500 km/h may account for 60 to 70% of the total vehicle weight.

At these higher speeds, however, the fuel consumption rises with the square of the speed so energy requirement for propulsion will possibly outpace the energy invested in production by a considerable margin.

6) Conclusion

The major impact of all these new technologies in transportation will be in several other fields than energy, such as regional development, safety, noise and other environmental issues. As Gerald Leach has also said a wider assessment of these technologies is necessary and should aim at more information on the social, environmental and economic impacts. And as in transportation, technologies come very close to the users (public), this social assessment of technology will become an essential factor in decisionmaking.

The usefulness of energy analysis should not be overrated as was recently done by an article in Science (12) which stated "in energy analysis many environmental and social costs and benefits are internalized directly".

Especially in the field of transportation this is doubtful as the direct energy use (fuel consumption) dominates and the available data are conflicting.

However, energy analysis can play a role in this wider assessment process as it serves to show how other analysis (especially economic) often optimize isolated systems in the short term, while the total (transportation) system in the long term might become energetically less effective.

Acknowledgement

I am indebted to Wilfried Smit from TNO, Centre for Energy Studies, for his research efforts and comments. As said before, little work has so far been done on this subject, but Eric Hirst from Oak Ridge (U.S.A.) and N.D. Mortimer from the Open University do deserve a special mention for taking the first steps in this field.

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	primary energy consumption × 1Mtoe		whereof consumption of oil	
energy sector and losses	61.4	6%	31.1	5%
industry	273.7	26%	125.1	21%
transportation	167.9	16%	164.4	28%
residential/commercial	259.3	25%	146.5	25%
non energy use of oil	52.4	5%	52.4	9%
electricity generation	227.1	22%	68.9	12%
total	1,041.8	100%	588.4	100%

Table 1: **ENERGY CONSUMPTION IN THE EC 1972 (SOURCE: OECD: ENERGY PROSPECTS TO 1985)**

	1960		1968		1970	
Vehicle:	$\times 10^{15}$ BTU					
production	0.78	7%	1.05	7%	0.71	4%
retail dealers	0.77	7%	0.99	6%	0.82	5%
fuel (refining included)	6.75	59%	9.60	62%	10.79	64%
maintenance insurance and taxes	3.03	27%	3.95	25%	4.44	26%
total	11.33	100%	15.59	100%	16.76	100%
total in MJ/ vehicle km	12.62		12.54		12.20	

Table 2: **ENERGY REQUIREMENTS FOR AUTOMOBILES IN THE USA (2).**

	Road freight transport					
	industry		retail traders		professional road haulage	
	$\times 10^6$ kWht		$\times 10^6$ kWht		kWht/£	
Vehicle						
production	9,200	25%	2,750	25%	11.52	23%
fuel	22,900	61%	6,550	60%	27,53	54%
maintenance	2,800	7%	800	7%	3.41	7%
Infra structure:						
new buildings					3.08	6%
construction, maintenance and lighting of highways	2,600	7%	750	7%	5.51	11%
Total	37,500	100%	10,850	100%	51.05	100%
Total in MJ/ tonnekm					2.69	

	Railway transport	
	$\times 10^6$ kWht	
fuel	26,300	78%
maintenance	6,850	20%
net capital movements (vehicles and infra structure)	400	1%
use of highways (by BR road vehicles)	50	0%
total	33,600	100%

total splitted up

freight: 1.39 MJ/tonnekm (load factor 93%)

passengers: 2.99 MJ/passengerkm (load factor 16%)

Table 3: **ENERGY REQUIREMENT FOR ROAD FREIGHT TRANSPORT AND RAILWAY TRANSPORT UK 1968 (3).**

	freight transport					
	liquid tankers and dry bulk carriers		conventional break bulk vessels		short see mixed cargo vessels	
speed	15 knots		20 knots		about 12 knots	
load factor	50%		80%		80%	
typical voyage	6,000 miles		10,000 miles		500 miles	
vessel:	kWht/tonmile					
construction	0.003	5%	0.02	9%	0.012	2%
fuel	0.055	87%	0.19	89%	0.40	80%
maintenance	0.003	5%	no data		no data	
infra structure:						
port facilities	0.002	3%	0.004	2%	0.088	18%
total	0.063	100%	0.214	100%	0.500	100%
total in MJ/ tonnekm	0.14		0.47		1.10	

	passenger transport					
	conventional vessel		hydrofoil craft		hovercraft	
number of passengers	1000-3000		60-540		60-540	
speed	20 knots		50-56 knots		50-56 knots	
load factor			100%		100%	
typical voyage	400 miles		200 miles		200 miles	
vessel:						
	kWht/passengermile					
construction	0.03	2%	0.01	0%	0.01	1%
fuel	1.2	92%	2.40	93%	0.8	82%
maintenance	no data		no data		no data	
infra structure:						
port facilities	0.08	6%	0.16	6%	0.16	16%
total	1.31	100%	2.57	100%	0.97	100%
total in MJ/ passengerkm	2.88		5.66		2.14	

Table 4: **ENERGY REQUIREMENT OF MARINE TRANSPORT UK 1968 (4).**

	freight transport			
	long range turbo fans		medium range turbo prop	
load factor	50%		50%	
typical voyage	6,000 miles		3,000 miles	
aeroplane:	kWht/tonmile			
construction	0.002	0%	0.01	0%
fuel	5.9	94%	6.1	94%
maintenance	0.30	5%	0.3	5%
infra structure:				
airport	0.05	1%	0.10	2%
total	6.25	100%	6.51	100%
total in MJ/tonnekm	13.77		14.34	

	passenger transport					
	normal capacity long range turbo jet		medium capacity turbo jet			
load factor	55%		50%		50%	
typical flight	3,600 miles		1,000 miles		150 miles	
	kWth/passengermile					
aeroplane:						
construction	0.002	0%	0.002	0%	0.002	0%
fuel	1.40	97%	1.27	94%	1.27	85%
maintenance	0.03	2%	0.06	4%	0.06	4%
infrastructure:						
airport	0.007	0%	0.026	2%	0.17	11%
total	1.44	100%	1.36	100%	1.50	100%
total in MJ/passengerkm	3.22		3.04		3.36	

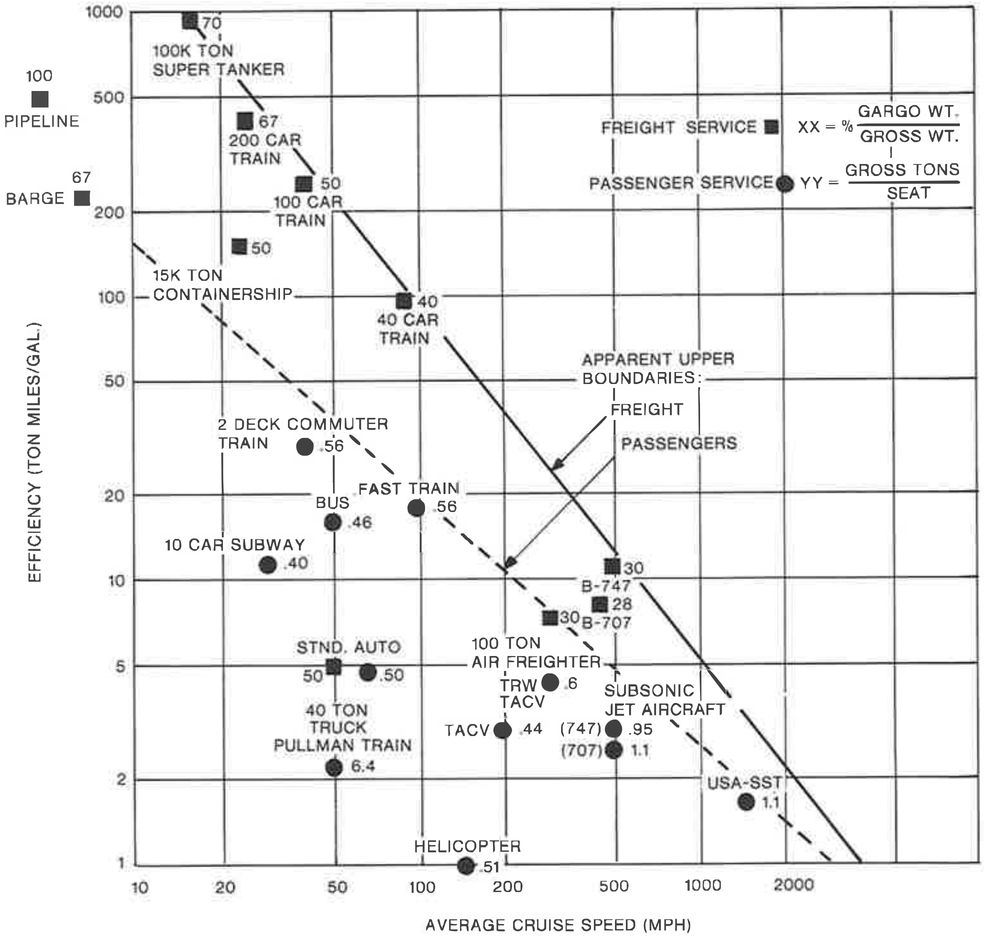
Table 5: **THE ENERGY REQUIREMENT OF AEROPLANES UK 1968 (5).**

			TNO survey	
	load factor	fuel consumption (refinery losses included)	load factor	fuel consumption (refinery losses not included)
passenger transport		MJ/passengerkm		MJ/passengerkm
automobile	ca. 40%	3.27 (US)	20-48%	2.01-4.77
train	16%	2.62	20-30%	0.65-2.43
vessel (hovercraft)	100%	1.75	—	—
aeroplane (medium capacity)	50%	2.86	49-50%	4.35-5.48
freight transport		MJ/tonne-km		MJ/tonne-km
truck	—	1.45	—	1.42- 1.76
train	93%	1.08	—	0.42- 0.84
vessel (short sea, mixed cargo)	80%	0.88	—	0.33- 0.48
vessel (big tanker)	50%	0.12		
aeroplane (medium range)	50%	13.48	—	15.28-24.79

Table 6: **FUEL CONSUMPTION ACCORDING TO ERIC HIRST AND N. D. MORTIMER COMPARED WITH RESULTS FROM OTHER STUDIES.**

	load factor	energy requirement
passenger transport		MJ/passengerkm
automobile (US)	ca. 40%	5.10
train	16%	3.35
vessel (hovercraft)	100%	2.14
aeroplane (medium capacity)	50%	3.04
freight transport		MJ/tonnekm
truck	—	2.69
train	93%	1.39
vessel (short sea, mixed cargo)	80%	1.10
vessel (big tanker)	50%	0.14
aeroplane (medium range)	50%	14.34

Table 7: **ENERGY REQUIREMENTS ACCORDING TO ERIC HIRST (2) AND N. D. MORTIMER (3,4,5)**



Reference: Rice [11]

Figure 1.

Energy Accounting of Packaging Materials for liquids and their transport viz bottles and pipes

Mr. A. Bolzinger
Shell Chimie
Paris
France

Like many other chemical companies, the Shell Group has been concerned by the drastic increase in the cost of energy and crude oil based raw materials.

Studies were carried out at the end of 1973 and beginning 1974 to compare the competitivity of traditional versus synthetic materials in the situation that crude oil costs had doubled and would possibly continue to increase at a high rate. The results of these published studies led to the conclusion that a drastic reversal of the past trend could not be expected. This was confirmed soon after by other large chemical companies.

The purpose of the present lecture is to explain the procedure which was followed in two specific studies concerning the comparison of plastics and natural/traditional products in the fields of bottles and pipes with particular reference to the French market.

Concept and Principles

The study aims to isolate the direct impact of oil/energy costs increases on the finished product costs.

Accordingly the only logical approach was to consider together the cumulative Hydrocarbon feedstock required, if any, and the cumulative process and transport energy through to the final user in order to obtain a "total energy requirement" for each product, this being expressed, as a common unit, in tons of crude oil equivalent (TOE).

Hydrocarbons converted or consumed in anyone petrochemical process have been debitted to the products of that process and no economic judgements on the relative value of co-products have been made, so that all co-products have been made equally energy bearing on a ton-for-ton basis.

This approach neglects both the short term fluctuations in cost/value (as seen in market price fluctuations) and the medium term financial cost/value (expressed as a profited manufacturing cost from existing or future plants).

However, if energy really is, or does become a scarce commodity then it is believed that "total energy requirement" is of use in comparing alternative materials and alternative applications. Such numbers can be considered as a long term equilibrium value of each material to society and the procedure applied as being more rapid than waiting for logic of market economics.

It is also worthwhile to recall that these studies were carried out during the period November 1973 through to January 1974 and that all figures given are related to that period. It is worth noting however that the method applied as described above is such that as long as the basic processes do not change, then the TOE calculated remain valid.

Table 1 gives energy relations used in the studies.

Bottles

. In order to carry out the study on representative materials it was necessary to determine those which were more commonly used on a large scale for making bottles. Table 2 illustrates the usage of different packaging material and demonstrates that PVC and glass were the major packaging media, and the more significative market of competition as being the mineral water.

It is also worthwhile to mention that the use of PVC in this field of application was significative, 115 000 T out of a total PVC consumption of 550 000 T. The same conclusion could also be drawn for glass.

. Material balances were worked out for both materials as described in the principles from crude oil through to the distribution. Figure 1 illustrated the energy/raw materials path for PVC bottles.

The same was done for glass bottles with taking in consideration one way trip bottles referred to as "disposable glass" and consigned glass bottles referred to as "returnable glass" for which we took a known number of trips of 20. Calculations were carried out for a unit quantity of 10 000 bottles.

The resulting total energy requirements are shown in table 3 which gives the TOE for the unit quantity and the equivalent for 1 T of PVC bottles.

. From TOE balances PVC appears to be always more competitive than disposable glass and doubts were raised for returnable glass which were investigated by mean of a complementary value study. The result of this investigation is given by table 4 in the form of the cost variation, calculated with the help of the TOE's, of one empty bottle to the utiliser, all costs being kept constant at their 1973 value except crude oil assumed to increase at selected levels.

From the table it can be noted that consumers have been paying 6 cts more the services rendered by the light disposable PVC bottles.

Any increase in oil cost at 20 $ per barrel was thought to be not significative in terms of added costs.

Pipes

. The same sort of market data analysis, as shown on table 5, selected PVC, cast iron, steel and asbestos/cement as being the major competitive materials in the significative field of water distribution pipes.

For the comparative study there was an underlying difficulty in that the pipe characteristics are dependent upon their required duty.

However two practical factors made possible the comparison.

First, the fact that Water Authorities have three classes of water distribution pressures (0 to 6 bars, 6 to 10 bars, 10 to 16 bars, one bar being 1,0197 kg/cm^2). The supplied pipe for any one class has to conform to the maximum limit of pressure of that class.

Secondly, the pipes are sold by weight, therefore any supplier seeks the minimum pipe thickness able to carry the max pressure load of the class, together with the diameter requested by the water flow.
As a consequence the study consisted:

First, to investigate in the pipes commercial catalogues the list of the proposed standard diameters in each class of pressure.

Second, to calculate for every case the weights of one meter pipe length.

Third, to rate in each class of pressure the so calculated unit length weights of the same diameter pipes, taking the corresponding PVC data as the unit value.

It was then possible to see, in each class of pressure, the standard diameters for which those unit length weights ratios were minimum between the PVC pipes and anyother raw materials.

By selecting for the study those diameters it was certain that if PVC was still competitive for higher crude oil prices, then it would be impossible to find anyother one for which PVC is uncompetitive.

Table 6 summarizes the results of this investigation showing in the class 0/6 bars the diameter 250 m/m as being the one for which the minimum unit length ratio exists between PVC and anyother raw materials selected for the competition.

The same diameter was found in the same manner in the class 6/10 bars and 125 m/m in the class 10/16 bars.

One ton of PVC pipes being taken as the unit in each of these three categories, the table also shows the corresponding length of pipes and the weights of the same length of pipes made from competitive materials.

. Material balances were carried out in the same way as for bottles covering PVC, steel, cement industries.

. Figure 2 gives as an example the energy track for the steel industry.

. Results are summarized in table 7.

Based on petroleum products costs currently applied end 1973 the energy (oil equivalent) values were calculated as shown in table 8.

Assuming the only variation to be the cost of crude oil, ratios of other relative values between crude oil derivatives being considered as constant, graphs have been drawn in order to compare PVC with each of the other traditional materials.

From those graphs it was concluded that steel and cast iron were competitive with PVC for 250 m/m/10 bars but never for the just following diameter 200 m/m in the same range of pressure, steel was competitive for 125 m/m/16 bars, asbestos/cement was never competitive in the range of diameters/pressures considered.

Furthermore, the energy related cost variation graphs show that in the case of an energy multiplying factor of 2, the maximum change in total cost will be only 10% an this, as expected, for PVC pipes.

Conclusion

From these studies, it is evident that the total energy cost factor in the materials considered was low-less than 10% in all cases - and is still relatively so. As a consequence, the direct impact of even drastic cost variation of energy taken in isolation do not have an effect on the final cost of the product such that this will become the decisive parameter in the choice of one material or another. Other parameters, such as technical necessities, marketing choices, industrial commercial practices and sometimes unfounded subjective opinions will be able to continue to exert their respective influences in the choice of the material for an application without the fear of making an appreciable energy error.

1 t. fuel equivalent to 11 t. steam
250 kg. fuel equivalent to 1 mwk
22 l. gas oil equivalent to 1000 t/m road transport
12 l. gas oil equivalent to 1000 t/m barge transport
7 kg. fuel equivalent to 1000 t/km rail transport*
* Average figure for the railway french state cy

Table 1 **ENERGY RELATIONS**

Prod. / Uses	Glass		PVC	Others*
	Return.	Dispos.		
Water	0.6	0.1	2.0	—
Wine	3.7	0.5	0.4	—
Others	2.7	1.1	0.5	2.0
Total	7.0	1.7	2.9	2.0

*PE,PE/cardboard CPXES, metal

Table 2 **FRANCE-YEAR 1972**

	T.O.E.	T.O.E. equivalent to 1 t. PVC bottles
PVC	0.58	1.7
Glass disp.	1.24	3.6
Glass ret.	0.34	1.0

Table 3 **RESULTS**

All costs, except crude oil, constant at 1973 value

Oil at	2-3$/BBL	10$/BBL	20$/BBL
PVC	16	18	20
Glass disp.	23	26	30
Glass ret. (20 trips)	10	11	12

Table 4 **COST OF ONE EMPTY BOTTLE TO USE** (French Franc)

1000 tons

	Total	Water distribution	Water distribution expressed as tons equiv. to cast iron
Cast iron	470	400	400
Steel	1750	55	70
Asbestos/cement	250	60	75
PVC	185	60	320

Table 5 **FRANCE-PIPE MARKET 1972**

Selected fields of competition by calculation		Calculated lenghts of pipe	Corresponding weights for (tons)			
			PVC	Steel	Cast iron	Asbestos cement
Diameters	Pressures					
250 mm	6 bars	110 m	1	3.2	4.75	6.45
250 mm	10 bars	75 m	1	2.14	3.16	4.28
125 mm	16 bars	200 m	1	2.3	3.96	3.76

Table 6 **PIPE DATE FOR COMPARISON**

T.O.E. of equivalent weights of pipes for same duty as 1 t. of PVC pipes

	Fields of competition		
	250 m/m-6 bars	250 m/m-10 bars	125 m/m-16 bars
PVC	1.6	1.6	1.6
Steel	2.2	1.5	1.6
Cast iron	2.4	1.6	2.0
Asbestos/cement	1.7	1.2	1.0

Table 7 **RESULTS IN VOLUME TERMS**

Costs of equivalent weights of pipes for same duty as 1 t. of PVC pipes (end 1973)

	Fields of competition					
	250 m/m-6 bars		250 m/m-10 bars		125 m/m-16 bars	
	Total: f/t	Energy:%	Total: f/t	Energy:%	Total: f/t	Energy:%
PVC	3140	9.7	3140	9.7	3140	9.7
Steel	4640	6	3100	6	3340	6
Cast iron	5220	6	3480	6	4360	6
Asbestos/cement	8000	2.8	5350	2.8	4700	2.8

Table 8 **RESULTS IN VALUE TERMS**

P.V.C. BOTTLES DIAGRAM

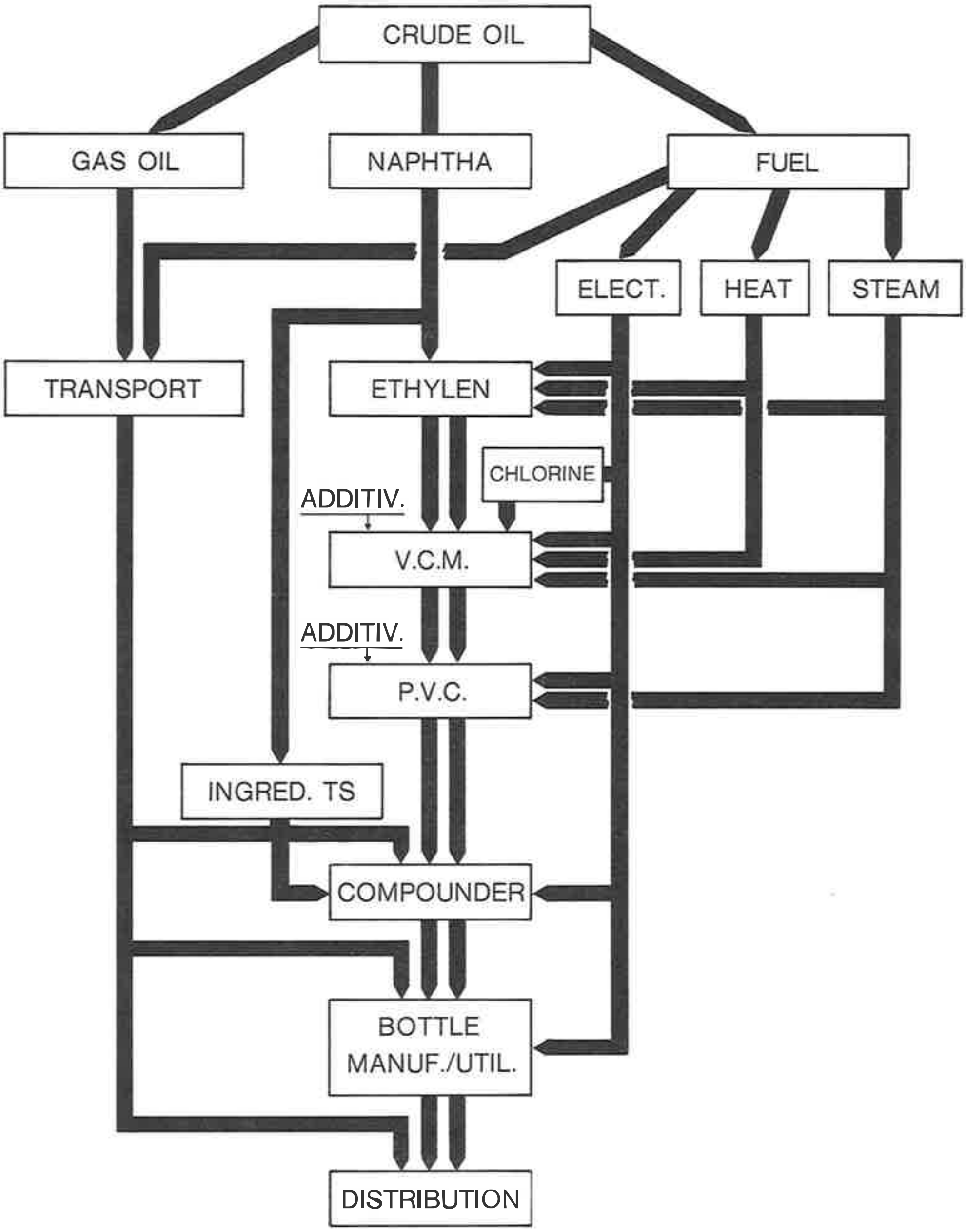


Figure 1.

STEEL AND CAST IRON PIPES DIAGRAM (EAST OF FRANCE)

DATA FROM IRSID

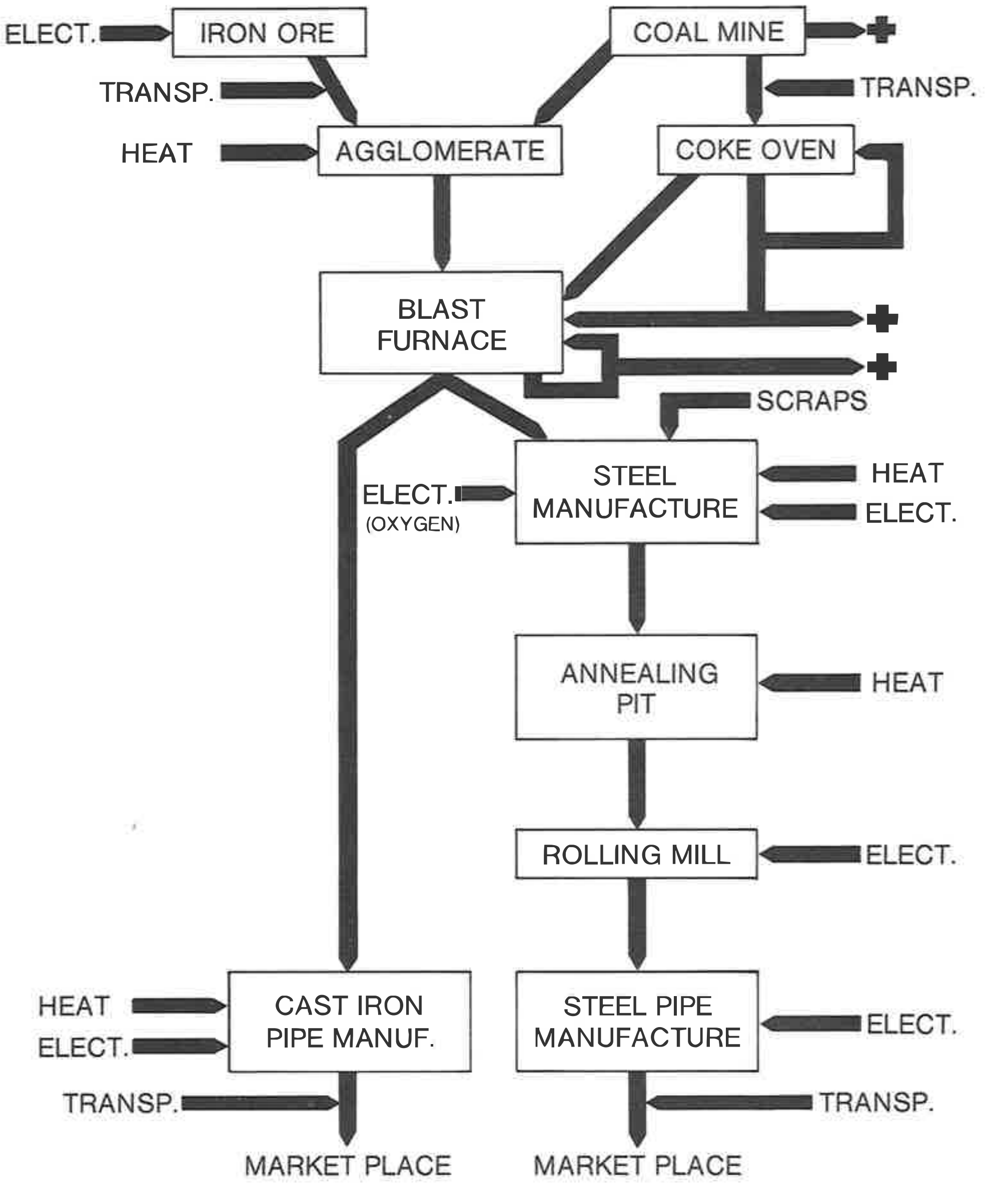


Figure 2.

PVC/STEEL

FF/T OF PVC PIPES COMPARED TO SAME LENGTHS OF STEEL PIPES

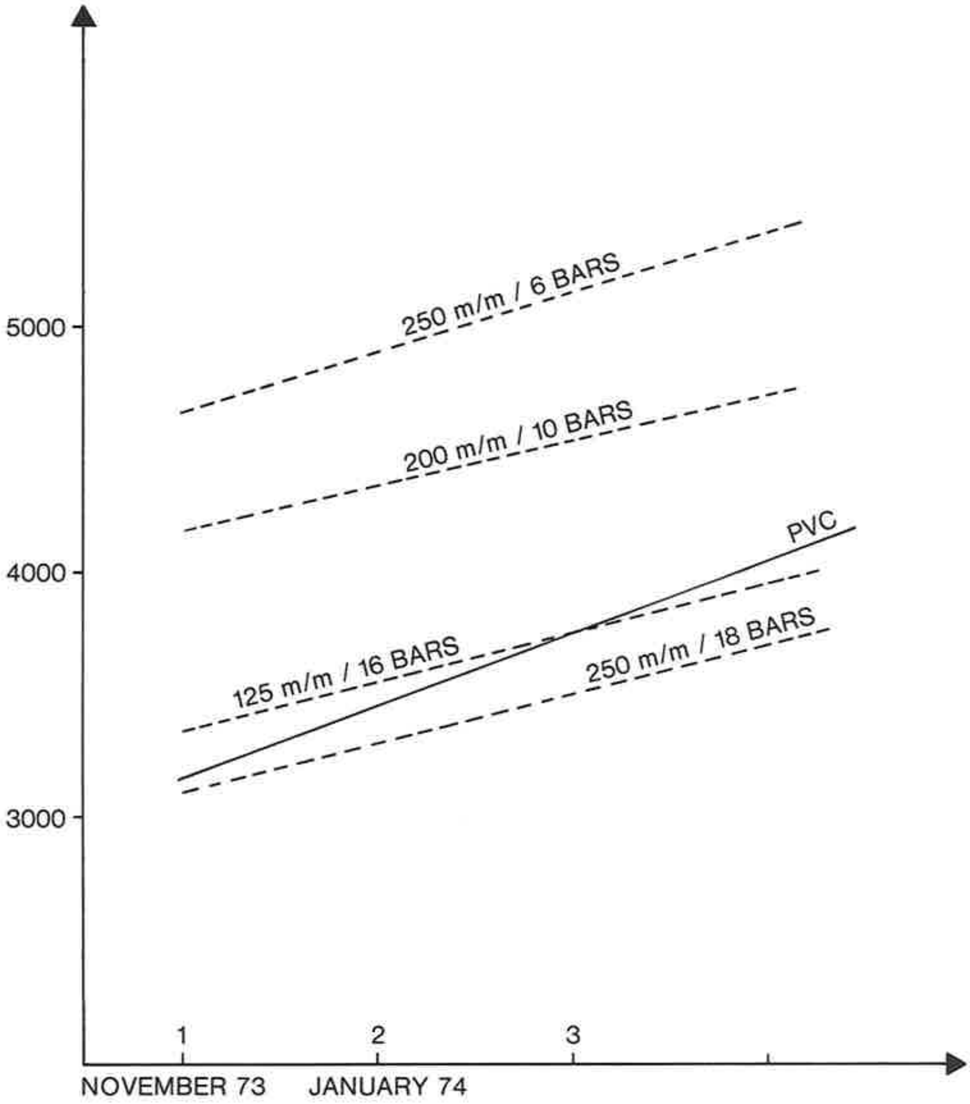


Figure 3. Multiplying factor for energy.

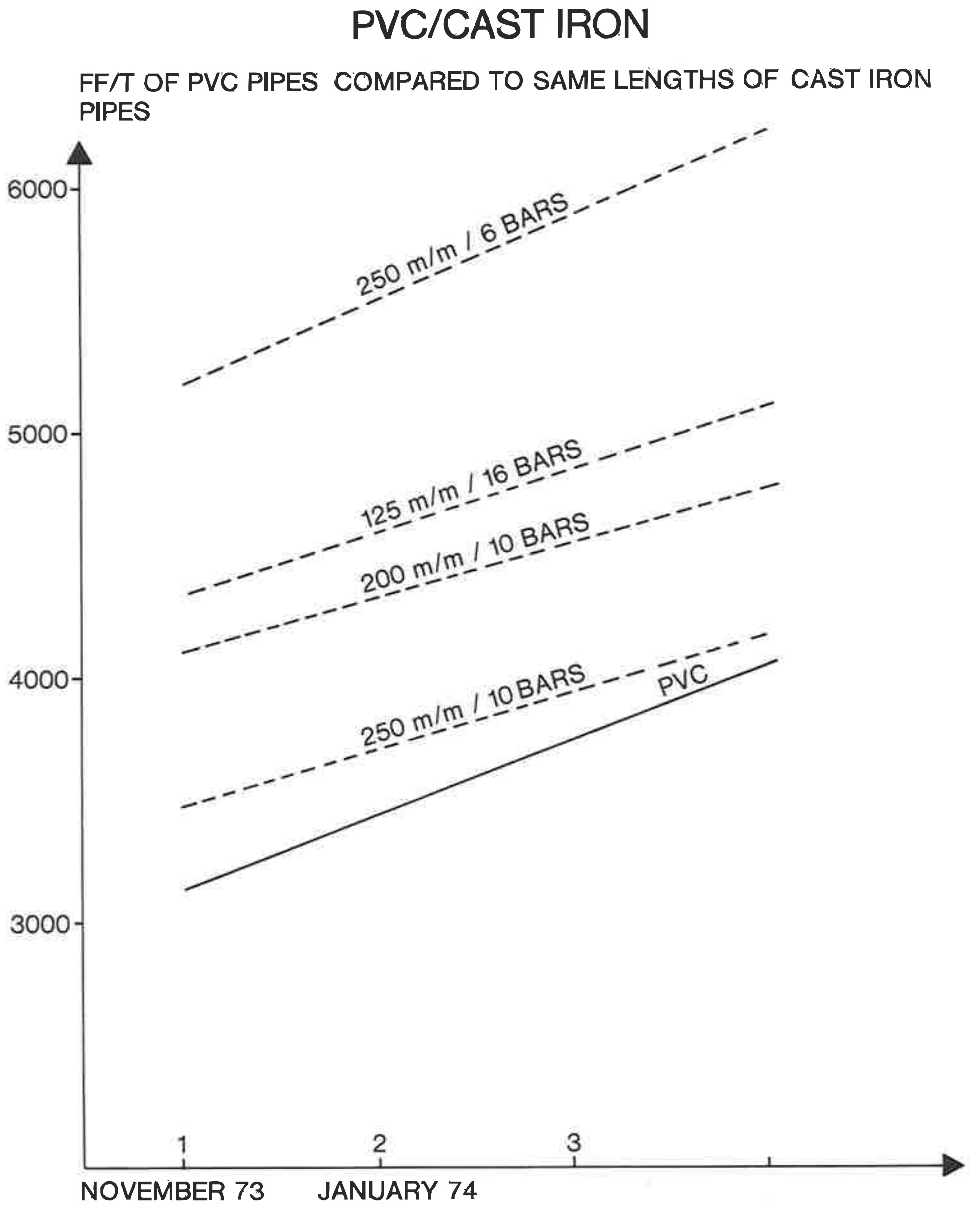


Figure 4. Multiplying factor for energy.

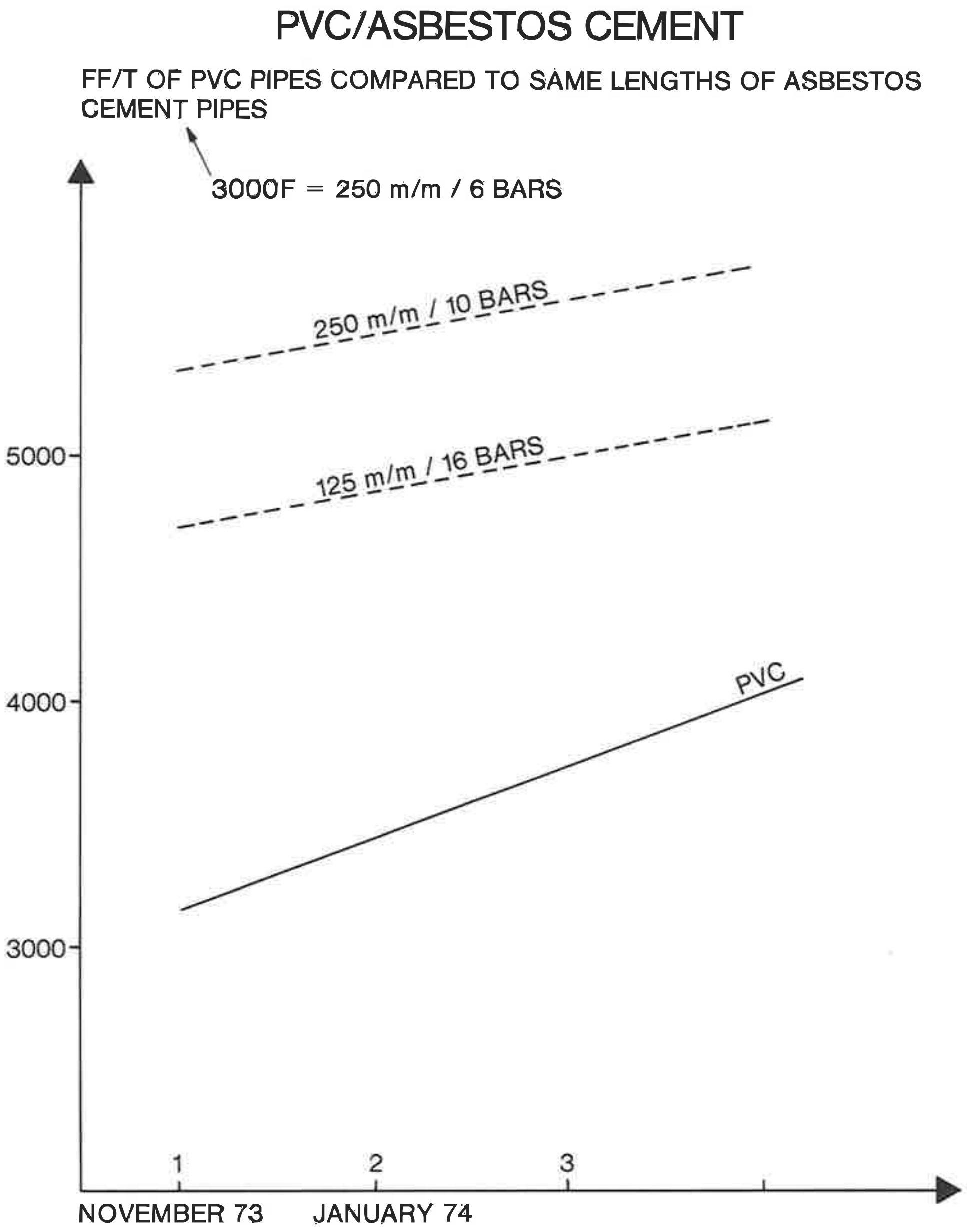


Figure 5. Multiplying factor for energy.

Energy accounting of steel

Dr. A. Decker
Director of Technology
Centre de Recherches Métallurgiques (C.R.M.)
Liege
Belgium

Introduction

"The question of fuel has always been of the highest importance in the making of steel, and one can boldly claim that, all other conditions being equal, its saving or its waste is sufficient to cause profit or loss for a plant" (1).

That was the first sentence of a paper entitles "Consumption and saving of fuel in iron and steelmaking" given by J.S. JEANS, Secretary of The Iron and Steel Institute at a meeting in Liege in 1882, ninety years before the energy crisis.

The question thus is not new and remains a permanent problem for the iron and steel industry. The steelmaker always establishes energy accounting just like Mr. JOURDAN, a hero of Moliere's comedy, made prose since ever without knowing it.

This industry is a big energy consumer. In 1974, its share in the world's total consumption was about 11%. In order to estimate this percentage, one must not forget that for that same year the world's steel production amounted to the enormous quantity of 710 millions tons.

After having shown in this paper the historical evolution of the energy consumption in the iron and steel industry, I shall distinguish between different steelmaking processes. This will allow to show that the iron and steelmaking processes are very sophisticated to assure the best possible yields. Recycling of steelscrap has here a very important influence which will probably still increase in the future.

As examples of energy contents it will be of interest to note those of some steel products like auto body sheets, structural steels for constructions such as bridges, buildings, etc. . . or simply tin-plate can.

It seems very difficult in the future to reduce very markedly the energy consumption per ton of steel in newly created steelplants, but the figure is quite different if one refers to the unit of product made.

For a matter of simplicity, alloyed steels are not considered in this study here. It refers only to bulk steels which make the greatest part of world's steel production.

Some historical facts

Fig. 1 shows an evolution in energy consumption for the making of pig iron during the last two centuries (1, 2). During a period of 175 years, the coal consumption has been reduced by about 16 times. The results are relative to the making of iron with lean ores. The situation was naturally much better with rich ores.

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(1) J.S. JEANS, Rev. Univ. des Mines, 1882. Meetings de mai et de septembre, p. 138 et suivantes.

(2) Rev. Univ. des Mines. Revue économique et statistique 1882, p. 536.

In order to show the variation over the past twenty years, I shall take as an example the evolution of the energy consumption in NIPPON STEEL during the last two decades per tonne of crude steel (fig. 2) (*) (3). The data of this figure confirm those of fig. 1 and leads immediately to the conclusion that the steelmaker approaches asymptotic results with the present conventional steelmaking processes, but also to the very important fact, that not only the total quantity of energy is of interest but also the type of energy: coke, fuel, oil, natural gas, kWh. Comments on that point will be given later.

The conclusion given for Japan is equally valid for the industrialized countries of Europe which always cared for energy saving.

Energy consumption in the iron and steelmaking processes

Without going into details it seems necessary to say a few words about steelmaking. It is necessary here to make a distinction between integrated and non integrated steel works.

The first type of plants, which produces about 80 % of the world's steel is based on ore, i.e. 75 % of the iron contained in the steel comes from iron ore and 25 % from scrap. There are several steps: sintering or pelletizing of the ore - which is generally a rich ore with 55 to 65 % Fe, reduction of the prepared burden in blast furnaces mainly with metallurgical coke to obtain liquid pig iron, refining of this liquid metal today mostly in basic oxygen furnaces with pure oxygen, teeming the liquid steel obtained continuously or discontinuously in convential ingot moulds, reheating and rolling one or several times to obtain the final product. As one cane imagine, the phase of the reduction of the iron ore, consumes the most energy.

In the second type of plant, liquid steel is mainly produced from scrap in electric arc furnaces followed by continuous or conventional casting, rolling and reheating as in the previous case. The phase which consumes most of the energy evidently is the electric arc furnace.

Besides these traditional ways, it is today necessary to take into account a new method of steelmaking. It concerns the so called direct reduction processes. Starting from ore, they produce sponge iron in various types of reduction furnaces. (Midrex, Purofer, Armco, Hyl, HIB, SL-RN, Krupp, etc.). This sponge iron is molten in electric arc furnaces with the addition of more or less scrap.

1. Whatever the final steel product it is necessary to look at these different routes and to compare them from the point of view of energy consumption in the iron and steelmaking plant itself, expressed in Gcal/t crude steel. As an example, fig. 3 represents schematically the classical route of the blast furnace and the oxygen blowing process to the level of liquid steel.

On the left hand-side, outside the box, are stated the requirements of each stage of the process and on the right hand-side, the surpluses exported. The central section inside the box, enumerates flow of materials and energy within the process itself.

In relation to the blast furnace, the choice of values has been based on the best current practice, namely the consumption of 470 kg of dry coke.

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(3) S. TOYODA. Transition of Energy consumption in steel production. Oct. 1974. IISI Munich.

(*) The steelmakers are accustomed to express the energy in kcal. For that reason kcal will be given as well as kWht or GJ.

The net requirements are given in the bottom left-hand corner of the figure. These quantities are 2,43 Gcal of thermal energy per tonne of liquid steel in terms of enthalpy of the fuels used plus 154+40=194 kWh of electric energy per tonne of liquid steel.

Similar calculations have been made for the best practices with scrap, in the electric arc furnace process, and the new direct reduction processes. Basic data are reported elsewhere (4).

Table 1 summarizes these results. A first difficulty appears when we try to make some comparisons: to express the energy consumption by a same unit. Which value is to be ascribed to electricity considered as a secondary fuel of high quality? In the ENSEC (4) study referred to and in a more recent IISI (5) study, 2000 kcal and 2500 kcal had been chosen respectively as energy needed for 1 kWh_e or 1 kWh_e = 2,33 and 2,91 kWh_t. Table 1 has been completed with the first assumption.

Considering table 1 arises two other remarks. Steelmaking from scrap needs three times less energy than steelmaking from ore. It has been assumed that steel scrap was not an energy bearer even if originally it was produced with energy. If we give a certain energy content to scrap should it correspond to a pig iron which needed 2 tonnes of coal, if the steel has been produced one hundred years ago, or only 500 kg of coke if it has been produced during the last decade from ore, or even only a third of that if the scrap had already been made from scrap. We believe it is correct to say that scrap is not more than an excellent iron bearer which needs little energy. It can be considered as super rich ore, unfortunately not too abundant. Some energy is necessary to collect and prepare scrap. This will be taken into account.

Which quantity should be chosen for the energy accounting of liquid steel?

One possibility is to take for the energy consumption in steelmaking a proportion between the one concerning the first and second route (the third one today has still a negligible influence) according to the relative productions of the two types of steel. However this is not completely realistic as an important part of the world's steel production is still made by the openhearth process which has not been considered here as it is obsolete, disappears more and more. Let me also mention that the energy consumption of this process is high.

If one has to choose for the years ahead, oxygen steelmaking and electric arc furnaces will share the steel production, and a ratio of 80/20 seems reasonable. This gives the last column in table 1.

2. The importance of the "type" of energy used has to be underlined here.
Already last century, BULL (6) suggested to produce some reducing gas from coal and to burn it in the blast furnace with hot air. Experiments in JOHN COCKERILL Works

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(4) The Use of Nuclear Process Heat in the Iron and Steel Industry Part II - A. Decker. Energy Consumption in Iron - and Steelmaking Processes - BNES - London - Nov. 1974.

(5) Energy consumption of the model plant - IISI Energy studies to be published.

(6) J. von EHRENWERTH. Oesterreichische Zeitschrift 1885.

in 1883 have allowed it to make 385 kg iron with 1.000 kg coke whereas, the normal operation without gas produced only 135 kg of iron with the same quantity of coke. These experiments show, that already at that time the objective was to reduce the coke rate in the blast furnace.

Today metallurgical coke coming from coking coals is still the most expensive fuel used by the iron and steel industry. This is the main reason why the permanent objective is to replace this costly energy by a cheaper one.

This tendency results in the partial substitution of coke by an injection of fuel oil or natural gas. That also partly explains the birth of new processes, like the direct reduction processes. Here the total energy consumption is higher as in the reference case we envisaged because electricity is a secondary fuel and natural gas has to be reformed into H2 and CO which also needs some energy.

This effort for substitution is only in its beginning stage. Here are to be mentioned the efforts made to develop new processes allowing to introduce greater proportions of non coking coals into the blend. Another way is to replace coke by a formed coke produced by the agglomeration of non coking coals. Let me mention here the Ancit, BBF-Lurgi, HNCP, FMC processes. These new techniques will go into industrial use in a more or less near future.

As an example, research is also being done to introduce lignite in some form into the iron and steelmaking process. As one knows, this could become interesting for an industrial area not to far from the mines (± 200 km for instance), like the one between Aachen and Cologne (W. Germany). At this site there are reserves of 55 billions tonnes of lignite. For an exploitation of about 100 millions tonnes per year, this gives possibilities for 550 years.

With the advent of nuclear energy, the steelmaker also looks at the possibilities to make use of this new source of energy either in the form of electric power or directly as process heat.

In other words, from case to case or from site to site, the energy situation of the iron and steel industries has different facets and is as important as the level of the energy consumption itself.

A point which may be of some importance is the place where energy is consumed. For example, the blast furnace burden i.e. the materials which have to form liquid pig iron could be mainly produced in units making partial direct reduction there where natural gas is plenty available (Arabia), use of the partially reduced material in blast furnaces, there where steel is produced (Europe). As fig. 4 shows, this way of operations could very strongly reduce the coke, i.e. the energy consumption in the European plant, where energy is less available. Naturally this procedure globally gives a much higher energy consumption per tonne of steel and seems to be a very expensive one.

3. The yield of the energy in the iron and steel industry is difficult to define.
The heat contained in the hot steel at about 1200°C is necessary to allow its rolling, but the residual heat after rolling is entirely lost. It could be partly recovered as some low grade heat. Strictly speaking, the yield of the energy equals zero.

One must consider as indispensable the heat needed for the chemical reactions (reduction of oxides), the heat necessary for the subsequent operations (in the hot metal, the product to be rolled, but not in the slag or in the sinter, the electrical energy for rolling and production of O2, etc.). Taking the ratio of these energies to the total heat consumption the yield is of 50 to 60 %. TOYODA (3) gives 55,4 % for the NAGOYA Plant of NIPPON STEEL. POTTKEN and BUHL (7) announce 58 % for KRUPP RHEINHAUSEN.

As an example, the thermal yield of the blast furnaces, including the hot stoves, is a record, as it is between 80 and 90 %.

Losses are thus mainly: the sensible heat of the different fumes, of the cooling water, of coke, sinter, slag, etc..

4. In table 1, the direct energy consumptions as primary fuels and electricity in the iron and steelmaking plant only have been taken into consideration. Some other energies outside the plant have to be considered here (Table II) (8) (9).

Each tonne of liquid pig iron produces as a by-product about 300 kg of slag. This slag may be entirely used for the cement industry, with a saving for this industry of at least 0,240 Gcal/t pig iron or 0,190 Gcal/t liq. steel. The steelmaking slag today has not yet found uses which can replace some energy, but research work is done in this direction. Taking these plus of Table II and the above minus of 0,190 Gcal/t into account, the difference per tonne of liquid steel amounts to 0,334 Gcal.

5. The steelmaker sells his steel as plate, strip, sheets, rods, reinforcing bars, etc. Each case has had a somewhat different energy consumption. Table III gives the results of these calculations per tonne of product and is based on Table I up to the liq. steel level and for the subsequent operations on the Model Plant studies of IISI (6), with again 2.000 kcal/kWh_e.

Taking into account the proportion between steel made in electric arc furnaces mainly from scrap and the classical route starting from ore through blast furnace and oxygen steelmaking, the values of Table III have to be decreased by about 15 % (column 4 Table I). This gives a fair idea of energy consumption for steel products. As a mean figure this makes about 4,5 Gcal/t product (5.270 kWh_t - 19 GJ/t product) for a product mix.

This result is not the actual mean figure of world's steelplants. As said in the beginning, the enrgy consumptions has been decreasing for 2 centuries, and each new plant has better results than the older ones.

The future of energy consumptions for steel products

As already said, the problem of decreasing the energy consumption in the iron and steel industry is very important, but the possibility of substitution of one type of energy by another is not less important.

In price figures, coke still is much more expensive per thermal unit than natural gas or fuel oil. Therefore the use of these products has been and is still very interesting. Processes are developed to make such substitutions possible.

One also looks for more energy independance, by using more atomic energy or lower grade fuels which are plenty available.

In addition to this trend of diversification, some energy savings are still possible in the iron and steelmaking industry, with regard to the figures given in this report. Some

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(7) H.G. POTTKEN und E. BUHL, Effects of the structure of a company on its energy economy with special consideration of the utilization of energy. Stahl u. Eisen 95 (1975) no. 3 - p. 9°.

(8) P.G. KIHLSTET. Royal Institut of Technology - Stockholm Sweden.

(9) ALBERNY et al. Irsid - July 1974.

studies are going on in this field. 5 to 10 % additional saving seems possible when having a practical possibility of using some low grade heat (for instance hot water or low pressure steam).

Progress in steel qualities or new grades of steel also has to be considered and will be very important and most promising for the future.

In order to be clear let me take an example: Deep drawing quality steels for car bodies have a yield strength of about 20 kg/mm^2 (28.000 psi, 196 N/mm^2) and a tensile strength of 32 kg/mm^2. The trend is now to use more resistant steels, with the view of lighter cars with the same resistance: cold strip with a yield strength of about 35 kg/mm^2 (50.000 psi, 343 N/mm^2) and a tensile strength of 54 kg/mm^2 and even more are now being tested.

The energy necessary for making both types of steel, the soft one and the more resistant one, is practically the same.

Some car builders envisage to use 100 kg of such steels/car by 1980.

The whole picture will then be completely different and the energy needed for one given use of deep drawing steel is reduced by 30 to 50 %. This trend is partly a consequence of the energy crisis but also of the desire for making safer cars.

The same reasoning can be held for structural shapes used for housing, bridges, ship building, etc. and also for tin plate products.

Bearing in mind savings of energy leads also to the desire of making products with longer lifes. Normal steels are not particularly resistant to corrosion. But, as an example, as long as the car user does not want his car for more than 5 to 7 years, this is not considered as a problem. It is not either a problem, if longer life times are needed: here zinc or aluminium coatings are of excellent help (galvanized steels, aluminium steels, etc.).

Comparisons between different materials

As energy is the "central point" of many discussions, the tempation is then to consider energy as the only factor and to compare the relative merits of different materials from this point of view.

Aluminium is assailed as being to big a consumer of energy. The aluminium makers answer by saying that for a given use, aluminium products need less energy than steel, and that on a long run, aluminium has a marked advantage in respect to global energy consumption till the end of the life of the products (10)(11)(12). Steel people disagree with such views (13). Comparing energy balances of some solutions made out of steel,

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(10) L'aluminium, facteur d'économie d'énergie dans la construction automobile, par A. GIRARD, mai 1974 - Rev. Aluminium, pp. 311-315.

(11) L'aluminium et les nouveaux défis industriels, C. GUIMARD - Revue de l'Aluminium - avril 1975.

(12) L'aluminium face à la crise de l'énergie - Rev. de l'Aluminium, déc. 1973 - pp. 639-642.

(13) Bilans énergétiques comparés, à mêmes services rendus, de solutions à base d'acier, d'aluminium ou de béton armé, par R. FORESTIER, O.T.U.A., mars 1974.

of aluminium or of concrete, they conclude by saying that "the energy needs of the solution based on steel are notably less than those based on aluminium or light alloys. Besides they compare favorably with solutions based on concrete, when taking into account the unavoidable phase of demolition of such constructions".

This controversy could become a long ping-pong match and probably would need a conference of several days to get a final answer.

In our opinion, this controversy is more of an academic nature. At first, the physical properties of the products to be compared are quite different and several variables have an influence at the same time: yield strength, tensile strength, flexion, compression, buckling, stability, fire resistance, fatigue, etc. Substitutions are not always possible.

One aspect is to look at the energy consumption. One could also look at the availability and the prices of raw materials or at the labor force which is necessary in each case.

This brings us inevitably to the question of price, which includes everything. If energy becomes scarce, it will automatically appear in its price and induce a shift from one type of material to another. This could eventually alter the competition between products.

A global view of the energy problem is also misleading. As already mentioned, the situation is quite different following it is possible or not to use high strength steel or for instance galvanized sheet in different uses. Each application is a different case and it seems not possible to generalize.

Conclusions

Some studies foresee that world's steel demand will amount to 1.140 million ingot tons by 1985. Independently of other fundamental problems such as the financing of investments or the availability of the needed raw materials, one sees immediately that the energy problem is not the least.

Taking this view point into account it seems that the direct reduction processes, followed by electric arc furnaces will not have a big future in our industrialized world as on one hand they still use 30 to 50 % energy more than the conventional blast furnace and oxygen steel making route and on the other hand natural gas is not plenty available on the continent. Only a few exceptions will appear for instance when using coke oven gas.

As the steelmaker did not wait the energy crisis to be interested by energy savings, he works daily on the means for decreasing the overall consumption as it is clearly shown since nearly two centuries.

This interest is materialized each time he has to buy new equipments or processes; he choses those consuming the less energy.

Reaching in the steelmaking processes themselves asymptotic limits, when the consumptions are expressed in energy per ton of steel (sheet, plates, structural steels, wire rod, reinforced concrete bars, etc.), much progress is still foreseeable when this energy is expressed per unit product made out of steel (motorcar, railway car, bridge, etc.). New generations of steel will make this spectacular in the future.

		BF/oxygen steel	E.A.F.	D.R. and E.A.F.	$\frac{O_2\text{ steel}}{\text{E.A.F.}} : \frac{80}{20}$
Electricity	kWh	194	460	731	
Natural gas	Nm^3	—	—	336	
Coke	kg	378	8	—	
Energy for coke making	Gcal/t steel	0,28	—	—	
Total	Gcal/t liq. steel	3,10	0,97	4,01	2,67
kWh_t/t liq. steel		3,600	1,130	4,660	3,110
GJ/t liq. steel at liquid steel stage		12,98	4,07	16,78	11,19

BF: Blast furnace - E.A.F.: Electric arc furnace - D.R.: Direct reduction

Table I- **ENERGY CONSUMPTION FOR LIQUID STEELMAKING BY SEVERAL PROCESSES**

	Mcal/t	Mcal/c.t.s.
Iron ore mining, crushing, grinding for magnetits and hematits (mean values)/t ore (8)	10,0	14
Coal mining/t coal	154,0	70
Transport 1000 km bulk carrier. 100.000t ore + 200 km train ore + 200 km train coal	45,0	80
Burnt lime (9)	—	75
Ferro lime (9)	—	85
Scrap handling and conditioning	60,0	200
		524

Table 2

1 tonne product	Gcal/t	kWh_t/t	GJ/t
Heavy plate	5,2	6.050	21,8
Hot strip	4,7	5.500	19,6
Cold strip	5,6	6.460	23,3
Tin plate	5,8	6.820	24,6
Galvanized sheet	6,0	7.020	25,3
Wire rod	4,6	5.310	19,1

Table 3 **ENERGY CONSUMPTION PER TON OF PRODUCT**

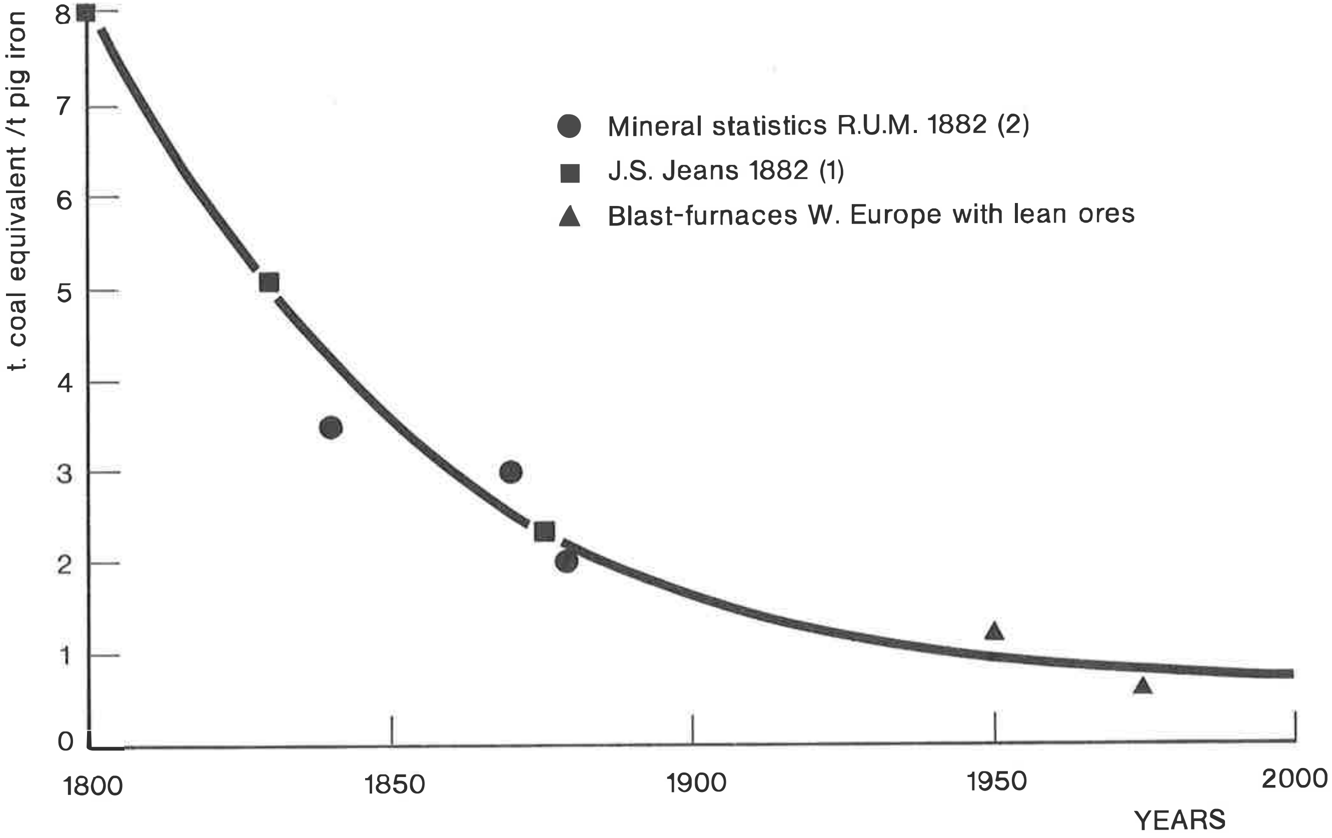


Figure 1. Evolution of energy consumption per tonne of pig iron.

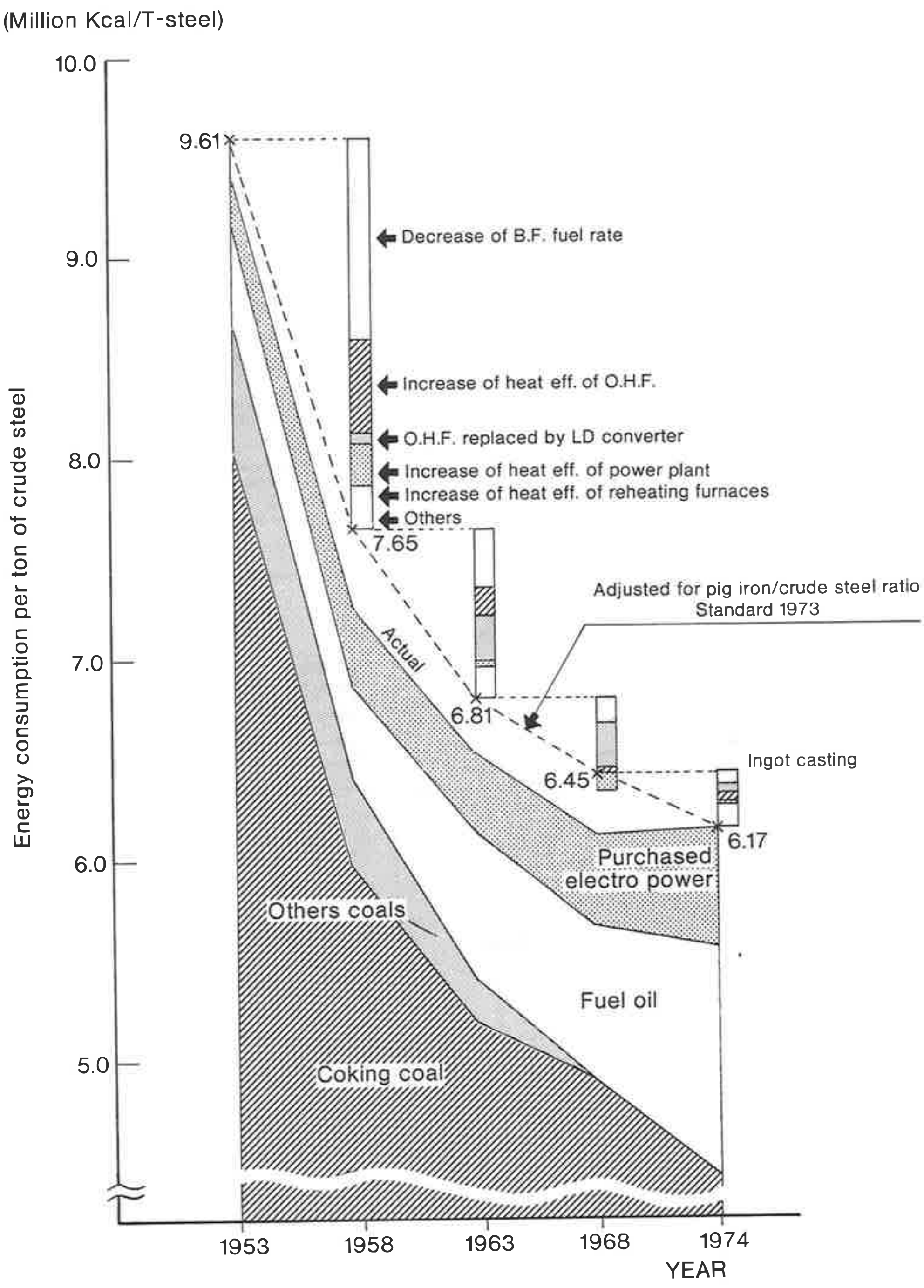
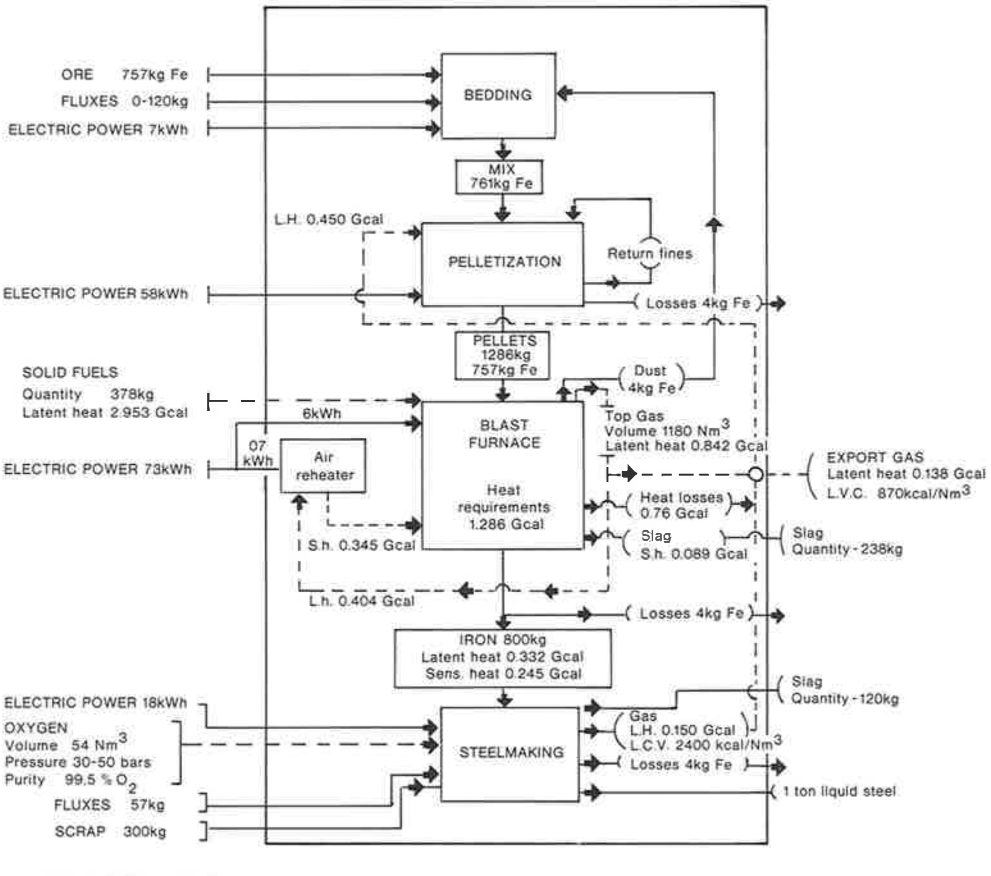


Figure 2. Transition of Energy Consumption per Ton of Crude Steel with Contributing Factors.



THERMAL ENERGY = 2.815 Gcal
ELECTRIC POWER = 154kWh
ELECTRIC POWER for high purity O_2 (0.75kWh/Nm^3) = 40kWh

Figure 3. Reference scheme (CRM).

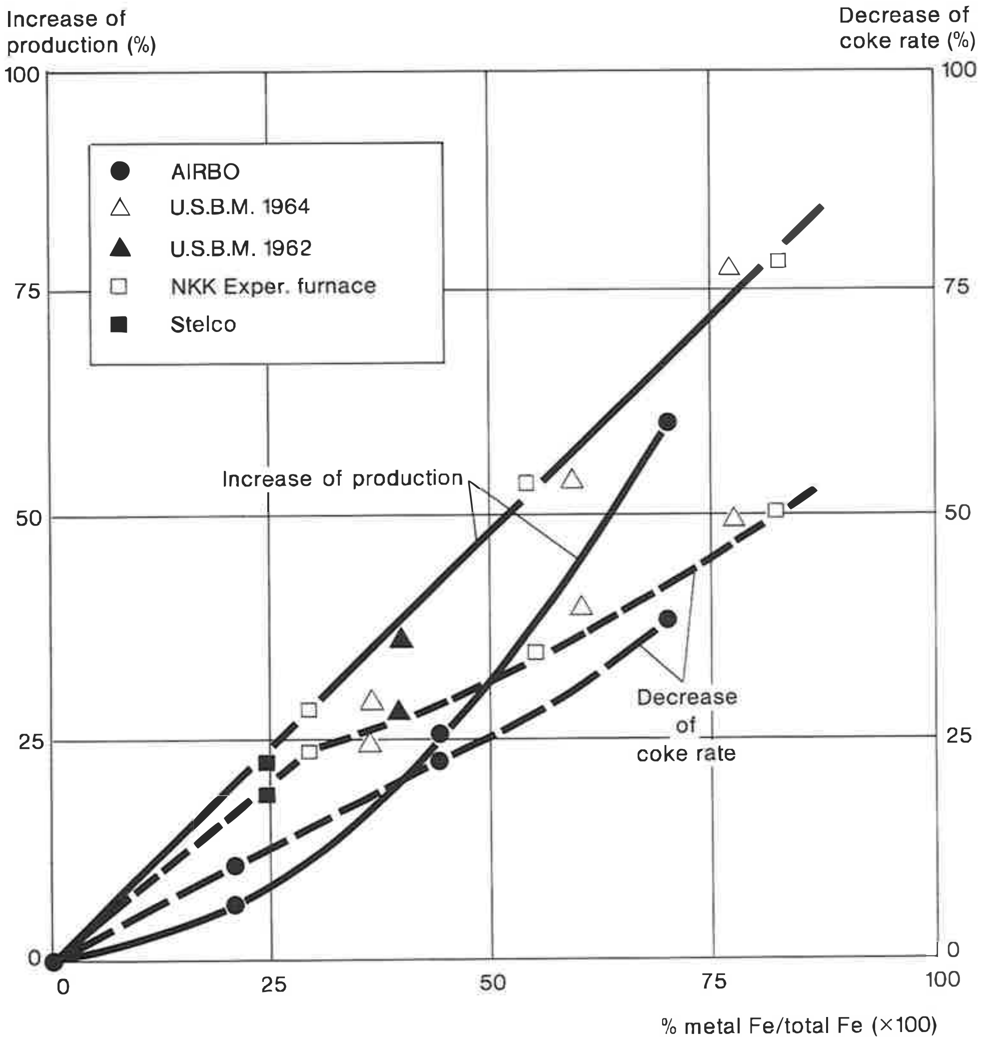


Figure 4. Evolution of the coke rate and of the blast-furnace production as a function of the metallic iron charged at the top.

Energy accounting of aluminium

Dr. D. Altenpohl, T.S. Daugherty and W. Blum
Swiss Aluminium Ltd.
Zürich
Switzerland

Introduction

Since the oil embargo and the increase in crude oil prices, there has been a growing awareness of "energy". Programs have been instituted for energy conservation and energy accounting is a current vogue. In any energy-analysis the complete life-cycle of the material in question must be taken into account. It is not enough to calculate only the energy requirements for the production of the material. Its "first use", re-use and recycling must also be considered and the energy needed to carry out those processing steps should also be included in any energy balance.

Figure 1 illustrates the life-cycle of an industrial material and/or product. For aluminium, the recycling step is very important because this step uses only a fraction of the energy required to produce the metal from its ore. Therefore, it can be seen that a comparison between materials is not valid unless total utilization is considered.

Production of aluminium

Published energy data for the production of aluminium shows large variations: from 13 to 90 kWh/kilogram of aluminium. The difference is not necessarily due to incorrect or erroneous calculations but stems from the different assumptions that are made, as well as whether only the theoretical energy requirements are considered or whether the energy actually needed to produce a product is taken into account. Many questions must be asked . . . and answered in an analysis, for example:

- What energy should be included in the calculation?
  - only the energy directly required in the processing or production?
  - the energy required to transport raw materials and the aluminium, and should the transport of supplementary material be included?
  - the energy requirements for the production of supplementary and process materials and products (petro coke, NaOH etc.)? Calculations of this type are especially difficult if the materials are produced in a process which results in more than one end-product, e.g., NaCl electrolysis: which portion of the total energy input should be charged to NaOH and which to Cl?
- How can the various types of energy be compared? The production of aluminium requires thermal energy (mainly for calcination of alumina) as well as electrical energy (mainly for electrolysis). How can these types of energy be compared and combined to provide an absolute number suitable for a total energy calculation?

  One possibility would be the direct use of physical conversion factors. This would probably be most appropriate for hydropower, where the energy potential can be practically only exploited in the form of electric energy. Where electricity is produced in thermal power stations, it would be probably be better to use a conversion rate of 3, i.e., three units of thermal energy to produce one unit of electrical energy. However since, world-wide, the aluminium industry is based on about 50 % hydropower, for general considerations a conversion factor of two would probably be more appropriate (the average between hydro- and thermal power electricity generation).

But even this calculation might have to be modified for local or regional considerations. One possible method is shown in the flow-chart (Figure 2).

Therefore, it can be seen that one major problem in energy accounting is the difficulty in comparing energy use when the energy is produced from different sources. Can a fair comparison be made between energy produced in a highly industrialized country as Japan (Figure 3), where due to a general scarcity of energy supplies, energy is generated to a large extent on the basis of imported oil, with for example, Canada or Iceland. In Iceland, there is ample hydropower and the population of the country would have difficulty in consuming all of its hydropower potential.

Certainly, similar situations exist in other regions which also form "electric islands". It may then be concluded that, in any energy analysis, specific assumptions must be made and defined, otherwise there van be no intelligent comparison.

In assessing the value of a material in a specific application, an energy analysis should not be the only criterion. Energy requirements cannot be looked at only statically. Past trends and future outlook should also be considered. For example, in the case of aluminium (Figure 4), the amount of energy used in electrolysis has been reduced considerably over the past decades through improved technology, and there is still the possibility of further reductions in the future. On the other hand, in the case of copper, the energy outlook is not too promising. Lower copper content of copper ores means that more and more energy will be required to win copper from its ores (Figure 5). Figure 6 gives data on conventional and unconventional mineral resources. The copper content of nodules of 1 - 1,5 % would be very attractive, as soon the nodules are available. Estimates for the time interval, when Cu and Ni from the Pacific-Ocean Nodules could have a measurable impact on world's metals supply vary between 5 and 20 years.

Aluminium products

Today, aluminium is the second most widely used metal in the world. There are many reasons for this. Aluminium has low density, high strength to weight ratio, good corrosion resistance and excellent thermal and electrical conductivity.

Transportation

One of the most advantageous uses of aluminium, in terms of energy effectiveness, is in the transportation field, especially where a mass has to be accelerated and decelerated frequently, as is the case in transit systems (Figure 7). Here the energy savings allow one to recover the additional energy that is required for the production of aluminium within a rather short period of time. In the case of subway cars it is only approximately two years. With busses, the energy can be recovered in about five to seven years.

Building construction

Aluminium's durability and resistance to corrosion greatly reduces maintenance. This makes aluminium very attractive to the construction industry. If one considers the effort and amount of energy necessary to protect many steel structures from corrosion, it becomes readily apparent that aluminium is a time and money saver as well as an energy saver. But one problem is, "how do you assign a value to such savings?" For example, how can the energy requirements for painting and maintenance of wooden and steel window frames about every three years be calculated so that a comparison can be made with aluminium frames that require almost no maintenance?

In addition, how does one assign a value to aluminium's use as a reflective insulator or a vapor barrier?

Packaging

Similarily in packaging, what energy value does one use for the protective properties of aluminium? How much is it worth to prevent foods from spoiling or provide longer shelf lives, not only for food, but also medicines? How can such an application really be expressed in energy terms? Aluminium is an absolute barrier to light and moisture and it can be combined with many new laminates which result in a product that combines aluminium's qualities with those of the companion material. One such product can be sterilized after filling which permits storage of perishable goods at room temperature, without refrigeration, which is an additional energy saving.

Aluminium recycling

Earlier, we mentioned the recycling of aluminium. Recycling is a very important consideration for energy calculations. Because aluminium does not deteriorate, it is readily recovered when a product outlives its usefulness. A real plus, for aluminium, is that the recycling process requires less than five percent of the energy originally used to make primary aluminium. The energy invested in an aluminium product can be used several times over, thus reducing the total energy needs of society. In addition, aluminium's high scrap value helps make the processing of municipal waste economic. This means that the more the public uses aluminium, in place of less recyclable materials, the more economical it becomes to recycle municipal garbage.

Conclusions

- In energy accounting or in energy calculations, we must always look at the full circle, from the ore to the final product as well as the re-use and recycling of a material. Only in this way can the true "cost" of any product application be measured.

  The energy needed to produce any material is only one criterion. "Total Energy Effectiveness", that is, energy costs throughout a materials' useful life must be taken into consideration.

- So called "energy accounting" is of limited value because so many assumptions must be made.

- Energy available in confined areas ("electric island" like Zaire or Iceland) is not commensurable with for instance electricity supplied in Eastern US, where brown out or black outs may happen.

- Therefore, only specific cases and/or applications should be analyzed and compared.

- In the final analysis, any materials usefulness must stand up to the criteria of cost, availability and performance and this should never be forgotten.

LIFE-CIRCLE OF AN INDUSTRIAL MATERIAL/PRODUCT

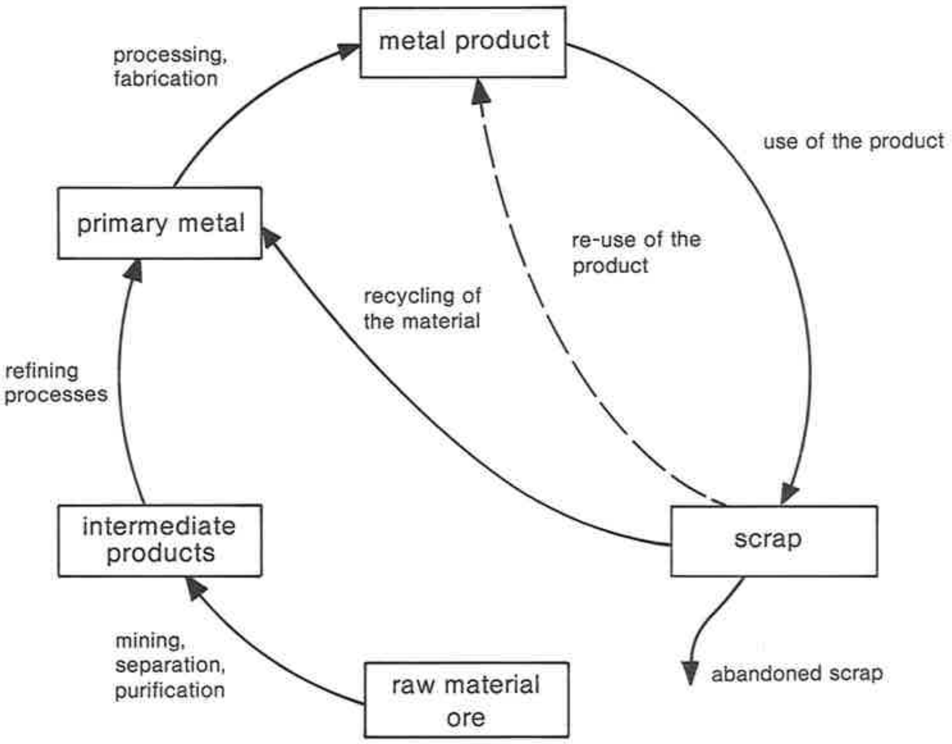
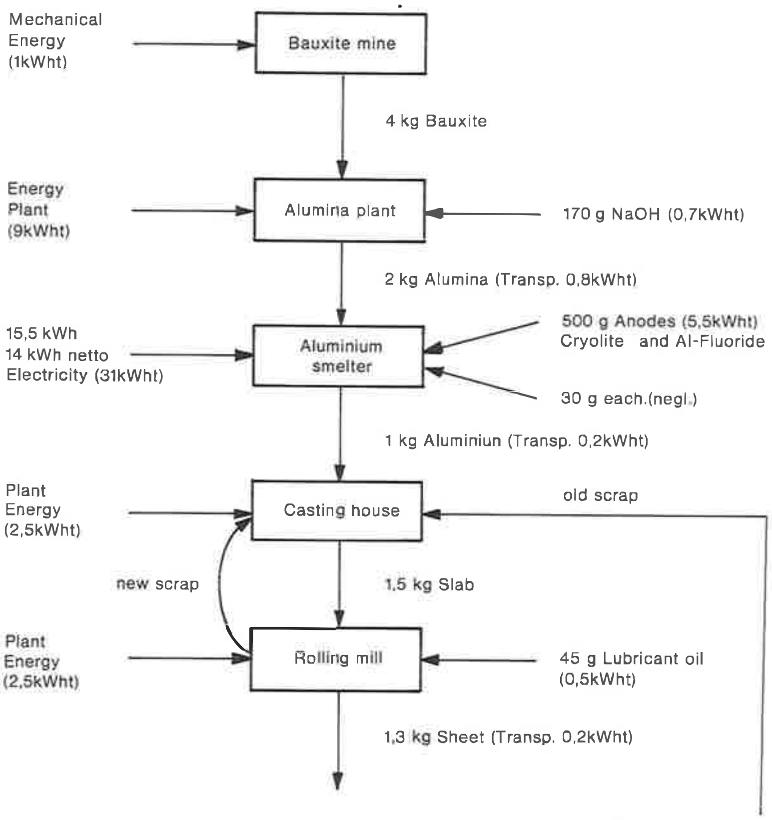


Figure 1.

POSSIBLE ENERGY – CHAIN FOR ALUMINIUM SHEET



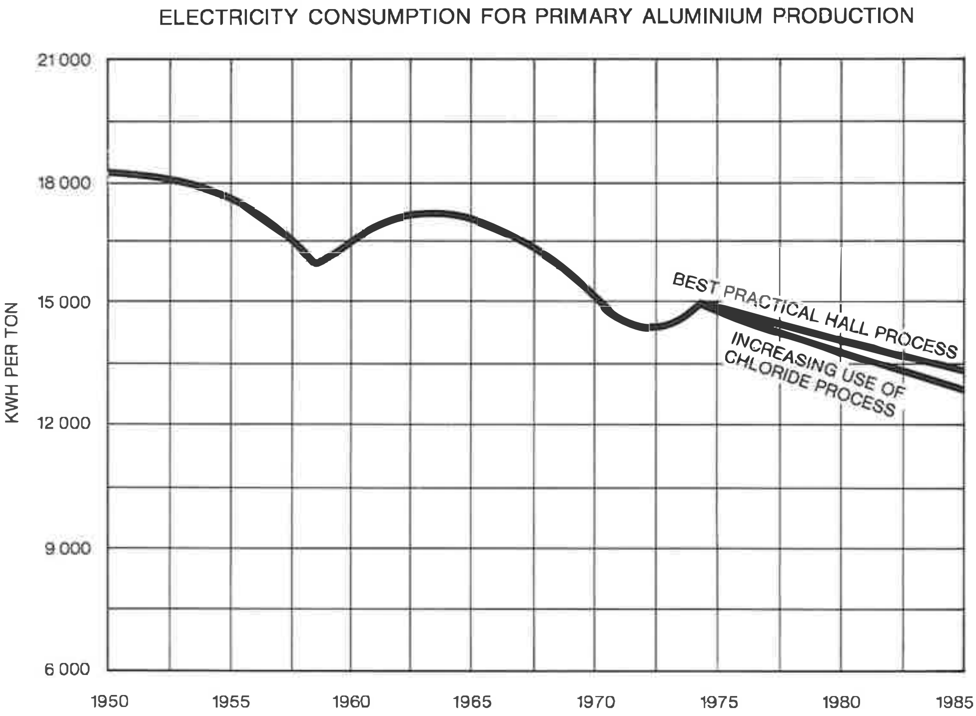
Source: D. Spreng, 1974

Figure 2.

	World	Europe	Japan
	%	%	%
Water	53	48	13
Coal	21	22	7
Oil	13	11	71
Natural gas	11	11	9
Nuclear	2	8	—

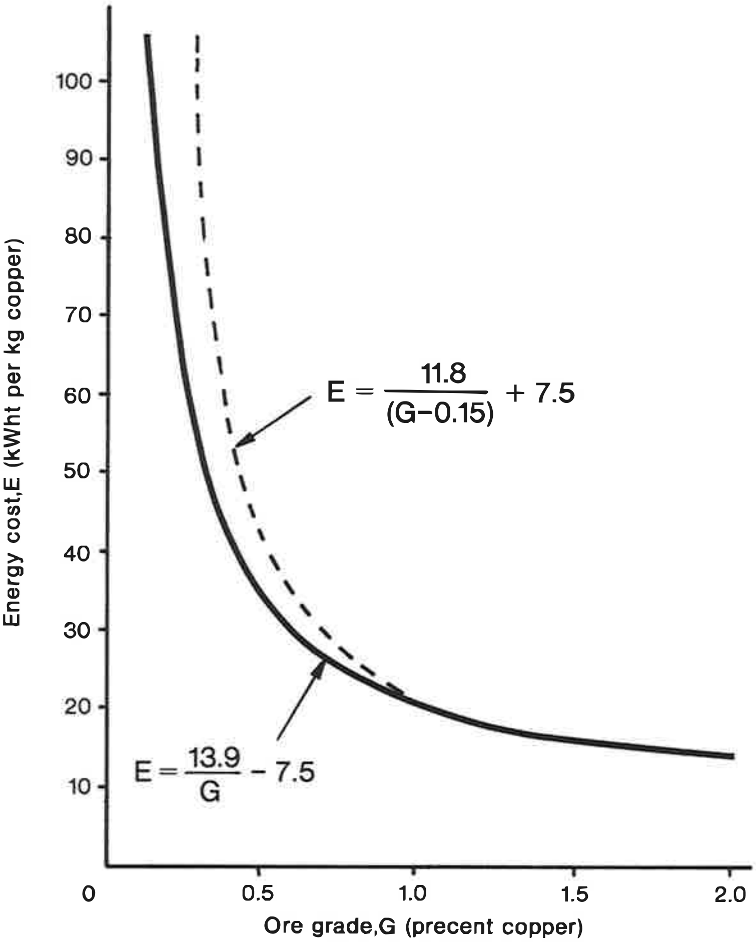
Source: Revue de l'Aluminium Febr. 1974

Figure 3 **ELECTRICITY SOURCES FOR ALUMINIUM SMELTERS**



Source: Gordian Ass

Figure 4.



Variation in Energy Cost of Copper with Ore Grade

Source: P.F. Chapman, 1974

Figure 5.

	Known Reserves in billon t	Production 1973 in billon t	Estimated Availability at P Constant Consumption in years
Iron	477	0,49	ca. 970
Aluminium in			
—Bauxite	ca. 3,6	12,6 Mio t	ca. 280
—Clay	400		ca. 30000
Copper in			
—Ores	0,308	8 Mio t	39
—Mn Nodules	ca. 12*)		ca. 1500
Nickel in			
—Ores	76 Mio t	0,586 Mio t (1972)	ca. 130
—Mn Nodules	ca. 10*)		ca. 17000
Coal	ca. 10800	2,3	ca. 2240
Crude Oil	220	2,8	79
Gas	200	1,0 (1972)	200

*) Estimates

Sources: C. W. Sames; OECD; Wirtsch.-Vereinigung Eisen und Stahl Ddf.; Jahrbuch für Bergba
Energie und Chemie 1974.

Figure 6 **WORLD'S RAW MATERIAL RESERVES 1973**

	Bus (Al-carosserie)	Railway car for grain	Subway car (without electromagnetic brakes)
Weight reduction by substituting aluminium for part of the steel (kg)	500	8 000	3 000
Additional energy requirements for the aluminium construction (kwht*)	51 400	120 000	90 000
Fuel or electricity savings per year (kwht*)	7 260	30 000	54 000
Number of years for energy savings to equal the additional energy requirements	7	4	1,6

*kwht = kilo watt hours of thermal energy

Source: D. Spreng, Dec. 73

POSSIBILITIES TO SAVE ENERGY THROUGH WEIGHT REDUCTION IN TRANSPORT USING AN "ENERGY-INTENSIVE" MATERIAL
Figure 7

Energy requirement of some energy sources

Dr. P.F. Chapman and Dr. D.F. Hemming
Energy Research Group of the Open University
Walton-Beltchley
U.K.

Introduction

Two reasons for considering energy are that it is an essential input to every production, transport and communication process, and, that it is non-substitutable. Any other input to a production process can, ultimately, be substituted or reduced to an arbitrarily low level, whereas there is a thermodynamically minimum amount of energy required to carry out any process. Energy analysis, then, is a systematic way of tracing the flows of energy through an industrial system so as to apportion a fraction of the primary energy inputs to the system, to each of the outputs of the system.

Energy analysis of sources of energy would seem able to shed light on the following:

(i) identification of possible energy savings in the energy industries which are themselves amongst the largest consumers of energy.

(ii) identification of feedbacks as indirect energies of material and capital inputs.

(iii) determination of the more favourable (energetically) of two possible energy sources (although there may be other overriding factors involved).

(iv) establishment of limits or 'points of futility' where no nett energy is produced.

(v) improvement of financial forecasting in evaluating the energy component of the fuel cost.

Since it embodies several of the other points, the latter will now be explored more thoroughly. As shown in Figure 1, the inputs to any production process can be described in terms of three factors; labour, capital (the cost of borrowing funds) and energy. One can then express the cost, C, of a product as

$$C = X_f P_f + X_c P_c + X_l P_l$$

where X_f = quantity of fuel (energy)
P_f = price of fuel (energy)
X_c = quantity of capital
P_c = cost of servicing capital
X_l = quantity of labour
P_l = price of labour

X_f is the quantity evaluated by energy analysis. It is possible to indicate a point of futility of sources of energy i.e. where for instance a barrel of oil is required from one source to produce a barrel of oil from another ($X_f = 1$). However, because of payments to labour and costs of servicing loans, the point at which a new source of energy becomes uneconomic will occur considerably before $X_f = 1$, depending on labour and capital intensities. On the grounds that even energy-intensive activities have about 10% of total costs in fuels, we estimate that at $X_f \gg 0.1$ problems may arise.

The methods available for energy analysis are statistical analysis, input-output table analysis and process analysis. The relative merits of all these methods have been discussed elsewhere [1]. Before considering some process analyses of energy sources, an overview of the energy industries of the U. K. (in 1968) can be gained from the results of a statistical analysis [2].

The data base for the analysis was the 'Report on the Census of Production 1968'. This publication documents all the financial transactions and, in most cases, the quantities of materials, energy, etc. transferred from one industry to another. It suffers from the disadvantage of being several years out of date, so recent developments such as the use of natural gas are not included. The energy supply industries form a complex interconnected system. For example oil refineries supply fuel to power stations which supply electricity to refineries. The refinery also supplies the fuel for the tankers used to deliver crude oil to the refinery. Every unit in the energy supply system takes an input from every other unit. The method used to calculate the 'efficiencies' of the fuel industries (defined as the ratio of total calorific output to gross energy requirement of inputs) involved the solution of a number of simultaneous equations (one for each industry) and the results are summarised in Table 1. This shows, for example, that to produce a MJ of a refined oil product requires a total of 1.13 MJ of primary energy.

The value of a statistical study of this type is firstly that it gives a consistent overview of whole sectors of the economy. The results obtained are also an essential input into what is effectively the first iteration of any process analysis. Thus one needs the statistical estimates of the energy requirements of fuels, materials, capital etc. (as a data base) before one can carry out a process analysis to obtain more detailed information. Process analyses of a number of energy sources will now be described.

1. Middle East Oil

Onshore oilfields in the Persian Gulf have the lowest total production costs in the world, and it is thus of interest to compare the net energy requirement of oil at the well-head in the gulf with that of other sources of both conventional and unconventional (synthetic) crude oil. It was decided to choose as a systems boundary, the point at which crude oil reached a refinery in UK, so that transportation costs from the Persian Gulf to Europe must be included in the net energy requirement. In this way one can directly compare Middle East and North Sea oil (where production costs are high but transportation costs are minimal).

1.1 Drilling

Specific data concerning Middle East drilling conditions is difficult to obtain, and since such factors as penetration rates, bit life vary not only from well to well but also within each well, representative data may also be difficult to define. However it will be seen that the net energy requirement to land a tonne of oil from the Gulf in the UK is not very sensitive to drilling data. For the purpose of calculation, the following average values (taken mainly from U. S. drilling data) have been assumed:

Average penetration rate 6m/hr while drilling
Average rig power 2000 h.p.
Downtime of rig - 50% of time on site
Completion materials as 25 tons casing steel, 20 tons cement/1000 ft of well
Weight of drilling rig ~100 tons

Using these figures, and data for net energy requirements of the required materials [5], one obtains an estimate of the process energy requirement for drilling of the order of 10,000 ± 2,500 MJ/m.

1.2 Exploration

Historical data concerning the quantities of reserves discovered in any year are published annually in such journals as World Oil and the Oil and Gas Journal. However, as

Warman pointed out [3] some caution is required in calculating an average finding rate since sources of error have arisen in reserve estimating in the past. These include ignorance of reservoir behaviour, inability to define the size of fields until they were fully drilled-up, misunderstanding and misreporting by both oil companies and governments. Warman suggests that the most meaningful results can be obtained by taking presently known reserves and dating these back to the year of discovery. Clegg [4] presents such data for Middle East oil fields from which one can estimate that in the ten year period from 1954-63 a total of 496 exploratory wells were drilled (average depth$\sim$3000 m.) to prove oil reserves of 119×10^9 bbls. Clearly the success rate will vary with time and for an earlier period of time it may well have been somewhat better as such huge fields as Ghawar in Saudi Arabia (1948) and Burgan in Kuwait (1938) had been discovered. From the figures above and using an energy requirement for drilling of 10,000 ± 2,500 MJ/m. one can calculate the net energy requirement of finding oil in the Middle East from 1954-63 as 0.88 ± 0.22 MJ/tonne.

1.3 Production

Once discovered and appraised an oilfield is drilled-up for production. Oil from a number of wells is then gathered and piped to a tanker terminal for shipment. Almost all fields in the Persian Gulf flow under gas pressure. From the production statistics published annually by the Oil and Gas Journal one can obtain data about the 'average' onshore Persian Gulf producing oil well. For the period 1950-63, the 'average' producing well was 1500 m deep from which oil flowed at a rate of 5000 bbls/day. This average includes fields such as Awali in Bahrain with a productivity of 325 bbls/day (1950-63) from wells 670 m. deep and such prolific fields as Kirkuk in Iraq with an average production (1950-63) of 13,400 bbls/day from each well of about 850 m. depth. Using the previous data and assuming a producing life per well of 25 years, the average energy requirement to produce oil in the Middle East is 2.30 ± 0.56 MJ/tonne varying from 0.50 ± 0.12 MJ/tonne in Kirkuk field to about 15.8 ± 4.0 MJ/tonne in the Awali field.

1.4 Transportation

From the well-head oil is transported first by pipeline to a deepwater terminal (say 50 km), and thence by tanker to Western Europe. Mortimer [6] gives the energy requirements of transportation by pipeline as being of the order of 0.78 ± 0.13 MJ/tonne-km. Mortimer also gives the energy required to transport oil by 250,000 dwt tanker via the Cape (18,500 km) as 1290 ± 130 MJ/tonne and by 45,000 dwt tanker via Suez (10,500 km) as 2210 ± 220 MJ/tonne. Both of these figures take account of cargo handling, amortized cost of terminals and a return journey to the Gulf carrying only ballast.

1.5 Summary

The inputs to the net energy requirement to deliver crude oil from the Middle East to a refinery in UK are summarised in Table 2. It is clear that, compared with transportation, exploration and production costs contribute in a very minor way to the total energy requirement of 1340 ± 130 MJ/tonne. In addition there is a possible ballast loss (from 0.1 - 10%) in the operation of tankers. In lieu of more accurate details of this loss, it has not been included in the analysis.

2. North Sea Oil

Since it is comparatively early in the development of the North Sea as source of hydrocarbons, and since oil companies will understandably explore the most promising geologic formations first, an analysis carried out now may tend to give a favourable bias to North Sea oil production. Fields yet to be discovered may not be as large as say Brent or Forties, and exploration and development costs will escalate as areas of deeper water and more severe weather conditions are encountered. Also the early succes rate in the North Sea of one commercial field for every 8 wells drilled may not be sustained and may approach the present world average of about 1 : 18. However, in carrying out an energy analysis of North Sea oil production it has been necessary to choose fields discovered and developed early in its history as an oil bearing region for reasons of availability of accurate data on development plans, field reserves etc. Two fields have been studied in detail - the large Forties field from which oil is transported by pipeline to a refinery at Grangemouth, and the small Auk field from which oil is transported to shore by a tanker/single-buoy marker system. Both fields were developed using steel platforms, and were particularly chosen to indicate the differences in energy requirements between a small and a large field. A detailed description of the analysis is available elsewhere [7], and only the results are presented here.

2.1 Exploration and Appraisal

Following a seismic survey of an area, a favourable formation will be tested by drilling, usually from a semi-submersible rig which has become the most popular type of rig for North Sea conditions. A suitable rig will weigh from 10,000-15,000 tons and may drill 40 wells during its working life. The time spent by a rig on a site varies considerably depending on such factors as weather conditions, penetration rate of drilling, well depth etc., but on average it will vary from 60-90 days and of that time 50-70 days may be spent actually drilling. During its time on site the rigs supply needs will be met by at least one vessel in transit at all times and another on standby. A helicopter will be assigned almost continuously to a rig and will make a round trip of about 500 km every day. Whether oil is found or not every well is completed using about 450 tonnes of casing steel and about 350 tonnes of cement for a 3000 m. well. Prior to any decision to develop a field it is necessary to appraise the reserves in detail. The energy inputs to an exploration (or appraisal) well in the North Sea are summarised in Table 3 which shows that the average energy requirement of a North Sea well is 307 ± 48 TJ.

Hamilton [8] reports that after the drilling of over 500 exploration wells and more than 130 appraisal wells in all sectors of the North Sea, proved recoverable oil reserves amounted to some 15-18 x 10^9 bbls while gas reserves totalled 60-70 x 10^{12} ft^3 giving a total of 3.766 x 10^9 tonnes of oil equivalent. From this, the average energy expended to discover each GJ of fuel in the North Sea can be calculated as 15.6 ± 2.6 MJ or the discovery of each tonne of oil required 53 ± 8 MJ (considerably higher than finding costs in the Persian Gulf). However, the energy required to find oil will vary considerably from field to field. Following the discovery of the Forties field (estimated recoverable reserves of 253 x 10^6 tonnes of oil and a further 14 x 10^6 tonnes of oil equivalence as associated gas), seven appraisal wells were drilled. Thus the energy required to discover each tonne of oil in the Forties field can be found to be 16.8 ± 2.6 MJ. For the much smaller Auk field (estimated recoverable reserves 6.7 x 10^6 tonnes) 4 appraisal wells were required, giving a finding cost of oil in the Auk field of 544 ± 82 MJ/tonne.

2.2 Field Development

The Forties field is one of the largest oil fields in the North Sea requiring four steel platforms to drain the reservoir with a planned maximum output of 400,000 bbls/day. The design of steel platforms to sit in about 120 m. of water required the construction of 'jackets' in special graving docks. Each jacket (~23,000 tonnes steel) was built on its side on a flotation collar, and, on completion, the graving dock was flooded, and the jacket on its flotation gear was towed to the field. By carefully controlled deballasting of the flotation gear the jacket is brought to an upright position, settles on the seabed and permanently secured by piles. The flotation gear is then unfastened, deballasted and towed back to the construction site. Each jacket then supported a steel deck weighting about 3,000 tonnes and some 15,500 tonnes of deck modules and equipment which were assembled once the jacket had been secured. The next phase of work on the platform was the drilling of the 27 directional wells for oil production. This will require some 2½ years of drilling during which supply vessels must again transport consumables, well completion materials etc. The energy inputs to prepare a Forties field platform for production are given in Table 4.

Because of the size of the Forties field and the expected maximum output, it was decided that oil would be piped 170 km to Cruden Bay by an 81 cm subsea line and thence to a refinery at Grangemouth by a 190 km landline. Laying the subsea line in deep water was a difficult and expensive process, following which it was buried to a depth of about 1 m. for protection. The energy inputs to the pipelines and associated facilities are summarised in Table 5.

The Auk field seems likely to be one of the smallest that will be exploited in the North Sea using current technology. The field has been developed with a single steel platform (3500 tonnes) sitting in 87 m. of water and secured to the seabed by 4,000 tonnes of piling. The jacket will support about 3,000 tonnes of deck and equipment from which 6 production wells have been drilled. Since production is expected at a rate of about 40,000 bbls/day, transportation of oil to shore will be by two 40,000 dwt tankers using an exposed location single-buoy marker (ELSBM). The energy requirements for the development of the Auk field are given in Table 6.

2.3 Discussion

The results of the process analyses of the two fields are given in Table 7 where the net energy requirement of delivering oil from the Forties field to Grangemouth refinery is seen to be 450 MJ ± 45/tonne (equivalent to 1.02% of its calorific value) and from Auk the net energy requirement of oil landed in UK is 955 ± 120 MJ/tonne* (2.16% of calorific value). The energy requirements for oil from the two fields arise in different ways. For oil from Auk, by far the major input is the discovery and appraisal of the field (~57%) but this has only a small impact (~4%) on the energy requirement of oil from the Forties field which is much more capital intensive and uses a more expensive means of transporting oil ashore. The energy required to transport oil by tanker/ELSBM can be calculated as 149 ± 16 MJ/tonne, whereas by subsea pipeline and then landline the Forties oil requires 276 ± 29 MJ/tonne although the latter method gives a continuous supply of oil in large volumes (400,000 bbls/day) with no downtime due to bad weather.

From the results obtained it is possible to calculate the energy payback times for the Forties and Auk fields - that is, the number of days of production needed to recover the energy invested in a field. If BP adheres to its original plans to complete production wells in batches of six from which oil will flow as development drilling continues, then one can calculate that the energy invested in each platform of the Forties field will have been returned as oil approximately 83 days after production begins (at about 25000 bbls/day). For Auk, since production will not begin until the field development is completed, it will be at an average production rate of 40,000 bbl/day, and the energy payback time for Auk can be calculated to be of the order of 26 days. Considering the expected lifetimes of the fields, both will be in the black for quite some time in the energy accounts.

It is also possible to use the results from the study of Auk and Forties to set up hypothetical fields and examine the effect of such parameters as field size, water depth and average success rate of exploration on the net energy requirement of oil recovery. It will be assumed that a field the size of Auk, found in 120 m. of water, could be developed using the same sized jacket as used for the Forties field on which was mounted the production equipment from Auk. It will further be assumed that this represents the smallest viable production platform for water depths of 120 m. Allowance must also be

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* Tanker losses due to ballasting are unknown but could be significant for the Auk field.

made for a reduced number of appraisal and development wells as the field size decreases. Transportation of oil ashore is assumed to be by a tanker/SBM system. The results of such calculations are shown in Figure 2 where it can be seen that a field with recoverable reserves from 100,000 - 200,000 tonnes would show no energy profit whereas a field with reserves from 1-2 x 10^6 tonnes would only achieve an energy ratio of about 10 : 1 (or $X_f = 0.10$).

3. Oil Shales

Energy analysis may have a special role to play in refining the financial analyses of future energy sources. This is perhaps best illustrated by recent reports [9] of escalating costs of oil shale production - "In the past each time the price of oil went up, shale oil companies promptly declared that their time had finally come . . . Now companies which once said shale oil would be profitable at $5.0, then $7.50, then $11.0 a barrel are hard pressed to name any figure at all." By evaluating the fuel component of the cost of producing oil from oil shales, energy analysis can be of use in such a situation. Part of the problem has also been that price rises of Middle East oil eventually produce price rises in steel and other materials, machinery and transport which are inputs to an oil shale complex. It seems unreasonable to expect that expensive sources of oil should be subsidised by goods and services produced using less expensive sources of energy.

Limitations on the use of water by an oil shale industry and problems associated with the disposal of enormous quantities of retorted shale seem likely to impose severe restrictions on the ultimate size of oil shale operations in Colorado, Utah and Wyoming. At present the technically most feasible means of obtaining a liquid fuel from oil shales is by room-and-pillar mining, crushing, above-ground retorting and upgrading to produce a synthetic crude oil which can be transported by pipeline to a refinery. The production of shale oil using in situ methods has often been advocated as a means of avoiding mining costs and spent shale disposal, but as yet it has not been demonstrated as feasible on a large scale and will not be considered here. Because there is no commercial plant in operation, most of the data must be drawn from pilot-plant experiments, making appropriate assumptions where necessary. This necessarily increases the error of the estimate.

3.1. Mining

It was assumed that the shale requirements of an oil shale complex of nominal capacity of 100,000 bbl/day would be met by the combined outputs of eight separate room-and-pillar mines each operating at a production rate of about 20,000 short tons/day. Mining was assumed to be in the 23 m. Mahogany Zone which was removed in two headings using explosives (Anfo) with scaling and roofbolting being deemed necessary for safety reasons. Broken shale would then be loaded by 4 m^3 electric shovels into 100 ton trucks for transportation to a centrally located crushing, retorting and upgrading facility some 16 kms away. A summary of the primary energy requirements of mining oil shale is given in Table 8. Details of the calculations made to obtain this data appear elsewhere [10].

3.2. Crushing

The results of calculations of crushing and screening oil shale are also given in Table 8. These are based on three plants, each with a capacity of 58,000 short tons/day, on stream for 90% of the time. Crushing is in three stages and a briquetting plant is included to recover fines. Crushed shale to be fed to a retort is in the form of particles from 2.5 to 7.5 cms in size. Overall dust losses are estimated to be 1.32% of all shale handled.

3.3 Retorting

The method used to separate the organic and mineral matter of oil shale is by the application of heat in a retort. Various designs have been suggested. The Oil Shale Corporations TOSCO II retort where heat is transferred to the shale by preheated ceramic balls has been demonstrated on a 1000 short tons/day semiworks plant. Gas combustion retorts as built by the U.S. Bureau of Mines and the Union Oil Company have proved to be less efficient than the TOSCO process. However, a commercial operation will require at least a twenty-fold scaling-up of retort size and technical problems will no doubt arise. Thus, in assessing an oil shale project one must make assumptions about retorting efficiency. Here an attempt has been made to use heat balances to estimate recovery of oil and gas from the retorting of various grades of oil shale.

Retorts are designed to be self-sufficient in heat, and the heat of retorting at temperatures of the order of 480°C is supplied by combustion of oil vapour and gas - products of the retorting. Some sensible heat will be recovered from spent shale before it leaves the retort, the amount depending on its exit temperature.

From data of heat of retorting presented by Cook [11], data of gross heating values of raw and spent shales from Stanfield et al [12] and assuming an exit temperature of spent shale of 180°C, one can estimate the heat content of products (shale oil and low BTU gas) for varying grades of shale and varying retorting losses. Two cases are considered - firstly optimum retorting where no heat losses occur from the retort and secondly, poor retorting efficiency where heat losses amount to 580 MJ/short ton of shale retorted. The results are expressed in Table 9 as the number of short tons of shale that must be retorted to produce 1 tonne of oil equivalence of products. Although all heat requirements for retorting will be met from combustion of organic matter on the shale, Kunchal [13] estimated that there would be an electrical requirement of 15.6 MJ(e)/short ton of shale retorted. Spent shale is assumed to have expanded 60% by volume and is also assumed to be transported by truck to a disposal area some 16 kms away.

3.4 Upgrading

As raw shale oil is too viscous to transport by pipeline, each oil shale complex requires an upgrading facility. Upgrading consists of the hydrogenation of raw shale oil - a step that also removes nitrogen (as ammonia) and sulphur. A plant processing 104,000 bbls/day of raw shale oil will consume 56.0 TJ of gas and 3.9 TJ(e) of electrical energy producing 100,000 bbls/day of a synthetic crude oil, 1230 tonnes/day coke, 208 tonnes/day ammonia and 85 tonnes/day sulphur. By convention, non-fuel products are charged at replacement energy requirements but since these are in small amounts they have a negligible effect on the result. Energy requirements are partitioned between coke and syncrude on calorific terms.

3.5 Miscellaneous Energy Requirements

It has been assumed in this study that a 320 km pipeline is constructed to link up with an existing pipeline for transmission to a refinery 1600 kms away.

3.6 Discussion

As mentioned previously, much of the confusion that arises in connection with oil shales occurs because many schemes designed for their exploitation are subsidised by using other cheaper sources of fuels. In order to avoid such problems it was decided that calculations would be based on a complex which generated its own electricity (at 30% generating efficiency) using gas produced during retorting and which used diesel fuel refined from syncrude produced by the complex (assuming a refining efficiency of 95%). Indirect energy inputs due to materials and capital were assumed not to be significantly effected by the shale oil complex. (This is equivalent to assuming that syncrude from oil shale only supplies a small fraction of national fuel requirements). These assumptions identify feedbacks in the system and are treated mathematically by a simple iterative process. The results of such calculations for various grades and for two retorting conditions are shown in Table 10 and plotted in Figure 3.

It will be noted in Figure 3 that even for very rich grades of shale, the net energy requirement of syncrude exceeds 10% of its calorific value which is considerably higher than the NER of oil from the North Sea - itself an expensive conventional source of crude oil. From this, one can conclude that as long as there are sources of oil like the North Sea, then, on a large scale, they will be exploited in preference to oil shales. The grade dependence of syncrude production is also clearly seen in the diagram. As leaner shales are processed, there is an increase in the tonnage of shale which must be mined, crushed and retorted to produce a given output of syncrude, and in retorting there is an increase in the amount of inert minerals which must be raised to the required temperature, and in the quantities of spent shale which must be handled.

4. Nuclear Power

As a detailed description of an energy analysis of nuclear power has appeared elsewhere[14], only the results of the study will be presented here. The inputs to build and fuel a 1000 MW(e) SGHWR power station are summarised in Table II, and the total energy requirement (assuming a 25 year working lifetime) was found to be 19071 TJ(e) + 22,091 TJ(th). In determining the gross electrical output, allowance must be made for the station load-factor (62%), electricity lost in distribution (7.5%), electricity used by the electricity industry (3.75%) and the energy required to make up the heavy-water inventories (3.45 MW). The net output outside the electrical industry can then be shown to be 546.8 MW and the energy output in 25 years is 431,000 TJ(e). The fraction, X_f of the gross output that is consumed by a nuclear power station can then be expressed as

$$X_f = \frac{19071\ \text{TJ(e)} + 22,091\ \text{TJ(th)}}{431,000\ \text{TJ(e)}}$$

In order to evaluate X_f it is necessary to incorporate explicit behavioural assumptions or demand forecasts in the analysis, depending on the way in which this electricity will be used. Two extreme cases will be considered. In the first case (Chapman's Convention B) the electrical inputs to the nuclear industries are assumed to come from nuclear power stations and the electricity is assumed to be purchased by consumers who presently use fossil fuels for performing work. Since electricity is about three times more useful than a fossil fuel for performing work each TJ(e) saves 3 TJ(th) of fossil fuel and $X_f = 0.06$. In the second case (Chapman's Convention A), the electrical component of the total energy requirement to build and fuel the station is assumed to be generated in fossil-fueled power stations, whereas the output is assumed to be used entirely for such uses as space-heating where 1 TJ(e) = 1 TJ(th). In this case $X_f = 0.23$. Clearly in actual fact the truth will lie somewhere between these two extreme cases, but this exercise does cast doubts on the use of nuclear power to generate electricity for space-heating.

Chapman [14] extended his study to consider a dynamic analysis of nuclear building programmes. He adopted a more realistic convention than the extreme cases mentioned above, whereby the electrical components of all mining, enriching and other operations were assumed to be supplied by electricity generated in a nuclear station, but thermal inputs were subtracted from the electrical output on a 1 : 1 basis.

The energy payback time for an SGHWR station was shown to be 2.23 ± 0.3 years and this indicates the length of time it takes the power station to produce an amount of energy equal to the energy invested in it, once the station has started producing an output. However it takes about five years to construct a station and one further year to bring the reactor up to criticality and check out the installation so the station produces an energy profit between 8 and 8.5 years after the beginning of the construction stage. This is significant because in this period a number of other power stations may be commissioned, and these will increase the energy profit, indicating that at the beginning of a rapidly growing nuclear power programme a substantial energy deficit may arise. This will only occur when the doubling time of growth in the number of power stations is significantly less than the overall payback time for one reactor (including the construction and commissioning times).

If the number of stations were doubling every two years then, while growth continues exponentially the number of stations under construction will always be about seven times the number of stations commissioned. Assuming that the energy inputs to each station under construction are spread uniformly over the 5 year construction period, it was shown that there would be a net energy deficit of 15606 TJ(th) per year per GW completed. For a programme where the number of reactors is doubled every 4 years it was found that there would be a net energy profit of 10825 TJ(e) per year per GW completed. It should be borne in mind that the slower programme takes longer to reach a given total capacity.

Energy analysis alone cannot indicate which of these programmes is 'preferable' although it may help by providing information on the consequences of certain policies. The choice between these programmes depends on whether the deficit of the faster programme can be 'afforded' and when the output is 'needed'.

Finally, the effect of the grade of uranium ore on the viability of thermal reactor systems was investigated. In general, the energy required, E, to produce a tonne of any material from an ore of grade G% can be written as

$$E = \frac{100}{G} (E_m + (S + 1) E_d) + E_f$$

where E_m = energy to mill one tonne of ore

S = stripping ratio (tonnes of overburden to tons of ore)

E_d = energy to mine one tonne of ore or overburden

E_f = energy to convert beneficiated ore to required material.

This model suggests that there is a grade of uranium ore at which the energy required to produce one tonne of uranium will equal the energy produced from that tonne of uranium in a thermal reactor. The SGHWR produces a yield of 107.7 TJ(e) per tonne of natural uranium. This is clearly the upper bound on the energy requirement for mining and milling uranium. To date satisfactory energy requirements have only been obtained for 0.3% ores and for the extraction of uranium from Chattanooga shales. If the model relating energy requirement to ore grade and stripping ratio is correct, these two data points can be used to estimate the cut-off grade of uranium ore. These predictions are shown in Figure 4 which suggests that the lower bound on uranium ore grade is about 20 ppm. Clearly a lot more data on different uranium mines, with different ore grades, rock hardnesses etc. is needed to substantiate this estimate.

It is important to realise that at this cut-off ore grade, the activity is producing no net energy output. In practice it is unlikely that a system would prove viable in simple economic terms without a yield of 5-10 times the energy input in the mine and a more practical limit would be about 100 ppm. If the effective cut-off grade for uranium deposits is about 100 ppm then this could have serious implications for the maximum thermal capacity which can be installed. Vaughan [15] has indicated that there may be a total of 6.9 m tonnes of uranium available at grades above 140 ppm, equivalent to a total 46,080 GWy.

Summary

The energy requirements for those sources of energy examined are shown in Table 12 where they are expressed as the fraction of total energy consumed in the production of a unit of gross output. Thus for instance in delivering a tonne of oil to Grangemouth from the Forties field, the equivalent of 0.010 ± 0.001 tonnes of oil are consumed. That is, the net output of the operation is equivalent to 0.99 tonnes of oil.

Clearly there are vast differences between the energy requirements of the sources of fuels examined. For example, oil produced at the well-head from the Kirkuk field in Iraq requires only about $^1/_{800}$th of the energy required to produce oil from the Auk field in the North Sea, and in general, the energy required to produce oil in the Middle East is between one and two orders of magnitude less than in the North Sea. It is interesting to note however that Middle East oil transported to the U.K. requires a somewhat higher total energy input than oil from the two fields examined in the North Sea. Despite its high energy requirement compared with oil at the well-head in the Middle East, the energy requirement of North Sea oil still only represents between 1-2% of the gross output. By comparison, syncrude produced from 30 gal/ton oil shale requires an energy input equivalent to about 13% of the gross output, indicating a significant feedback mechanism in operation. Syncrude from 10 gal/ton shale requires an input of from 23-32% of gross output (depending on retorting efficiency). As mentioned previously, at this level of feedback, the economic viability of such a scheme is in doubt.

Using energy analysis it is possible to indicate points of futility where no net energy is produced (i.e. $X_f = 1$). For North Sea oil fields using current technology this appears to occur at a field size of 100,000 - 200,000 tons of recoverable reserves of oil. For oil shales exploited using above-ground retorting, the outer limit is at a grade of about 5 gal/ton. For uranium ores used to fuel a burner reactor, the cut-off grade was found to be of the order of 20 ppm. However, it should be remembered that at $X_f = 1$, there is no net output and the price of the fuel would be infinite. Because of payments to labour and capital the upper limit of economic viability may well occur at values of X_f from 0.1 to 0.2 Thus uranium ores of a grade of 100 ppm U_3O_8 or less may not be economically viable using current burner reactors and this in turn implies an upper bound for the total thermal reactor capacity. For oil shales exploited using above-ground retorting and room-and-pillar mining 15-20 gal/ton shale may represent the upper limit of economic viability, depending on the efficiency that can be achieved in a commercial-scale retort.

Acknowledgement

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Industry	'Efficiency' η %	$\varepsilon \frac{100}{\eta}$
Coal	96.0	1.04
Coke ovens	84.7	1.18
Gas production	71.9	1.39
Oil refining	88.2	1.13
Electricity	23.9	4.19

Table 1 **THE ENERGY REQUIREMENTS OF DELIVERED ENERGY; U.K. 1968**

Input	**Energy Requirement (MJ/tonne)**
Exploration	0.88
Production	2.30 (0.5-15.8)
Transport to terminal (pipeline)	38.9
Transport to U.K. (250,000 dwt tanker)	1290
Total	1340 ± 130 MJ/tonne

Table 2 **NET ENERGY REQUIREMENT OF MIDDLE EAST OIL**

Input	**Energy Requirement (TJ)**
Exploration Rig	18.0-26.8
Transportation of Rig to Site	12.6
Drilling Energy	129.0-180.5
Drilling Consumables	1.0-1.4
Well Completion Materials	24.1
Supply Vessels	59.4-89.0
Shore Base	13.5-16.8
Helicopter	2.1-3.0
Total	259.6-354.3 TJ

Table 3 **ENERGY INPUTS TO THE DRILLING OF AN EXPLORATION WELL IN THE NORTH SEA**

Input	Energy Requirement (TJ)
Graving dock and facilities (used twice)	179.2
Flotation collar and pile guides (used twice)	340.6
Jacket materials (23,000 tons steel)	1092.9
Jacket construction and materials transport	177.2
Towing jacket to field	54.0
Piles (7,300 tons steel) and pile driving	424.1
Deck and modules (+ 20% for spares replacement)	2851.2
Transport and assembly of deck and modules	149.4
Direct energy of drilling 27 deviated wells	1740.5
Drilling consumables	10.5
Well completion materials	645.1
Production hardware	272.9
Supply requirements during drilling	1931.0
Shore base	448.2
Helicopter	27.7
Total	10,340 ± 1030 TJ

The Forties Field requires four such platforms.

Table 4 **ENERGY INPUTS TO THE PREPARATION OF A FORTIES FIELD PLATFORM FOR PRODUCTION**

Input		Energy Requirement (TJ)
Subsea Pipeline:		
Materials:	67,000 tons steel and transport	3943.7
	coal tar wrap	27.7
	122,000 tons concrete	263.5
Construction		
Pipylaying:	Barge capital cost	324.0
	Barge running cost	817.3
	Supply costs (vessels and base)	1605.7
Pipeburying:	Barge capital cost	144.0
	Barge running cost	1524.1
	Supply costs	237.6
Subsea Pipeline:	Total	9117.4
Landline to Grangemouth:	Materials (45,000 tons steel and transport)	2169.5
	Construction	212.4
Oil/Gas separation facilities		2016.0
Pipeline to Dalmeny		154.1
Forth tanker terminal		2304.3
Total		16070 ± 1600 TJ

Table 5 **ENERGY INPUTS TO FORTIES FIELD PIPELINES AND FACILITIES**

Inputs	Energy Requirement (TJ)
Jacket (materials and construction)	203.0
Towing to site	1.9
Piles and pile driving	220.4
Steel deck	21.4
Modules (+20% spares and transport)	449.8
Drilling six production wells	1109.6
Exposed location single-buoy marker (ELSBM)	288.0
Total	2290 ±250 TJ

Table 6 **ENERGY INPUTS TO THE PREPARATION OF THE AUK FIELD FOR PRODUCTION**

	Energy Requirement (MJ/tonne)	
	Forties Field	**Auk Field**
Exploration, discovery, appraisal	17.0	544.3
Field development	210.0	296.8
Pumping oil to terminal	215.1	—
Tanker operations	—	106.0
Servicing platforms during production	7.4	7.4
Total	450±45 MJ	955±120 MJ
% of Calorific Value of crude oil	1.02	2.16

Table 7 **ENERGY REQUIREMENT TO LAND A TONNE OF CRUDE OIL FROM FORTIES AND AUK FIELDS IN THE UNITED KINGDOM**

		MJ/short ton of shale
Mining:	Drilling blast holes	13.5
	Explosives (Anfo)	10.5
	Scaling operations	1.2
	Roof bolting	4.4
	Mineyard and buildings	0.1
	Ventillation and watering	3.1
	Mining-road construction	1.8
	Shovel loading	9.6
	Truck haulage	21.4
		65.6
Crushing:	Direct energy consumed	9.8
	Abrasion of metal parts	12.4
	Briquetting plant	3.6
	Capital equipment	1.6
	Dust losses	1.3
	Total	94.3 ± 10.0 MJ

Table 8 **ENERGY REQUIREMENT FOR THE MINING AND CRUSHING OF COLORADO OIL SHALE**

Shale Grade (US gal./short ton)	Number of Short Tons of Raw Shield to yield 1 Tonne of Oil Equivalence of Products.	
	Retorting Losses = O	Retorting Losses = 580 MJ/short ton
2.5	155	—
5.0	62.4	384
10.0	27.3	43.0
15.0	17.6	23.1
20.0	13.0	15.7
30.0	9.32	10.7
40.0	7.09	7.84
50.0	5.58	6.03

Table 9 **RETORTING VARIOUS GRADES OF OIL SHALE**

	Net Energy Requirement of Syncrude (MJ/tonne)	
Grade of Shale (US gal./short ton)	Optimum Retorting Conditions	'Poor' Retorting Conditions
5.0	20,700 ± 4000	
10.0	10,000 ± 2000	14,000 ± 3000
15.0	7,500 ± 1600	8,900 ± 1800
20.0	6,500 ± 1300	7,100 ± 1400
30.0	5,600 ± 1200	5,800 ± 1200
40.0	5,100 ± 1000	5,300 ± 1000
50.0	4,800 ± 900	4,800 ± 900

Table 10 **NET ENERGY REQUIREMENTS OF PRODUCING SYNCRUDE FROM OIL SHALES**

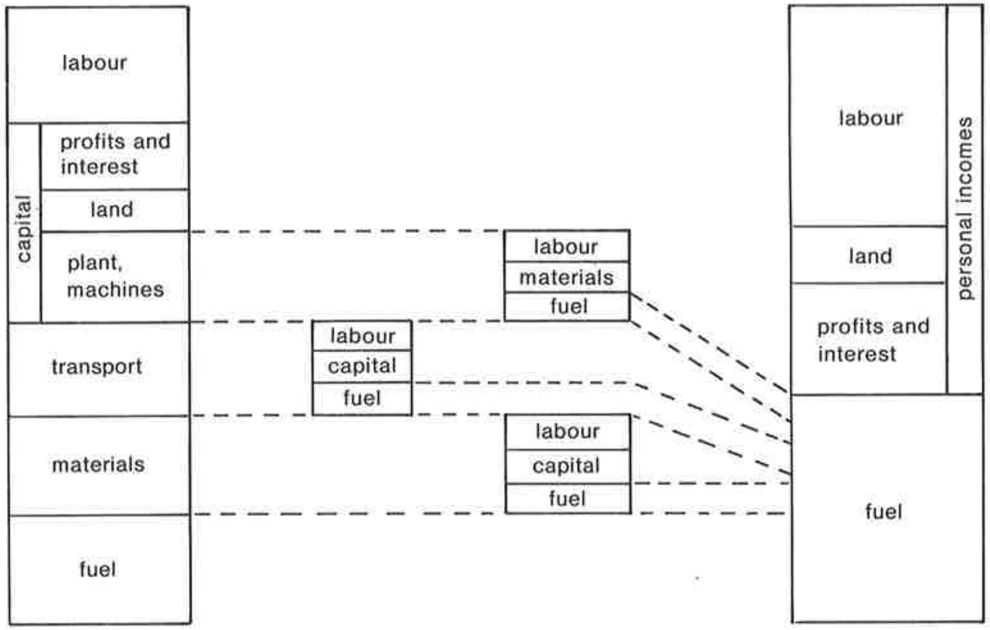
Input	Energy Requirement	
	TJ(e)	TJ(th)
Capital equipment (power station)	1,102	12,131
Heavy water	585	5,400
Initial core: mining, milling	62	640
enrichment	2,857	115
fabrication	28	18
	4,634	18,304
Refuelling for 25 years	14,437	3,787
Total	19,071	22.091

$$X_f = \frac{19{,}071 \text{ TJ(e)} + 22{,}091 \text{ TJ(th)}}{431{,}000 \text{ TJ(e)}}$$

Table 11 **TOTAL ENERGY REQUIREMENTS FOR 1000 MW(e) SGHWR POWER STATION**

Source of Energy	$X_f = \frac{\text{Total energy consumed}}{\text{Gross energy produced}}$
Middle East oil at well-head	$0.27\text{-}3.9 \times 10^{-4}$
Middle East oil delivered to U.K.	0.031 ± 0.003
North Sea oil from the Forties field	0.010 ± 0.001
North Sea oil form the Auk field	0.022 ± 0.002
Syncrude from 10 gal./ton oil shale	$(0.23\text{-}0.32) \pm 0.03$
Syncrude from 30 gal./ton oil shale	$(0.128\text{-}0.132) \pm 0.01$
Nuclear power from 1000 MW(e) SGHWR station (0.3% uranium ore grade)	0.06-0.23

Table 12 **SUMMARY OF ENERGY REQUIREMENTS OF VARIOUS ENERGY SOURCES**



The cost C, of a product can be written as

$$C = X_f P_f + X_c P_c + X_L P_L$$

Figure 1. The Division and Sub-division of Factor Payments into Payments to Labour, Capital and Fuel.

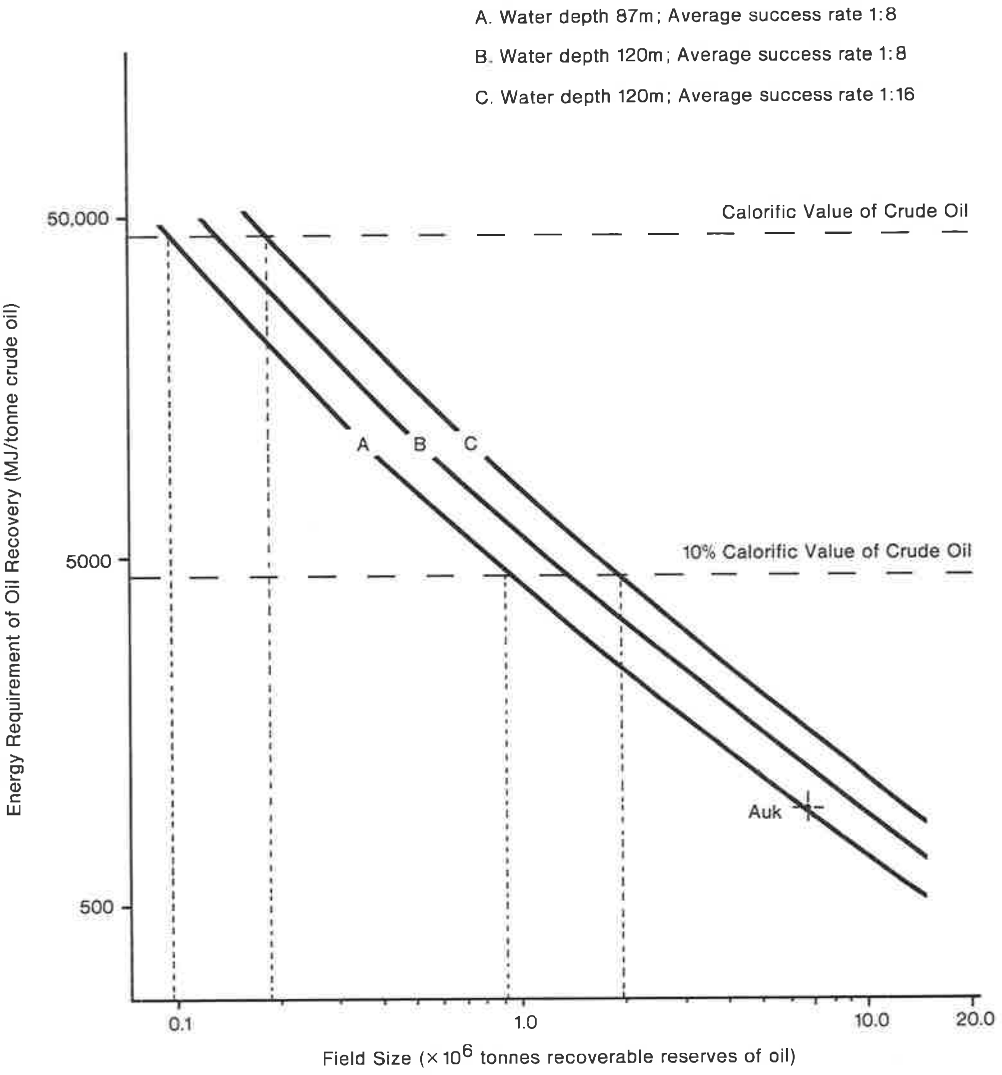


Figure 2. Variation of Energy Requirement of Oil Recovery with Field Size.

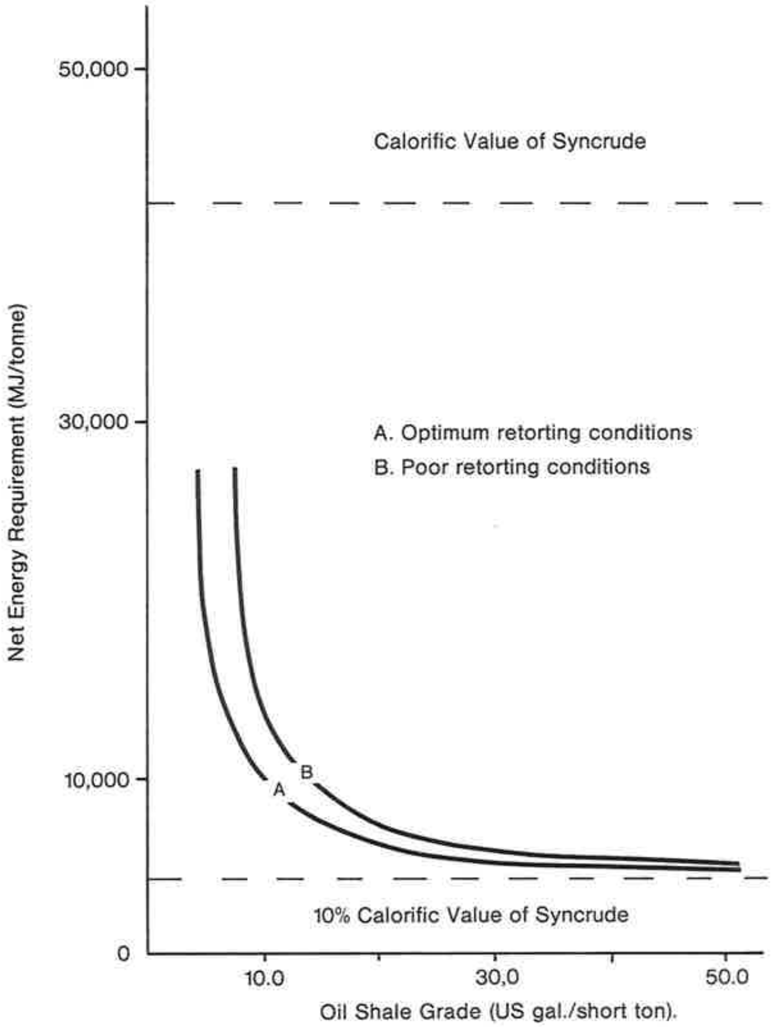
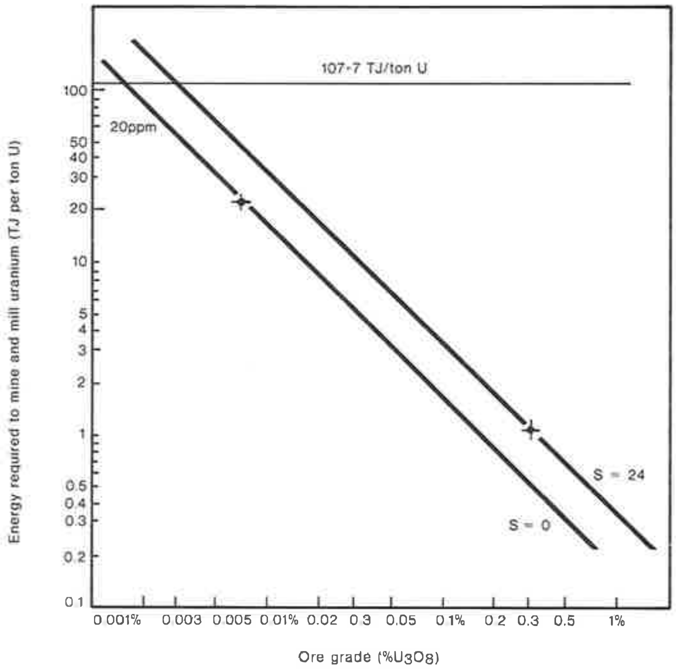


Figure 3. Net Energy Requirement for the Production of Syncrude from Various Grades of Oil Shale.



The energy required, E, to produce a tonne of any material from an ore can be written as

$$E = \frac{100}{G}(E_m + (S+1)E_d) + E_f$$

where G = percentage ore grade
E_m = energy to mill one tonne of ore
S = stripping ratio (the ratio of tons of overburden to tons of ore)
E_d = energy to mine one tonne of material (either ore ore or overburden)
E_f = energy to convert beneficated ore to required material.

Figure 4. Predicted Cut-off Grade of Uranium Ores

Energy analysis of materials and structures in the building industry

Professor Ir. P.C. Kreijger
University of Technology, Department of Architecture, Group Science of Materials
Eindhoven
The Netherlands

Summary

With the help of 5 examples, an overall view is given of the importance of energy analysis for the building industry.
Such analysis can be used for both micro- and macro considerations as is shown.
In the 1st example the effect of manufacturing processes of cement and baked clay bricks on the energy consumption is shown. Based on the energy content of building materials, the effect of type and amount of materials in building structures on the energy consumption is calculated in example 2.
The 3rd example shows the energy saving by better insolation of dwellings and a comparison of the economic value of such savings with the costs of achieving them.
The 4th example compares the yearly energy consumption for the construction of buildings in the Netherlands with the yearly energetic exploitation of buildings.
The 5th example indicates the economic importance of the Dutch Building Industry as well as the energetic importance and the effect of fuel price rises on delivery prices.

Introduction

Energy analysis may be anything you want it to be, depending on interest and use on which the analysis will ne focused.
Hill and Walford (1) for example list 6 different forms of energy accounting, ranging from the fossil fuel accounting by the environmentalist to the energy flow analysis by the systems analyst, see table 1.

So firstly one has to decide what specific energy interests there are in building industry. In this respect 5 examples are given, ranging from specific to general:

1. The effect of manufacturing processes of building materials on the consumption of energy. This gives the opportunity either to save energy by carefully studying the flow diagrams or to estimate the effect of alternative processes.
2. Effect of amount and type of materials in structures and buildings on the consumption of energy and water and the emission of pollution. From the energetic point of view, structures from different materials can be compared then, which gives us a new criterion to select the materials for our structures and buildings (2, 3).
3. Energy saving by increasing the insulation of our dwellings mostly neglects the effect of the energy content of the extra building materials necessary for the increased insulation e.g. double glass panes instead of single, cavity fill insulation, etc. However, apart from energy content and the decrease of heat losses there is the relationship between the value of the savings and the cost of achieving them. Therefore a comparison of energy-content, yearly heat losses, building costs and yearly heating costs for different constructions are given
4. In general one wonders about the ratio between the energy content of buildings and the energy needed for the exploitation of buildings (heating, cooking, electricity). Since finally buildings are demolished, the energy cycle of a building is only complete if also the demolition-energy is known.
5. Since we all know the great economic importance of the Building Industry, we should like to know the energetic importance. This knowledge also gives us the effect of fuel price rises on delivery prices in Building Industry.

In the following it will be tried to deal with these five problems.

1. Effect of Manufacturing Processes on the Consumption of Energy

The energy content of a product in fact is the sum of three components:

- the energy required to manufacture the product = → direct energy
- the energy required for commodities and services involved in the manufacturing process (including distribution) = → indirect energy
- the energy required for the manufacture of the capital goods involved, such as machinery, buildings, roads, etc. = → indirect energy

Although the reality of the indirect energy is recognized, this has not been taken into account for the calculation of the energy content of building materials and the comparison of the various manufacturing processes, since the buildings in which the manufacturing processes take place are not only the result of the principle "fitness for purpose" but depend largely on community connections. This means that for the same process one firm for example will choose an aluminium construction whereas the other firm will take sand lime bricks.

In fact use was made of flow diagrams of the processes of manufacturing products indicating for each step the appearing flow of material, energy, water, waste and pollution, and recycling, see fig. 1 (4).

From fig. 1 it follows that raw materials (M_1) are mined from the environment for which energy E_1 and water W_1 are necessary and where waste and pollution (A_1) will arise.

Transforming raw materials to materials leads to indices 2, whereas for the transfer of materials to products indices 3 is used. Recycling may be applied between industries (R_1) but also between consumer and industry (R_2, R_3) with consequently energy and water consumptions (E_1^1, E_2^1, E_3^1, W_1^1, W_2^1, W_3^1).

Energy necessary to decrease the loading of the environment is designated by E".

On the basis of such flow diagrams, it will be possible (5, p 37) to

- cut losses within and around processes monitoring energy consumptions more closely, possibly backed up by automated process control;
- use heat more intensively by means of increased heat exchange;
- use heat more efficiently in combustion processes, or to provide for a greater furnace efficiency;
- use substitute processes requiring less energy;
- switch in some cases from electricity to natural gas or oil as a heat source;
- form larger production units, which generally enhance the profitability of investment aiming a reduction of operating costs and enabling the various processes to be geared to each other more efficiently.
- make waste heat available for heating houses and buildings
- use larger scale combination of heat and electricity production.

A few examples about the effect of the process of manufacture will be given:

1.1. Cement manufacture

The production sequence for the manufacture of cement is: → mining and preparation of raw materials → clinker production grinding and mixing of product cement. During the first step two processes can be used, the wet process or the dry process. For the wet process the raw materials are ground in the right ratio after adding water which produces a thin mud or "slurry" being mixed and finally burnt in the kiln. In the dry process the raw materials are broken, dried, ground, mixed and finally burnt in the kiln.

The so formed portland cement clinker is either ground together with gypsum giving portland cement (pc), or ground together with granulated blastfurnace slag and gypsum giving portland blastfurnace cement (hc).

Table 2 gives (6) the raw materials necessary per ton cement, the total Dutch production and consumption in 1973 and the world consumption in that year.

The wet or dry process does not effect the amount of raw materials used, although the manufacture of pc takes about 30% more raw materials than hc does.

From table 3 it follows that the wet process requires 47% more energy than the dry process.
The energy content of Dutch pc is 6,6 MJ/kg, of Dutch hc 2,5 MJ/kg, which data means for 1973 $18.6.10^{12}$J for the whole Dutch cement production.

The same production of only hc would have given in 1973 an energy saving of 31%, whereas clinker production according to the dry process only would have increased the saving to 44% (or $9.3.10^{12}$J.).
These figures show that serious study of flow diagrams are worthwhile.

1.2. Baked clay bricks

In the manufacture of baked clay bricks several types of kilns are used with different energy consumptions an consequently greatly determine the energy content of bricks. On the basis of fig. 1 Cornelissen (7) calculated the energy content of bricks (inclusive of mining of raw materials and transport of bricks to the building site) and which is given in table 4.

The range of energy content per type of kiln is due to the different ways of making the green bricks. The calculated weighed average energy content of 7260 MJ/1000WF is 26% less than that stated by the CBS 1971 (namely 8920 MJ/1000 WF), which is caused by the fact that the calculations are related to large and modern plants. Consequently, if other plants improve their production process, 23% energy saving can be reached (which savings equal about 1% of the natural gas consumption in 1971). Now if we compare this figure of 9000 MJ/1000 WF with the energy content 30 years ago, we find an amount of 3000 MJ/1000 WF.
The large difference is caused by artifical drying of the green bricks and the much more mechanised process.
These figures can be compared with the energy content of sand lime bricks which amounts to 2500 MJ/1000 WF.
Also these figures show the use of flow diagrams.

2. Effect of type and amount of materials in structure and buildings

Based on fig. 1, the energy content was calculated per kg. and per l. of material (4, 6). Table 5 gives data for several (building) materials.
The effect of these data can be seen if some structures are calculated.
The main structural building materials are concrete, steel and brickwork.
For a column of 1 m. height and able to bear a load of 1000 ton, the three materials get different dimensions. Consequently both energy content and dimensions are influenced by the type of material.

Fig. 2 gives the results of this example for a structure which is loaded in compression.
Also beams can be compared in this way. For a live load of 400 kg/m^1 wood, reinforced concrete and steel, beam-dimensions were calculated for increasing span and from these the energy consumption per m^1 beam. The results are given in fig. 3, in which for concrete also the effect of the use of portland cement and portland blastfurnace cement is given.

It is evident that regarding energy content, wood is the best structural building material, followed by concrete. It can be shown, that the higher the quality of concrete, the less energy is consumed. Steel consumes considerably more energy than concrete although the part of energy due to the self-weight of beams is much less for

steel than for concrete.
Finally a comparison is made for façade elements 1 x 1 x 0.1 m^3 made of brickwork, gravel concrete and light-weight concrete, manufactured at the building site. (6) Table 6 gives the comparison.

The energy content of the gravel concrete element is less than both the other two thanks to the energetic advantageous aggregate gravel. Changing gravel by expanded slate would almost double the energy content of the ready mixed concrete. The amount of steel (mould + reinforcement) makes 44 and 30% of the total energy content of gravel and light-weight concrete respectively 90% of the energy content of the brickwork element is formed by the bricks and is about equal to the energy content of the light-weight concrete element.

From the foregoing it is evident that new selection criteria can be chosen, such as minimum energy content, minimum water content or minimum pollution content, since for each type and amount of material the amounts of energy, water and pollution which are involved in manufacturing the material, can be calculated on the basis of fig. 1.

3. Energy saving as a result of better insulation of dwellings

The average wall construction of Dutch dwellings is the half brick cavity wall with single glass windows and consequently great thermal loss by transmission which must be eliminated by relatively high central heating capacity. In the Netherlands an average house loses 12 KW at a temperature of - 10°C, while for example in Sweden at - 18°C a loss of 5 KW is normal practice.
Energy can be saved by cavity fill insulation and use of double glazing. To compare the effect of the increased insulation, the energy loss by transmission has to be calculated since the energy loss by (natural) ventilation is independent of increased insulation.
The transmission loss of energy can easily be calculated on a year-bais from the air to air thermal resistance and the amount of grade-seconds per year, (8, 9). This loss of energy will decrease by better insulation, this saving of energy however is decreased by the energy content of the extra insulation material, (10). From the energy content of the materials used (as given in table 5) and assumed life times of 20 and 40 years for windows and cavity walls respectively, this energy was also calculated. Table 7 gives these data.

From the table it follows that for an overall energy consideration, the energy content of the materials themselves cannot be neglected since this amount may reach as much as 15% of the transmission loss.

The façade of the living room of many houses is about 10 m^2 (3.60 x 2.80 m^2), for which façade-surface the effect of the percentage of glass is given in figs. 4a and 4b. From the figures it is evident that from the point of view of energy saving the percentage of glass has to be a minimum. Given for example 40% glass in the façade (4 m^2), this means for normal construction of cavity wall with single-glass a yearly loss of $8.6.10^9$J, which decreases in the case of cavity fill insulation to $7.1.10^9$J and further to $4.2.10^9$J if also double glazing is used.

Consequently in this case a yearly saving of $1.5.10^9$J (17,5%) takes place by cavity fill insulation, which increases to $4.4.10^9$J (51%) if also double glazing is used. However, we now must compare the economic value of such savings with the costs of achieving them. In table 8 the yearly heating costs necessary to eliminate the thermal transmission losses are calculated as well as the building costs, of course based on some assumptions.

The 1976 energy prices in the Netherlands for occupants of dwellings are:
natural gas $6.5.10^{-9}$ gld/J

oil (central heating) $9.3.10^{-9}$ gld/J
electricity 27.10^{-9} gld/J

Since it is expected that within due time the energy prices for natural gas and oil will be the same, an energy price of 10.10^{-9} gld/J is assumed for the calculations. (8) To calculate the yearly building costs, Vos and Tammes are followed (8), so for glass an annuity of 0.11 gld/(gld. year) is used (lifetime 20 years, interest 9%) and for the cavity wall 0.093 gld/(gld. year) (lifetime 40 years, interest 9%) (6).
For the earlier mentioned façade of 10 m^2 the total costs are given in fig. 5 as a function of the percentage of glass surface.
From table 8 and fig. 5 it follows that the building costs of a glass construction (wood frame included) are more expensive than those of a cavity wall although for greater glass surfaces these costs are comparable in the case of single glass. The heating costs however do make glass windows expensive.

Cavity fill insulation leads to lower total costs, thanks to the increased insulation and consequently decreased heating costs. Double glazing is cost-increasing although with about 10% glass in the façade the same total costs are reached as for the standard construction.
If we take 40% glass in the façade again, the yearly costs are ƒ 210,- those by cavity fill insulation decrease to ƒ 200,-, whereas double glazing would increase the costs to ƒ 237,-.
If we compare the yearly building and heating costs in guilders we get:

Cavity wall + single glass =ƒ 125,88 building costs+ƒ 84,00 heating costs.(40.0%-66.7%)
Cavity wall + fill insulation + single glass =ƒ 131,60 building costs+ƒ 68,70 heating costs.(34.3%-52.2%)
Cavity wall + double glass =ƒ 190,38 building costs+ƒ 54,80 heating costs.(22.4%-28.8%)
Cavity wall + fill insulation + double glass =ƒ 197,10 building costs+ƒ 39,80 heating costs.(16.8%-20.2%)

So the heating costs may vary from 40 to 17% of the total costs or from 67% to 20% of the building costs.
The economic optimum for 40% glass surface in the 10 m^2 façade is 34.3% heating costs and 65.7% building costs. Only if the price of the heating energy increases very much, double glass may become economic (see fe lit 9 for more calculations on the effect of energy price).
In table 8 also are calculated the costs of the energy content in the building costs which happen to be about 2%. So, economically the energy content of the building materials is rather uninteresting, whereas from the point of view of energy analysis the energy content had to be taken into account.
For the energy analysis of total buildings see for example (14, 15).

4. Comparison of energy needed for building, (energetic) exploitation of buildings and demolition of buildings

Fig. 6 gives an estimate (4) for the year 1972 of the energy needed in the Netherlands for new buildings and for the energetic exploitation of buildings. It was impossible however to get a reliable idea of the energy used for the demolition of buildings.

From fig. 6 we see that hardly 4% of the national energy consumed in the Netherlands in 1972 is needed for new buildings while at least 22% is needed for the energetic exploitation of existing buildings. For the new buildings 58% of the energy is

needed for the building materials, 4% for the transport of these materials and 38% for the erection and assembly of the building. Regarding the energetic exploitation 75% of the energy is needed for heating, 18% for coocking and 7% for electricity (light, refrigerator, washing machine etc.).
From these figures it follows that projects based on saving of energy for heating should have priority if the target is to save as much energy as possible in the shortest time.
This was in fact stimulated in the Netherlands by the State giving a grant for better insulation of dwellings to the amount of 1/3 of the costs up to a maximum of 1000 guilders. An idea of the effect of such a grant with respect to the costs of increased insulation can be found in 3 (table 8).

5. Economical and energetic importance of the building industry and the effect of fuel price rises

- The Dutch Building Industry in 1973 was responsible for (11) 16,5% of the Gross National Product and for about 60% of all national investments. At that time about 12% of the occupational population worked in the building industry and about 3% in direct supplying industries, thus totally 15%.
  Due to the economic crisis, however, it is expected (12) that these figures will decrease to about 10% of G. N. P. in 1980, connected with 12% of all active workers, while in 1980 only 47% of all national investments will be buildings, roads and civil engineering works.
  For 1990 these figures are expected to be 7, 10 and 32 respectively. While unemployment in building industry now (Jan. '76) is 33.000 (on a total of 223.000), this figure is expected to increase to 95.000 in 1980 and 125.000 in 1990.
- In 1973 the total Dutch energy consumption was 2606.10^{15}J. (13) from which amount the energy industry itself used 20.1%, the other industry 34.7%, transport 10.2%, residential energy consumption in houses 22% (heating 16%) and the rest 13%. Building industry only used 2.2% of the total energy consumption or about 6% of all industrial sectors (= 34.7%) together, the energy industry excluded (see also lit 5, P 34 and 158).
  So the first conclusion is that building industry uses relatively little energy.
- In lit (5, P 140-144) it was calculated that the share of the accumulated energy costs in the total production costs of the building industry was about 3%. The term accumulated is used here since not only the direct energy consumption costs are dealt with but also the indirect costs, namely the extra input of energy for goods, services and capital goods that are required for the output of the direct production. This figure of 3% gives the limited effect of original fuel price rises on delivery prices in building industry. Much more sensitive to the increase of fuel prices are the energy industry (electricity 33%, coal 22%), metal industry (17%), chemical industry (12%) and transportation (especially aviation and shipping, 11%). All other sectors showed an accumulated energy cost share of between 2 and 5% as is shown in Table 9 (5, P 145).

6. Conclusion

The economical importance of the Dutch Building Industry follows from the fact that in 1973 it was responsible for 16.5% of the Gross National Product, which percentage is expected to decrease to about 10% in 1980, however.
From the energetic point of view, the building industry is not important since in 1973 it only used 2.2% of the total Dutch energy consumption. It was also shown that the share of the accumulated energy costs in the total production costs of the building industry was about 3%, which figure gives the limited effect of original fuel price rises on delivery prices in building industry.
For the thermal exploitation of buildings (heating, cooking, electricity) in 1972 about 7 times more energy was used than for the erection of new building (materials and transport included). Saving of energy for heating (16.7% of the total Dutch energy

consumption in 1972) should consequently have priority if saving of energy is the target.
In this respect it was calculated that for an ordinary 10 m^2 façade of a living room with 40% single glass and 60% cavity wall, cavity fill insulation decreases the yearly loss of transmission energy with 17.5%, whereas double glass instead of single glass increases this 17.5% to 51%. The energy content of the extra insulation materials cannot be neglected in this calculation, since it may rise to 13% of the total loss of energy. However, the economic value of such energy savings only are present in the case of cavity fill insulation, namely 5% yearly, economic saving, while extra double glazing increases the yearly costs by 13%.
The energy content of several building materials is given and it was calculated that regarding a minimum energy content, wood is the best structural material, followed by concrete, bricks and steel respectively.
There is a great difference in the energy content of concrete made with Portland cement (pc) and with Portland blast furnace cement (hc), while also the manufacturing process of the cement itself (wet or dry process) is important in this respect.
It was calculated that the same Dutch production of only hc instead of about 50% pc and 50% hc would give in 1973 an energy saving of 31% whereas clinker production according to the dry process would have increased this saving to 44% ($9.3 . 10^{12}$J).
Finally, the manufacturing process of baked clay bricks, is important for the energy content of the bricks, caused by the type of kiln used.
Comparing the present average of about 9000 MJ/1000 WF with the figure of 3000 MJ/1000 WF of 30 years ago, we find that the large difference is caused by the artificial drying of the green bricks and the much more mechanised process.
All these data make it evident that energy analyses are important tools for the Building Industry.

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Form of energy accounting	Insight desired	Users	Basis of Conventions
Fossil fuel accounting ie analysis in units of fossil consumed	Resources depletion Environmental impacts	Environmentalists, resource groups etc.	Result expressed in terms of fossil fuel utilisation. All energy utilisation/conversion systems regarded as devices for burning fossil fuels. No intrinsic value attached to energy.
Fuel demand production Analysis	Utilisation patterns. Changes in demand patterns. Production capacity required	Fuel and energy suppliers. Planners.	Economic conventions.
Energy systems analysis (including process analysis)	Effectiveness of energy utilisation/free energy	Energy technologists	Standard thermodynamic conventions
Thrift analysis	Waste of energy	Civil servants	—
Energy input/output analysis	Energy content of goods. Use of energy in the economy	Service to other users. Policy analysts	Economic conventions associated with matrix techniques
Energy flow analysts	Comparison of energy systems using different fuels	Systems analysts	Separation of all forms of energy

All present forms of energy accounting ignore the energy content of labour.

Table 1 **FORMS OF ENERGY ACCOUNTING (1)**

Materials \ Process	pc		hc	
	wet	dry	wet	dry
marl	1.665	1.716	0.651	0.671
slate	0.360	0.259	0.141	0.101
extra water	0.434	—	0.170	—
gypsum	0.046	0.046	0.046	0.046
blastfurnace slag	—	—	0.60	0.60
Totally	2.502	2.021	1.608	1.418
Total Dutch production in 1973 in 10^6 ton	1.75		2.80	
Total Dutch consumption in 1973 in 10^6 ton	2.95		3.05	
World consumption 1973 in 10^6 ton	690			

Table 2 **CONSUMPTION OF RAW MATERIALS IN TON/TON CEMENT FOR CEMENT MANUFACTURE (6)**

type of cement	pc		hc	
process	wet	dry	wet	dry
Mining and transport raw materials	30	50	60	60
fuel in kiln	5930	3600	2320	1410
electrical energy for clinker, grinding, expedition	1110	1110	770	770
transport to consumer	150	150	150	150
Totally in MJ/ton	7,230	4,920	3,300	2,390
weighed average of Dutch production (MJ/ton)	6,400		2,950	
weighed average of Dutch consumption (MJ/ton)	4,650			

Table 3 **ENERGY CONTENT OF CEMENT (MJ/ton) (6)**

firing process	loading of kiln	type of kiln	energy content (MJ/1000WF)	weighed average in 1971 MJ/1000WF
permanent place	permanent place	clamp	13900-14400	
permanent place	moving	tunnel	7250-7670	7260(8920)
moving	permanent place	ring type	6870-7060	(total production
moving	permanent place	chamber type	8440-9160	2.10^9WF)

Table 4 **EFFECT OF TYPE OF KILN ON ENERGY CONTENT OF BRICKS (DELIVERED AT THE SITE) (7)**

Materials	Energy content		Materials	Energy content	
	MJ/kg	MJ/l		MJ/kg	MJ/l
sand, gravel	0.1	0.16	ready mixed concrete	0.8	1.9
light weight aggregates	4.0	2.5	reinforced concrete*)	2.5	6.0
lime	6.3	8.2	prefab concrete elements*)	2.0	4.7
portland cement	6.4	8.0			
portland blast furnace cement	3.0	3.8	steamed prefab concrete elements	2.3	5.5
gypsum	3.6	2.9			
water	0.004		light weight concrete	2.3	4.15
			light weight reinforced concrete*)	3.8	7.2
baked clay bricks	4.3	7.7	steel	30	236
sand lime bricks	0.84	1.5	reinforcement	23	180
clay brick masonry	6.0	11.0	prestressed steel	28	220
sand lime brick masonry	2.7	4.9	aluminium	120	325
glass	21	56	copper	30	270
rockwool	14	2.2	zinc	50.5	360
asbestcement	5.1	9.0			
coal	29.3		wood(sawn)	4	2.4
oil	43		plastic	40	40
natural gas		35	bitumina	20	20

*) inclusive 100 kg reinforcement per m^3 concrete

Table 5 **ENERGY CONTENT OF BUILDING MATERIALS**

concrete				brickwork		
	amount	energy content (MJ)			amount	energy content (MJ)
		gravel concrete	light weight concrete			
ready mixed concrete	0.1 m^3	257	470	baked clay bricks	75	570
reinforcement	7 kg	160	160	mortar	25	62
steel mould (used 100 ×)	1,7 kg (per use)	38	38			
Total		455	668	Total		632

Table 6 **ENERGY CONTENT OF FACADE ELEMENTS (1 × 1 × 0.1 m^3) MADE OF GRAVEL CONCRETE, LIGHT-WEIGHT CONCRETE AND BRICKWORK. (6)**

Material (1 m^2)	Energy content $10^9 J/m^2$	Loss of energy content $10^8 J/(m^2 year)$	Air to air heat resistance $m^2 K/w$ (6)	Loss of thermal[3] energy by transmission in $10^8 J/(m^2 year)$ (6)	Total loss of energy in $10^8 J/(m^2 year)$	Loss of energy content in % of total loss of energy
a. single glass window	0.40	0.20[1]	0.17	14.7	14.9	1.3
b. double glass window	0.76	0.38[1]	0.34	7.4	7.78	4.9
c. cavity wall	0.81	0.21[2]	0.6	4.2	4.41	4.8
d. cavity wall with cavity fill insulation	1.01	0.25[2]	1.5	1.7	1.95	12.8

1) based on 20 years life time

2) based on 40 years life time

3) based on $0.25.10^9$ sK/year (6)

Table 7 **YEARLY LOSS OF ENERGY CONTENT AND OF HEATING ENERGY BY TRANSMISSION (SEE ALSO 10)**

Material	building costs		costs of energy content		heating costs$^{1)}$ to eliminate transmission losses gld/(m^2 year)	total costs gld/(m^2 year)
	gld/m^2	gld/(m^2 year)	gld/(m^2 year)	in % of building costs		
a. single glass window 1 and 10 m^2 resp.	200/105	22.00/11.55$^{2)}$	0.20$^{4)}$	0.9/1.7	14.70	36.70/26.25
b. double glass 1 and 10 m^2 resp.	350/255	38.50/28.05$^{2)}$	0.38$^{4)}$	1.0/1.4	7.40	45.90/35.45
c. cavity wall	110	10.23$^{3)}$	0.21$^{5)}$	2.1	4.20	14.44
d. cavity wall with cavity fill insulation	122	11.35$^{3)}$	0.25$^{5)}$	2.2	1.70	13.05

1) based on energy price of 10.10^{-9} gld/J.

2) based on 20 years lifetime and 9% interest.

3) based on 40 years lifetime and 9% interest

4) based on 20 years lifetime

5) based on 40 years lifetime

Table 8 **YEARLY COSTS OF ENERGY AND BUILDING COSTS.**

Sector	Coal	Oil	Gas	Electricity	Total
Primary metal industry	8.5	1.7	2.2	4.6	17.0
Chemical industry	0.5	5.5	3.5	2.4	12.0
Shipping and aviation	0.0	10.2	0.2	0.3	10.8
Other transport	0.2	6.5	0.5	1.1	8.3
Paper	0.1	1.3	2.0	1.4	4.8
Trade	0.1	2.8	0.6	0.6	4.1
Food (animal)	0.1	1.9	1.1	0.9	4.0
Agriculture, forestry fishery	0.1	1.9	0.9	0.7	3.5
Building industry	0.3	1.6	0.4	0.7	2.9
Textile	0.1	1.2	0.7	0.8	2.8
Metal products engineering	0.6	1.1	0.4	0.7	2.7
Clothing, footwear	0.0	1.7	0.3	0.6	2.7
Transport vehicles	0.4	1.3	0.4	0.6	2.6
Electrical engineering	0.3	0.8	0.3	0.5	1.9
Drink, tobacco	0.1	1.0	0.4	0.3	1.8
Energy industries:					
electricity	2.1	8.1	19.4	3.9	33.4
coal	15.3	0.3	6.1	0.1	22.8
oil	0.0	4.5	0.2	0.7	5.4
gas	0.1	0.3	0.1	0.1	0.6

Table 9 **SHARE (%) OF THE ACCUMULATED ENERGY COSTS IN TOTAL PRODUCTION COSTS (1972) (5,p145)**

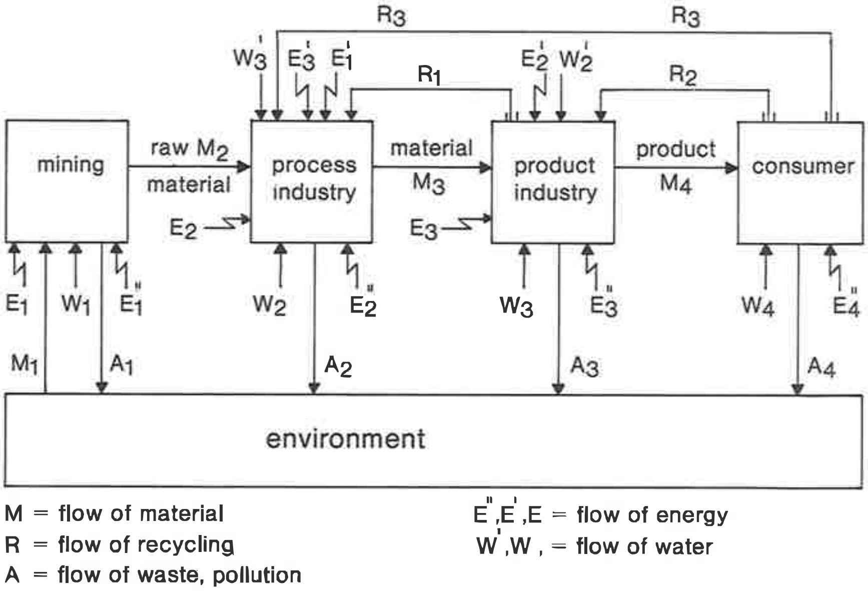

Figure 1. Flow diagram for materials, energy, water, waste and pollution and recycling.

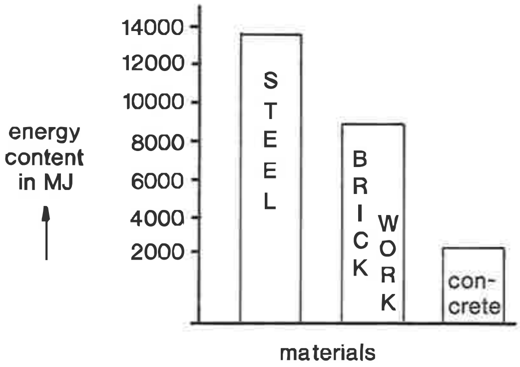

Figure 2. Energy consumption of a 1m high column, bearing 1000 ton load and constructed of various materials.

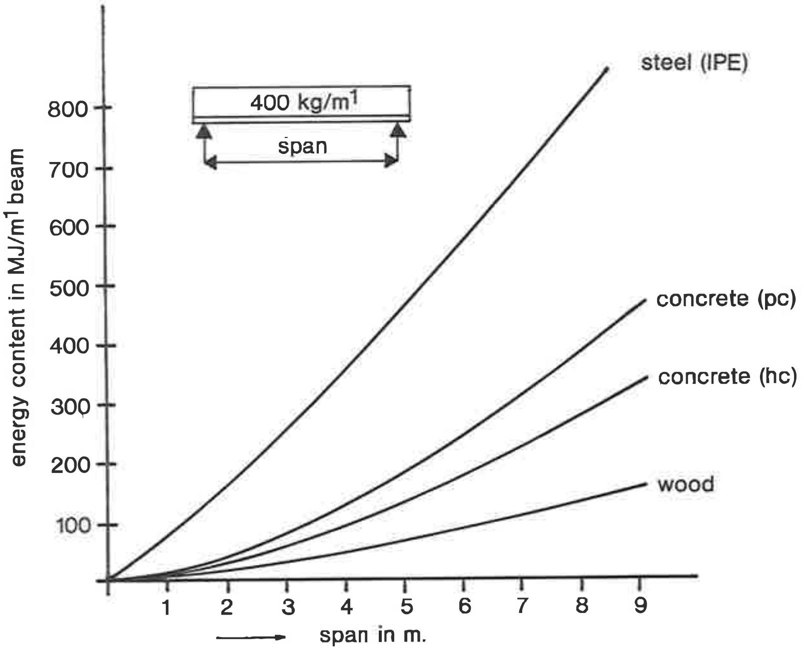

Figure 3. Energy content (per m¹ beam) of wood, reinforced concrete and steel as a function of the span, for simply supported beams.

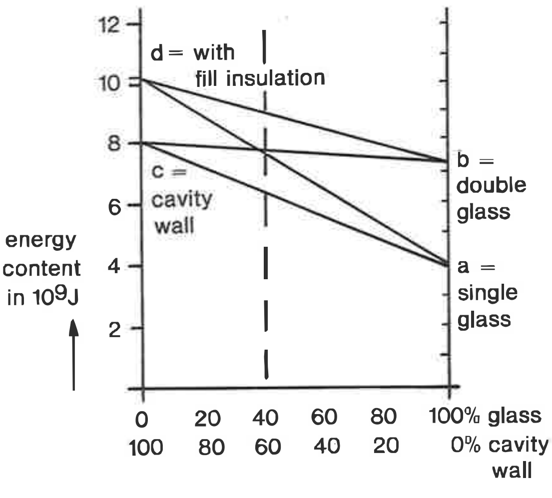

Figure 4a. Energy content of 10 m² facade as function of percentage glass.

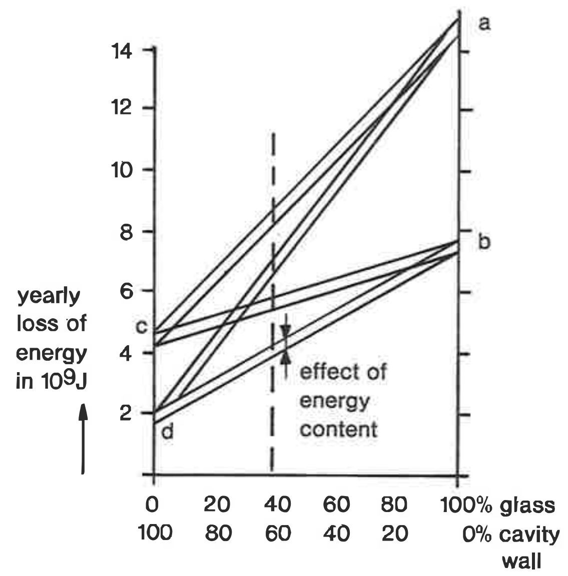

Figure 4b. Yearly loss of energy through 10 m^2 façade as function of percentage glass.

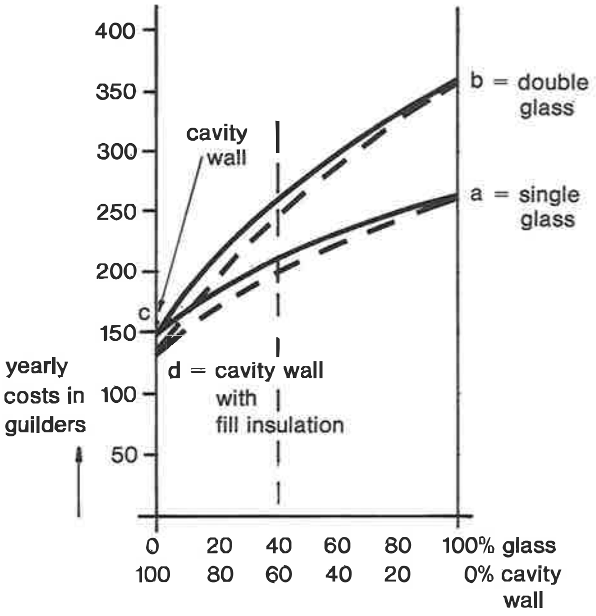

Figure 5. Yearly costs of building and energy.

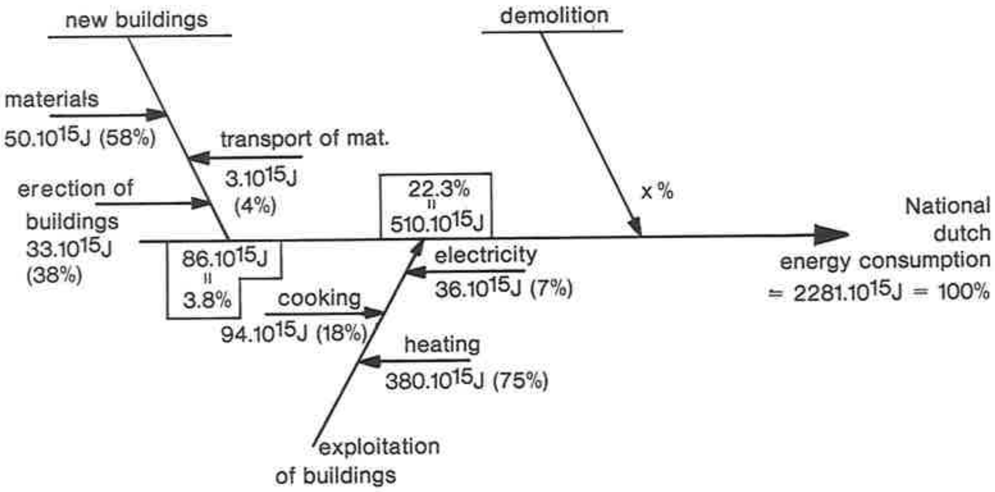

Figure 6. Energy related to buildings in 1972. [4] (in 10^{15}J)

PANEL DISCUSSION

Panel:

Dr. D. Altenpohl
A. Bolzinger
Dr. A. Decker
Prof.Dr. W. van Gool, Chairman
Dr. D. Hemming
Prof.Ir. P.C. Kreijger
G. Leach
Prof.Dr. T.V. Long
Dr. M. Slesser
Ir. E.J. Tuininga

(Van Gool) We have received a large number of questions, and it is impossible to answer all in just one hour. Some, however, can be dealt with briefly and quickly, as they go far beyond the scope of energy analysis. By now it will be clear that energy analysis is no magic wand that might be able to answer any question in the field of energy that is posed to it. There are some levels of sophistication that I would like to mention; you can start with the direct energy costs of a process - the PER value - and go upstream to arrive at the gross energy requirement - the GER value. In theory you can go still further upstream to arrive at an analysis of total energy systems, but at the moment we are not able to do that.

Quite a few questions referred to these total energy systems, and although the members of the panel could give a lot of information about these systems, I will give you short answers only, as a comprehensive treatment of one question could easily take more than an hour.

Several questions refer to the relation between energy analysis and ecology or environmental impact. This one is typical: "What is the preferred way to account for the environmental impact of the process under consideration in a particular energy analysis?" Questions like these lie outside the province of energy analysis. The environment is a problem in itself, and energy analysis cannot deal with all aspects of it. When you have analysed a certain process for energy, of course you may use the figures to compute the amount of waste heat it will generate. This can be used to say something about the environmental impact of the process, but the moment you start to do that, you have left the field of energy analysis, and you have entered the field of, let us say, environmental or ecological analysis.

Another general question that turned up a number of times deals with the acquisition of information and data. "The EEC and the International Energy Agency of the OECD seem to be working on data banks, but what is going on? What is the USA doing?" Another asks: "Should not some organisation collect and disseminate the data. Who should pay for it?" Interestingly, it is added: "We are aware of the CCMS excercise (Committee on Challenges of Modern Society)".

Well, the gathering of information is an extremely complex subject, and to discuss it generally is out of the question. I only can say something about the way we in Holland are trying to solve the problem. The Reactor Centre Netherlands will be transformed into the Energy Centre Netherlands, and the ECN will play a central role in collecting information about energy and making it available. However, I have to add that the actual collection of data will not be done by ECN only, but also by several other parties. The important point is to have one national information centre where all relevant data are available.

A part of the question was: "Who should pay for it?" I am not going to say anything about it, as it is a political question which should be answered by governments and parliaments.

Turning to the CCMS study, I think it is important. It has collected quite a number of data, and I have just heard that the Committee is trying to get published their facts and

findings as soon as possible.
Another general question is: "Can Energy Analysis be used to predict the future energy demand?" Obviously it can not be used for that. If you have a dynamical model of energy requirements, you can use the results of energy analyses as inputs, but that is all.
By now we should turn, I think, to the questions that have been put to the other members of the panel. Many questions were about methodology, so I intend to give Dr. Long and Dr. Slesser somewhat more time to answer the most important in their pile.
Dr. Long, will you start with some of the questions that have been put to you?

(Long) The first question I have here, is: "The sensitivity of the outcome of a particular energy analysis to variations in the input data, has not received sufficient attention. The supposed relative merits of electricity generation from nuclear fission are strongly dependent on the assumed load factor in conventional electricity generation.
Is the panel prepared to comment on the usefulness of energy analysis in view of such uncertainties in the input data?"
My comment is that any analysis is only as good as the data and the assumptions made. I don't think that one should take decisions based on energy analyses alone, and this will cover several other questions in my pile. The evaluation of energy requirements for the provision of a particular good or service, which is the objective of energy analysis, provides one with one element in calculating the money cost of that item or service. It is an important element, I believe, because one traces both the energy flows and the material flows in an integrated way. When talking about process energies for individual processes, one can easily loose sight of the method behind the analysis, which links energy and materials.
The data may be uncertain, and the uncertainties should always be stated. In my opinion, some sort of error-bounds ought to be placed on all studies which are done. Several of the figures in my paper do have error-bounds, and on the question of the energy requirement for reclamation of strip-mined coal lands, the error bounds were plus or minus 50 per cent. Still, it could be showed that the energy requirements were relatively small, and that was, I think, an important conclusion. Generally, one finds that the error limits are around 10 per cent.
Energy analysis should not be used in isolation, but as a component of an economic analysis. It can tell how one can respond under a perceived constraint in energy and it can be used to evaluate the impact of government policies. Governments may think that certain measures will reduce the use of energy, but such claims should always be analysed very carefully. For government measures usually are outside the market system, and unless the consequences are carefully analysed beforehand, one can easily end up with a policy costing more energy instead of saving it.
The next question asks "The opinion of the panel on the conversion of various energy forms into Gigajoules. Does the panel agree that, for instance, hydro-electricity should be valued at the same rate as electricity from primary energy? How could the energy content of fossil fuels be taken into account and how could its results be used to select the most efficient source?"
Partly, this is a question of detail. In most studies that have been done, one uses the national average value for the efficiency of electrical generation. But if analysing a particular industry which, as the aluminium industry in the USA, uses hydro-plants to produce electricity, one may make the evaluation more precise by using the actual efficiency of generation in that industry. I think that one should always state one's assumptions when aggregating the energies of various fossil fuels into one thermo-dynamic equivalent unit of a GJ, on the basis of the enthalpies or free energies of combustion. The general question contains an argument that comes up quite often. People say: 'We know there are various qualities of energy, why should not we take that into account?' My answer is that energy is defined really for a change, it is something that is conserved under a change. When we talk about a kJ, we mean a unit of energy that goes into a process during a change and then it is meaningless to ask wether a kJ of natural gas is better than a kJ of coal. If one wants to discuss the relative utilities of fuels in a process, one has to evaluate the total energy requirement of the process by adding up the fuels on the basis of their enthalpies of combustion. Then one can com-

pare processes, the first using natural gas, the second coal, a third electricity, the fourth oil and so on. You can do it in this way, but you cannot compare processes on the basis of second-law efficiencies alone. I would like to make one last point. This kind of disaggregated data should be presented in the paper, so that the reader can see for himself how much oil, natural gas or another fuel is used in the process.

(Van Gool) I am sorry to interrupt you, but you have only a few minutes left.

(Long) I'll answer two other questions, the first very quickly. It asks: "Are not we overemphasizing energy analysis? Should not we be looking at other resources too?" My comment is that we should be looking at other resources. Indeed, our Group is called the Resource Analysis Group and not the Energy Analysis Group. Specifically, we are looking already at water, as water appears to become another scarce resource just as energy is. We are trying to use the same techniques as we are using in energy analysis, but of course there are differences, of which the most important is the possibility of recycling.

The last question I'm going to answer is about the use of input-output tables, when applied to the evaluation of micro-economic processes. It includes the question whether one should use energy to dollar conversions. Well, I'm not an expert, but my opinion, for what it is worth, is that input-output tables should only be used for macro-economic evaluations. There are three good reasons for this. The first is that the data on which these tables are based, are quite out of date; in the input-output tables that are in use presently in the USA, you may find together data from 1963, 1967 and perhaps from 1971. The reason is that it takes an inordinate amount of time to prepare them. Secondly, the data are very aggregated, even at the 360 sector level used in the United States; there the chemical industry is listed just under this head and not divided up further.

Thirdly, energy is included in five rows that are segregated from the rest of the input-output table, and are corrected for price variations. It seems to me that these are not energy input-output tables, but financial ones. They may be very useful for macro-economic evaluations, but it is not obvious to me that they will give a better evaluation of the energy flow in a process than an energy analysis, which is a micro-economic evaluation carried out according to the IFIAS Convention. I think that, for the reasons given, the use of input-output tables would give rise to rather big errors.

(Van Gool) Thank you. I know that you could talk about these problems and questions for another hour, but now we have to turn to Dr. Slesser.

(Slesser) Just as Dr. Long, I'll try to select the most important questions, as I certainly cannot deal with all questions that have been put to me on methodology.

The first is quite general and asks whether we should distinguish between renewable and non-renewable sources of energy. Yes, we must make that distinction, but as far as I know there is no satisfactory method of linking these two types of energy into one parameter. The IFIAS Convention therefore treats solar energy and its derivatives like wind and so on, as a free good, just as it treats rain as free good. It concerns itself with the amount of energy resource, that is to say the stock taken from the world supply, sequestered to deliver a good or a service at any point in the system that interests you.

We might link this with the second question: 'Isn't it more important to think about materials than in fact to think about energy? The contribution of materials to the end-product seems to be much larger than that of energy."

This leads to some discussion on the theory which relates the use of energy to economic activity and I think that from Dr. Long's lecture we can see that there are quite a number of points of view here. One of the values in estimating the energy requirement of various commodities is to try to link it into some general theory. For example, I already have enough information to demonstrate that there is a trade-off between energy and land, between energy and time and between energy and intensity of activity. There also is a trade-off between energy and materials. For example, if your requirement is that of fresh water, say for irrigation pruposes, one can estimate the amount of energy required to make a thousand cubic meters of water available. The upper limitant is probably the desalination of sea-water. At the present moment we desalinate sea-water by a distillation process, but if we go to a semi-permeable membrane method we may reduce the energy requirement for producing fresh water. This shows that we can trade-off materials against energy and that energy can become a very important parameter for measuring these trade-offs. The next question asks: 'What are the system boundaries? Is it the factory, is it the country or is it the world?' Let me repeat what I said in my paper: The upstream boundary under the IFIAS Convention is the resource in the ground, you cannot go any further back than that. The downstream system boundary is the point that interests you, and the GER of a product at the factory gate will undoubtly be less than the GER delivered to the domestic customer. And in the Netherlands it will be less than, let us say, in Indonesia, if you have to convey it from Europe to Indonesia. So you choose a downstream system boundary that satisfies the point of interest you have.

Then we have: 'What is the panel's opinion about accounting for the quantities of energy resources that are not exploitable by economic or physical terms?' I'll answer this one with the help of a plot (Figure 1) which can be interpreted in a number of ways. It could be the cumulated amount of oil in a given oil field, it could be the cumulative amount of all energy resources in the world, it does not really matter. As you exploit a resource, the marginal PER* may initially fall slightly, we have a certain amount of evidence to support this. Eventually, as Dr. Hemming showed in his paper, we would expect it to rise and rise, till you arrive at the point where the marginal PER is greater than the calorific value of the fuel. Then you have reached the point of futility. But you never need to know what is the total quantity of the resource. As time elapses, you may discover new resources which effectively extend the curve to the right. You may have competing resources, and that is why the figure contains two lines. You may find at one point in time that the PER to deliver, let us say, oil is less than that of coal, but in some future point in time the PER of coal may become less than that of oil. But at no time you need to concern yourself with the total stock, that is a figure which emerges as you go along.

The next question asks: 'How do you justify the addition of different energy inputs?' I would like to start with a simple example from economics. If I am constructing a factory in Scotland and I buy equipment from Holland, I have to convert the cost from guilders into pounds. But the rate of exchange is by no means an absolute process, it is a relative process. The same goes for accounting in energy terms. If we sum gigajoules of coal, of oil, of natural gas and so on, we are undoubtely incurring errors. We could do it absolutely exactly if we accounted in terms of available work. But as I showed yesterday, the errors are not very big and are drowned in the noise as far as present standards of energy analysis are concerned. Now we come to the question of electricity. If you want to put a GJ value to it, my approach is to use the opportunity cost. You take the territory you are living in and you find out what is the avarage energy requirement to make electricity in that territory. Dr. Hemming and myself have given you figures for the UK; he used 4.17 MJ of energy resource for 1 MJ of delivered electricity and I gave you a lower figure for a later year. Now this are figures for the UK, and it would be stupid to apply the same figures to France, the Netherlands or anywhere else, for you have to determine what your local opportunity cost figure is.

The last question I would like to answer is: "How do you handle the energy content of old scrap?" Roughly speaking, we would approach it also on the basis of opportunity. You use steel to make washing machines for example, and eventually the machines go on the scrap heap. I take that the question means that scrap iron has a potential value as there is some energy locked into it. What credit should we give for that? Well, if the scrap stays on the scrap head till it has rusted away, you give no credit. But if it

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*) PER (Process energy Requirement = GER - Enthalpy content of resource delivered)

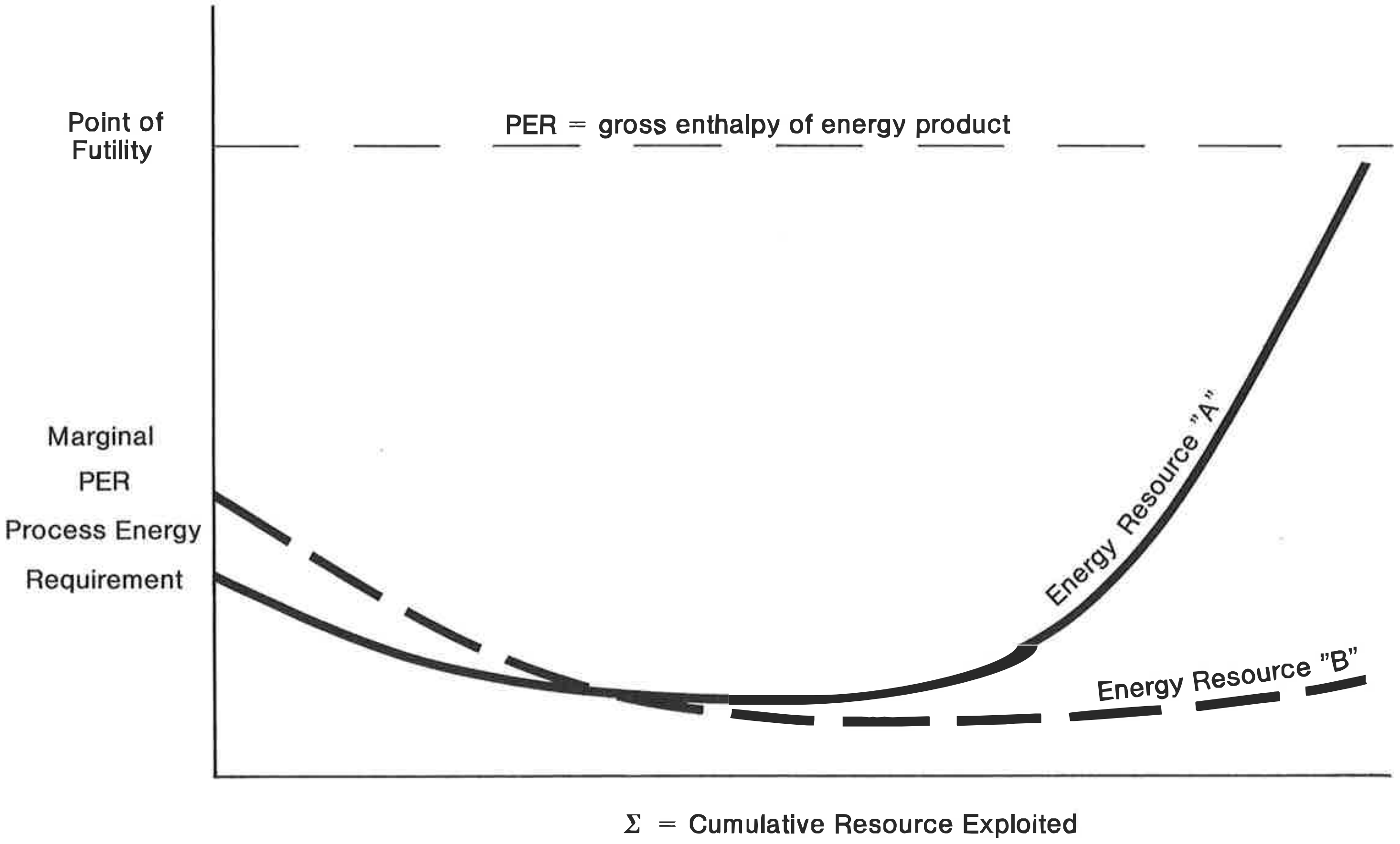
Point of Futility
PER = gross enthalpy of energy product
Marginal
PER
Process Energy
Requirement
Energy Resource "A"
Energy Resource "B"
Σ = Cumulative Resource Exploited

Figure 1.

finds itself recycled inside the economy, you first determine the energy requirement of restoring that scrap to steel and you substract this from the energy requirement of makking the same amount of new steel. This approach is reasonably self consistent, I think.

(Van Gool) Thank you. Your last point on scrap was very important, I think, as this question returns quite often. Mr. Bolzinger, may I ask you to take over from Dr. Slesser ?

(Bolzinger) The first question runs: "Does the energy price quoted in the table about the returnable glass bottle which makes 20 return trips, take into account the energy price of transport to the factory and the whole cleaning process ?" I can give a very brief answer: Yes, it was. You can find it in my paper, but I'll give a short summery now. We studied the cost of manufacturing and using 10.000 returnable glass bottles, that would do twenty return trips. So the waste factor was set at 5%. We calculated the costs for three different levels of oil prices. We found that the costs of transport and cleaning represented 2% of total costs for the lowest oil price and 6 and 12% respectively for the medium and highest oil prices.
The next question is very short: "Has the energy of feedstock been accounted for ?" With a restriction, the answer is yes again.
When determining the energy cost of glass bottles, we did not take into account the extraction cost of sand and of crude oil. But everything else is in.
The next question is a bit tricky, as I don't see what is aims at. It says: "Has the life expectancy of returnables been sufficiently considered ?" In our study of returnables we assumed that in the mean a bottle would do twenty return trips. The waste rate is set at 5 per cent, and when starting with one thousand bottles, this means that after each return trip you have only 50 bottles that have been broken or have become unfit for further use. It seems to me that this is a rather good performance. Of course, you have to remember that the whole thing is statistical. The first fifty bottles that will not be used again, are in the first batch, but a number of bottles will be used more than twenty times.
The last two questions should go together, as they have an environmental flavour. The first asks: 'What are the energy requirements for the waste disposal of PVC ?' and the second: 'What about the chlorine if the PVC bottle is not used again ?'. I'll be very quick about that. PVC has a heat of combustion of 5000 kilocalories per kilogramme, and it will be liberated when you burn it. Of course, that will generate hydrochloric acid. I have two remarks here, and the first is that we can cope with that problem; it is possible to remove the acid from the smoke. Secondly, waste has many materials in it containing chlorine and PVC used for bottles is not the worst offender. In France at least, it is estimated that when you burn waste, PVC adds only one per cent to the total amount of hydrochloric acid generated.

As to the net energy requirement for waste disposal of PVC, if one uses the heat generated by burning waste, there is no net energy requirement. The energy inputs for handling and transportation of waste are balanced by the energy output.

(Van Gool) Thank you very much, Mr. Bolzinger. I now turn to Mr. Leach, who has a few questions.

(Leach) I have two questions, and one is to Mr. Woodhead. It says: 'How much room is there for more natural fibre production ?'. My answer is simple: I don't know and I don't really think that this is a question for energy analysis.
The second question is about: 'How does one account for imports of food ?'. The suggestion is that it is done with a certain lack of methodology, as the question goes on with: 'And how should one do it ?'.
Obviously, the ideal way to put an energy charge on a food import is to take the growth energy requirement of the country of origin, in my own studies I did this wherever I had the data.
It was available for US maize and grain and soya and for Peruvian fishmeal for example.

But industrialised countries as Holland or the UK import many food products from many different countries and clearly one does not have all data for all countries of origin. The next best thing is to make a rough estimate based on national figures. If the imported foodstuff can be grown normally in the importing country, there is another way to arrive at a figure: one computes the energy cost of growing an additional amount of the food product equal to the amount imported. This method too has its pitfalls and it will give an estimate only. Returning to methodology, we know quite well what ought to be done, but often we cannot be as methodological as we would like because we lack data.

(Van Gool) Thank you, Mr. Leach. I now turn to Mr. Tuininga.

(Tuininga) The first question refers to the comparison between rail transport and truck transport, where for trucks the energy requirements of highway construction were included. The question runs: "Was the energy cost of railway construction taken into account in the railway case?" Yes, it was. But, as I pointed out in my paper, the year studied was 1968, and that was not a wholly normal year for British Railways, as they kept their investment in new tracks, equipment and so on as low as possible. Then there are two questions that can be answered together. Some felt that "medium distance coach transportation should have been included" and others that we "should have made a comparison between barges and rail and trucks". Yes, we should have done that, but we lacked data to do it. All we could find were some figures about fuel consumption, and none of the energy needed for building these systems. The data we have, suggest that the energy consumption of transport by barge is slightly lower than by railway and is about one third of that of trucks. A recent UK study on transportation by inland waterways gives about the same figures.
Last but not least, I would like to clear up a misunderstanding. I have been asked by some: "Why did the only speaker from TNO cast doubt upon the usefulness of energy analysis at the Conference organised by TNO?" I may have been not as clear as I wanted, so I wish to state that I did not want to cast doubt on energy analysis as a method. Today and yesterday we have seen that energy analysis is an important and powerful tool. However, I said in my paper - and I'll maintain it - that energy analysis is not broad enough to cover all aspects of complex systems such as transportation systems. These systems have consequences that cannot be measured in terms of energy, for example social consequences. Energy analysis is a powerful tool, but in analysing very complex systems it should be embedded in a wider method, such as technology assessment.
Secondly I think that scientists should question their own methods on principle, that they should ask themselves whether the methods they use are suitable for solving the problem in hand. Let us be humble and accept that sometimes we have to doubt our own methods.

(Van Gool) Thank you, Mr. Tuininga. Of course I agree that we should question our own methods from time to time, but let us not forget what Michael Faraday said, when after a lecture in which he presented something new, he was asked by a high lady: "Mr. Faraday, what is the use of it?" He answered in a flash: "Madam, what is the use of a new born baby?" Let us not doubt the viability of our new babies too early, we should give them a chance to grow up and show strength.

May I now ask Dr. Altenpohl to answer his questions?

(Altenpohl) In some respects I do agree with Mr. Tuininga, for I think that energy analysis has become a kind of a buzz-word.
Many think that by energy analysis one can solve almost any problem of society, but as the Chairman has said in his introduction, energy analysis is not a magic wand that will answer any question posed to it. To use energy requirement as the only criterion for deciding between a wooden or an aluminium window frame seems rather narrow, as important factors - e.g. performance or convenience - are left out of the assessment.

The first question I have is: "Can you give a few typical examples of energy accounting being important in the aluminium industry?"
Well, I could give many examples, but in view of the limited time I'll have to select a few. The first is the alumina process which is very important in our industry. Today, most alumina is made from bauxite, but some other minerals are used or are under consideration for use.
Energy analysis is a very important part of the decision process whether to use minerals other than bauxite.
Then we have the Bayer process to make alumina. It is used all over the world, but there are two variants of it that differ in energy intensiveness. One route, that is used mostly in the US, takes about 50 per cent more energy than the other route, used mostly in Europe. Here energy analysis is important for our industry, and I heard during lunch that the American aluminium industry is seriously studying this second process and may switch over to it in the next few years. My second example comes from the US too. There a number of aluminium smelters are using natural gas as their primary fuel. However, natural gas is coming into short supply and the government is curtailing its use for activities such as metal smelting. So these firms are doing energy analyses to determine whether they should switch to coal or oil as their new primary.
I would like to repeat a remark of Dr. Decker in slightly altered form. His remark related to the steel industry of course, but I think it is equally true for the aluminium industry and in fact for every metal smelting or metal refining industry. These industries realised that they were large users of energy tens of years ago and have sought for ways to lower their energy requirements. They started to do this in the past when energy was still relatively cheap and nobody even thought about an energy crisis. This policy was, and is, based simply on economic cost criteria.
Then I have quite a number of questions clustering around recycling and garbage. A typical one is: "You only gave the energy for remelting recycled aluminium, can you give also the energy requirement for sorting garbage, separating, transporting etcetera?"
No, I cannot give you these figures, we don't have them yet. It can be very variable; if there is a boy scout drive to collect discarded aluminium, and a scout induces his mother to drive him aroundin the big family car and just picks up six empty beer cans in a whole afternoon, then you can be sure that there is a negative energy balance. We don't have figures on the energy requirement of sorting garbage professionally. We looked into it as we would like to have some idea of the supply of recycled aluminium we can expect in the future. In doing this study we discovered of few things. First, that the lifetime of aluminium product varies enormously. A window frame may last fifty years, the life of a beer can is measured in weeks. With many of the short lived products you can expect to have seasonal fluctuations in sales and so in supply of scrap. Another thing is that we expect that within five years or so few car radiators will be made of copper or brass anymore, 80% will be made from aluminium. Such a radiator has a lifetime of five to seven years and in the long run the switch to aluminium will influence the scrap market. Another expectation is that the car industry in particular, but other industries too, will get interested in products that can be recycled easily. Most products can't today, but we expect that industry will start the manufacture of products with a built-in ease of recycling quite soon. I hope this explains to some extent why I cannot give figures about the energy requirement of recycling.
Mr. Chairman, that were the most important questions that have been put to me.

(Van Gool) Thank you, Dr. Altenpohl, it is always a pleasure to hear you digressing. I now turn to Mr. Decker, who has a few questions about steel.

(Decker) I have only three. The first says: "What could be the added enthalpy in going from steel to the finished product, in comparison with the total enthalpy requirement of steelmaking? How should one account for the enthalpy value of a steel product after the end of its economic life?" Well, the enthalpy needed to make a finished product out of steel depends on the type of product. I can only give a rough estimate: in general manufacturing of a product from steel takes an amount of energy equal to 15 to 30 per cent. of the energy used for making the steel in the first place.

For the enthalpy value of scrap one can follow the convention described by Dr. Slesser. One works out the energy difference between making steel from ore and from scrap, for instance in an electric arc furnace. This is the energy value of the scrap, and it will be higher the better the quality of the scrap is.
My two other questions do ask the same thing, and I'll answer this one: "How do you account for the low energy requirements to all finishing operations after the stage at which crude steel is made?" Strictly speaking, I cannot account for it, I only can give some figures. Roughly, reheating one ton of steel for rolling, uses about $1\frac{1}{2}$ GJ and the rolling operation takes about 100 kWh for one ton. The exact values depend on the type of product; thick slabs can be made in one rolling operation, for lower gauges one has to repeat the reheating and rolling two or three times.

(Van Gool) Thank you, Dr. Decker. Dr. Hemming is one member of the panel having still a number of important questions before him. Could you keep a good eye on the clock and try to answer in a few minutes?

(Hemming) I'll give it a try anyway. I have been asked "whether I have accounted for the different qualities of oils from different sources". To answer that one has to look at the confidence one has in the figures. I would not claim more than an accuracy of plus or minus 10 per cent. and I think that variations in quality would be drowned in the noise.
I am also asked to comment on the cost of processing fuels with a high sulphur content. This is answered by the system boundary one chooses. I chose the point where oil enters the refinery, but if one extends the study further to include the energy requirements of finished products, then the sulphur contents of fuels will come into the discussion.
The next question is about disposing the spent shale and environmental quality. Well, at the moment this is very much a matter of speculation. A part of the large water requirement for oil shale operations comes about by revegitation of the spent shale. In the figures I presented I have assumed that spent shale will have to be carted for about ten miles for disposal, but I have not gone into more detail than that. Then comes: "What is the merit of energy analysis in cases like Middle Eastern oil or North Sea oil, where the energy is small?" I think the answer to that is that it is always nice to know just where you are, and by looking at possible future sources of liquid fuels, where we might be heading, and it certainly looks that we are heading for more energy intensive fuels. Now I have: "In bringing oil from the source to the destination, what can be saved on transport costs?" This is a pertinent question for Middle East oil, as transportation loomed large in the energy input, but being not really a tankerman, I cannot answer that. And finally I was asked "What will the energy cost of North Sea oil be, if the destination is not the UK, but Middle Europe?" This will add to the energy cost, but the distances are not large and certainly for tanker operations I don't think it would be very significant.

(Van Gool) Thank you. There are still some questions on buildings, I think.

(Kreijger) The first question is: "Have you looked into the energy requirements of service dwellings versus below service dwellings?" The answer is no, I have not looked into it. The next is: "Have you taken solar input into account in the glazing studies, position of house, windows etcetera?" Yes, we took it into account, it is in the calculation of the average losses of heat of a house. Of course, you can calculate it separately, and the figures for it can be found in my paper. The last question: "What is the effect of indirect energy on building energy costs in total?" I did not need this figure, so I did not calculate it. The direct energy consumption in MJ per guilder of total production was 2.43, while the accumulated energy was 6.69. It should be realised, however, that these figures are averages.

(Van Gool) Thank you. We still have a few minutes left and I think that Professor Long and Dr. Slesser each have a question left that they would like to answer.

(Long) Well I have here: "The panel's opinion is asked about the future role of energy accounting in company management. For instance, what about energy budgetting, and are already examples of applications?" Well, I pointed out in my paper that Dow's Chemical Company International runs their whole operation using energy analysis as a management tool. They will go to a plant manager and say: 'We know the total amount of direct plus indirect energy that flows into this plant, and the total amount which flows out. We want you to reduce the amount that you require by 10 per cent.' Six months after he has done that they will pat him on the back and say: 'That is good, but now we have calculated the theoretical minimum and we want you to get within 10 per cent. of that.' It represents a large, variable monetary cost that is locked up in this parameter, and they can change their pricing daily, based on the price of a unit of energy, under the assumption that they can come up with a good overall price for a unit of energy. It makes them very profitable. One thing I would like to emphasize, is that materials and energy, which are summed up in an energy analysis, are the variable costs which are associated with managing a company and with decisions. Many times you are locked in to labour costs and to capital cost, and the only way to make a profit is by decreasing the energy and materials used in a process through housekeeping or knowledgable conversation; so it does become a very profitable tool for management to use in making decisions.

(Van Gool) Thank you. I now turn to Dr. Slesser.

(Slesser) May I take the opportunity of saying that I had the same question before me and that I would have given the same answer, though probably not as well. The last question is: "When one works out the energy requirement, do you use the gross or the net heat of combustion?" IFIAS recommended to use the gross heat of combustion with air, and to use the value a 1 bar of pressure and 273 degrees Kelvin. A very good reason for this is that, if at any time in the future we are using gross energy requirement figures in connection with a consideration of the climate, gross enthalpy of combustion is not a relevant figure.

(Van Gool) Thank you. Ladies and gentlemen, our time is up. I thank the members of the panel for their contributions and the members of the audience for posing so many clever questions.

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