A series of articles exploring and reviewing the rapidly-expanding study of the energy costs of production processes, encompassing foods and agriculture, transport, materials, petrochemicals and products, and their importance for policy making.

2. The energy cost of fuels

P.F. Chapman, G. Leach and M. Slesser

In the UK, the energy industries are the largest *consumers* of energy, using 30% of the present total. New sources of energy are likely to be even more demanding of fuels. In this article, the second in the series on Energy Budgets, the authors analyse the energy supply industries in the UK and examine implications for the future. They recommend that more attention be paid to materials recycling and to the development of renewable energy sources to avoid continuing inflation of energy use.

Dr Chapman is a member of the Science Faculty of the Open University, Milton Keynes, Buckinghamshire, UK; Mr Leach is a Visiting Fellow at the Science Policy Research Unit, University of Sussex, Brighton, UK; and Dr Slesser is Senior Lecturer in the Department of Pure and Applied Chemistry, University of Strathclyde, Thomas Graham Building, 295 Cathedral Street, Glasgow G1 1XL, UK.

The events of late 1973 made it transparently obvious that energy, in the form of fuel supplies, is crucial to a modern industrialised society. This rude awakening to the significance of energy has led to increased research into future sources of supply and, very belatedly, research into how energy is utilised in a modern economy. At last we are asking ourselves the question 'how much energy do we *need*?' This question has no definitive answer; any answer will depend on the assumption made about standards of living, personal mobility, sources of food and materials and, of course, possible technological developments. One way of approaching this question is to examine how we presently make use of the energy consumed.

Perhaps the most startling result of this examination is that the largest energy-consuming sector of our economy consists of the energy industries. The five energy, or fuel, industries – coal mining, oil refining, coke, gas and electricity production – jointly consume more than 30% of the total energy input to the UK. Put another way, for every 100 units of energy or fuel input to the UK less than 70 units is delivered to a consumer for use.

There are three reasons for examining the energy efficiency of the fuel industries in more detail:

- the fact that the fuel industries are themselves the largest consuming sector offers the chance of reducing the demand for primary energy supply without adversely affecting the rest of the industrial system;
- the energy wasted by industries constitutes a major hazard to local,[1] and perhaps global,[2] climate. Whatever the limit on the 'safe' heat release into the atmosphere it is clearly desirable to minimise the ratio of the 'heat wasted' to energy delivered to consumers;
- it is essential to know the energy efficiency of individual fuel industries in order to evaluate the energy costs of manufactured products or processes.[3] With this information it is possible to compare the total efficiency of two processes which consume, say, one ton of coal or 1000 kWh of electricity.

[1] C.I. Griffiths, *Meteorological Magazine*, March 1974

[2] For example, see 'Inadvertent climate modification' SMIC (MIT Press, USA, 1971), or P.F. Chapman, *New Scientist*, Vol 47, 1970, p.634

[3] P.F. Chapman, 'Energy costs: a review of methods', *Energy Policy*, Vol 2, No 2, June 1974, p 91: the first article in this series on Energy Budgets

The fuel supply industries form a complex interconnected system with each industry supplying fuel to every other. For example, oil refineries supply fuel to electricity generating stations which supply electricity to the oil refinery. An oil refinery may also provide the fuel used by the tankers which deliver crude oil to the refinery. These interactions require a careful method of analysis based on a systems approach. In addition to consuming fuel the fuel industries also consume large quantities of materials and machines which require energy for their production. This 'indirect' energy consumption must be included in the analysis. Finally, most of the industries produce more than one product as output. It is therefore essential to have an acceptable convention for partitioning the total energy costs of the inputs between the different outputs.

The first part of this article outlines the method used to analyse the energy supply industries using the data provided in the *Report on the UK Census of Production 1968*.[4] The results obtained are compared with those derived from other sources. The second part of the article attempts to put these results in a wider context by examining some of the implications of alternative sources of energy.

Method of analysis

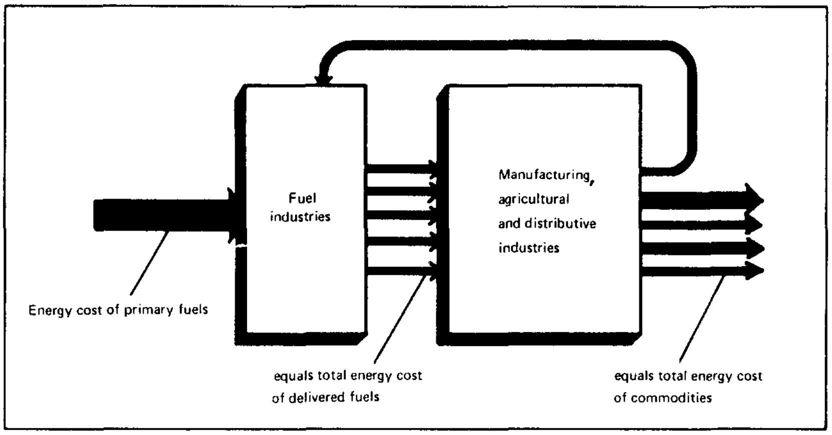
The maximum energy which can be extracted from a fuel is called the *calorific value* of the fuel. For example, the heat energy available in one ton of coal is about 8000 kWh, the exact value depending upon the type of coal. When the coal is burned some of the available energy may not be utilised either because the coal is only partially combusted or because some of the heat generated is 'lost' up the chimney. The calorific value of coal is therefore a measure of the amount of heat energy potentially available.

In evaluating the energy cost of a product it is the total energy available which is counted as part of the energy cost, not simply that part of the energy which is utilised. However, it is not sufficient to consider simply the calorific values of the fuels used in a particular process; account must also be taken of the energy expended in making the fuel available for use. For example, the mining and transport of coal involve the consumption of fuel, so the total energy cost associated with the consumption of a ton of coal is the sum of its calorific value and the energy expended in producing the ton of coal. The sum is called the energy cost of coal. It is the purpose of the present analysis to evaluate the energy costs of fuels as delivered to industrial or domestic consumers.

The network of industries in the UK can be divided into two sectors, as shown in Figure 1. The first sector comprises the five fuel industries and has, as basic inputs, the raw fuels: oil in the ground, coal in the ground etc. Other inputs are machinery, plant, equipment, materials and services, such as transportation, from the industrial sector. The industrial sector is, in this model, a large 'black box', which consumes fuels and raw materials to produce final commodities. The goal of energy analysis is to apportion the total energy input in the form of primary fuels between

[4] *Report on the Census of Production, 1968* (HMSO, UK, 1971)

Figure 1. The 'fuel supply' and industrial sectors



commodities. Thus for the total system there is a convention of 'energy cost conservation'. This states that the sum of all the inputs (x_i) times their respective energy costs (E_i) should equal the sum of all the outputs (y_j) times their respective energy costs (E_j). Formally this can be written:

$$\sum_{\text{inputs}} x_i E_i = \sum_{\text{outputs}} y_j E_j$$

When the analysis is complete the energy costs of the outputs (E_j) reflect the proportion of the primary fuel inputs required for their production.

The present analysis is concerned with the inputs and outputs of the fuel industries. It is important to note that the conservation of energy cost is *not* the same as the conservation of energy since, for example, the energy flowing into the fuel industries is *not* equal to the energy content of the fuels flowing out.

The steps in proceeding with this analysis are first to identify all the inputs and assign energy costs to each and second to identify the outputs and calculate their energy costs.

The fossil fuel inputs to the fuel industries – oil, gas and coal – are given energy costs equal to their calorific values. There are two other primary inputs, namely nuclear fuels and hydro-electricity. There is no generally acknowledged 'calorific value' for a nuclear fuel and various authors count this input in different ways. In this analysis the nuclear input is given an energy cost equal to the heat generated in the nuclear reactor. This is compatible with using the calorific values of fuels since, in principle, the heat from a nuclear reactor could be substituted for the heat obtained by burning coal. For hydro-electricity the energy cost is taken as the electricity output since this is the *heat* equivalent. (In practice hydro-electric installations are between 80% and 90% efficient at converting mechanical energy into electricity.)

The remaining inputs to the fuel industries are materials, machines and transport, all products of the industrial sector. The energy costs attributed to these items are those deduced by a preliminary analysis of the 1968 Census Report. These inputs represent about 2·5% of the total energy cost input,[5] so the use of approximate energy costs (accurate to ± 10%) for these does not involve significant errors in the final result.

[5] P.F. Chapman, 'The energy cost of fuels: UK 1968', Open University Energy Group: Research Report ERG003, November, 1973

The outputs of the fuel industries involve a different type of problem, namely deciding how to apportion the input energy costs between the different outputs. There are four obvious possibilities.

1. Assign all the energy costs to the principal output, since this is required product.
2. Assign the energy costs on a financial basis so that every output of an industry has the same energy cost per £ value.
3. Assign the energy costs on a weight basis so that every output has the same energy cost per ton.
4. Assign the energy costs on the basis of calorific value so that all outputs have the same ratio of energy cost to calorific value.

Assumption 1 implies notions of purpose or usefulness inappropriate to a study based on physical variables. It also results in logical absurdities when the same end product (gas) is the principal product of one plant (gasification plant) but a secondary product of other plants (coke ovens etc). Assumption 2 is convenient since then the flow of energy can, in principle, be traced through a system by techniques of financial analysis (eg the input-output table method).[6] It is a dangerous procedure since the price of products changes with time and may be different to different purchasers. The partitioning on a weight basis (Assumption 3) is an attempt to relate the energy cost to a physical property of the product. However, this and all the other procedures outlined above could result in the absurd situation of having the energy cost of a product less than its true calorific value. (This is absurd because the analysis could then make recommendations for saving 'energy costs' without altering the real consumption of energy!) Thus the only convention which is physically sensible is to apportion energy costs on the basis of calorific value. This is the basis of the method described below.

If the analysis is to be based on calorific values then there are two sets of data required. The first is the physical quantity (in tons, gallons etc) of each output of a given industry. The second is the calorific value of each of the outputs. This procedure allows an independent check on the data for each industry since no industrial plant should produce more calorific value than it consumes.

Having identified all the inputs (x_i) and assigned energy costs (E_i) to them and identified all the outputs (y_j) and their respective calorific values (C_j) it is now possible to evaluate an 'efficiency' for each industry. This efficiency is defined as being equal to the total calorific value of outputs divided by the total energy cost of inputs. It is thus a *conventional* efficiency and *not* a true efficiency like energy out divided by energy in. Denoting the efficiency by η this can be written

$$\eta = \frac{\text{calorific value out}}{\text{energy cost in}}$$

$$= \frac{\Sigma\ y_j\ C_j}{\Sigma\ x_i\ E_i}$$

Thus the energy cost required to produce one unit of calorific

[6] D.J. Wright, 'Energy costs of goods and services : an input — output analysis, to be published in *Energy Policy*, December 1974.

value output is the reciprocal of this efficiency. The reciprocal of 'efficiency' can be denoted by ϵ, so that

$$\epsilon = \frac{1}{\eta}$$

The energy cost of an output is the proportion of the energy cost of the inputs required for its production. The input energy cost required for each unit of calorific value output is simply ϵ. Thus if an output has a calorific value C_j kWh/ton then its energy cost will be $\epsilon\ C_j$ kWhth/ton:

$$E_j = \epsilon\ C_j$$

Thus, provided the constants, ϵ, appropriate to each industry can be evaluated, the energy cost of an output can be deduced from its calorific value. Herein lies a problem, for each energy industry actually supplies fuels to each of the other fuel industries. Thus to calculate the efficiency (or ϵ) for the electricity industry we first need the efficiencies of all the other fuel industries, since these are inputs to the electricity industry. But electricity is also an input to all the other industries!

This problem is solved by setting up the five simultaneous equations describing the inputs and outputs of each industry. The procedure is as follows:

(a) Identify all the outputs for industry A, find their calorific values and calculate the total calorific value out, C_a.
(b) As explained above, the total energy cost of the output of this industry is then equal to $\epsilon_a C_a$.
(c) Identify all the inputs to industry A other than those from other fuel industries. Assign energy costs to each input and work out the energy cost input from these sources, E_a.
(d) Calculate the total calorific value of the input to industry A from another fuel industry, say industry J. Call this C_{ja}. The energy cost of this input is equal to $\epsilon_j C_{ja}$ where ϵ_j has not yet been found. This is repeated for all the other energy industries which supply industry A.

Now we can use the 'conservation of energy cost' to obtain the equation for industry A:

energy cost out = Σ energy cost in

$$\epsilon_a C_a = E_a + \sum_j \epsilon_j C_{ja}$$

This equation has only five unknowns (the five values of ϵ for each industry) and we can obtain five such equations. So the equations can be solved and the values of all the ϵ's found.

Solving the equations

Applying the technique outlined above to the five UK fuel industries results in the five energy cost equations[5] which summarise the operation and interdependence of the fuel industries in 1968 (see Table 1). The multipliers, ϵ_m etc, are the reciprocals of the efficiences of the industries involved. Thus 'reading' the first equation from left to right gives:

Table 1. Equations linking the energy industries (1968)

$1160{\cdot}94\epsilon_m$	=	1187·63	+		+	$0{\cdot}146\epsilon_c$	+	$0{\cdot}04\ \epsilon_g$	+	$0{\cdot}24\epsilon_o$	+	$5{\cdot}07\epsilon_e$
$223{\cdot}0\ \epsilon_c$	=	0·41	+	$235{\cdot}45\epsilon_m$	+		+	$10{\cdot}60\ \epsilon_g$	+	$1{\cdot}14\epsilon_o$	+	$0{\cdot}41\epsilon_e$
$187{\cdot}74\epsilon_g$	=	7·72	+	$81{\cdot}09\epsilon_m$	+	$66{\cdot}6\ \epsilon_c$	+		+	$75{\cdot}56\epsilon_o$	+	$1{\cdot}09\epsilon_e$
$1077{\cdot}5\ \epsilon_o$	=	1092·2	+	$0{\cdot}04\epsilon_m$	+	$75{\cdot}73\ \epsilon_c$	+	$25{\cdot}25\ \epsilon_g$	+		+	$1{\cdot}34\epsilon_e$
$182{\cdot}77\epsilon_e$	=	127·3	+	$520{\cdot}42\epsilon_m$	+	$2{\cdot}48\ \epsilon_c$	+	$0{\cdot}269\epsilon_g$	+	$82{\cdot}27\epsilon_o$		

Note: m = coal mining; c = coke; g = gas; o = oil; e = electricity. All numbers are x 10^9 kWh

- calorific value of coal mining output is 1160·94 x 10^9 kWh
- this calorific value times ϵ_m is the energy cost out
- the energy cost out *equals* the sum of the terms on the right hand side which are energy cost inputs
- the energy cost input from materials consumed and coal in the ground is 1187·63 x 10^9 kWh.
- the energy cost of fuel purchased from the coke industry is ϵ_c times 0·146 x 10^9 kWh
- the energy cost of fuel purchased from the gas industry is ϵ_g times 0·04 x 10^9 kWh etc.

The total energy cost input to all the fuel industries from primary fuels and raw materials is the sum of all the terms on the right hand sides which are *not* multiplied by an ϵ_j. Thus the primary input to the energy industries is 1187·63 + 0·41 + . . . = 2415·26 x 10^9 kWh. The *net* energy output of the energy industries has to be calculated by subtracting the fuels delivered to other energy industries from the gross output. Thus the gross calorific output of the coal industry is shown as 1160·94 x 10^9 kWh. But of this 235·45 x 10^9 kWh was delivered to the coke industry (shown in second equation), a further 81·09 x 10^9 kWh to gas, 0·04 x 10^9 kWh to oil and 520·42 x 10^9kWh to electricity. The *net* output of the coal industry is thus 323·94 x 10^9 kWh. The *net* output of all the fuel industries is 1646·7 x 10^9 kWh. Thus the *overall* efficiency of the fuel sector is 68·17%, indicating a loss of more than 30% of the primary energy input (see Figure 2).

Solving these five equations for the five unknowns, ϵ_c, ϵ_m etc., gives the values and corresponding efficiencies set out in Table 2. Also shown in Table 2 are similar results deduced from the 1963 Census Report[7] and values deduced from less detailed data in the

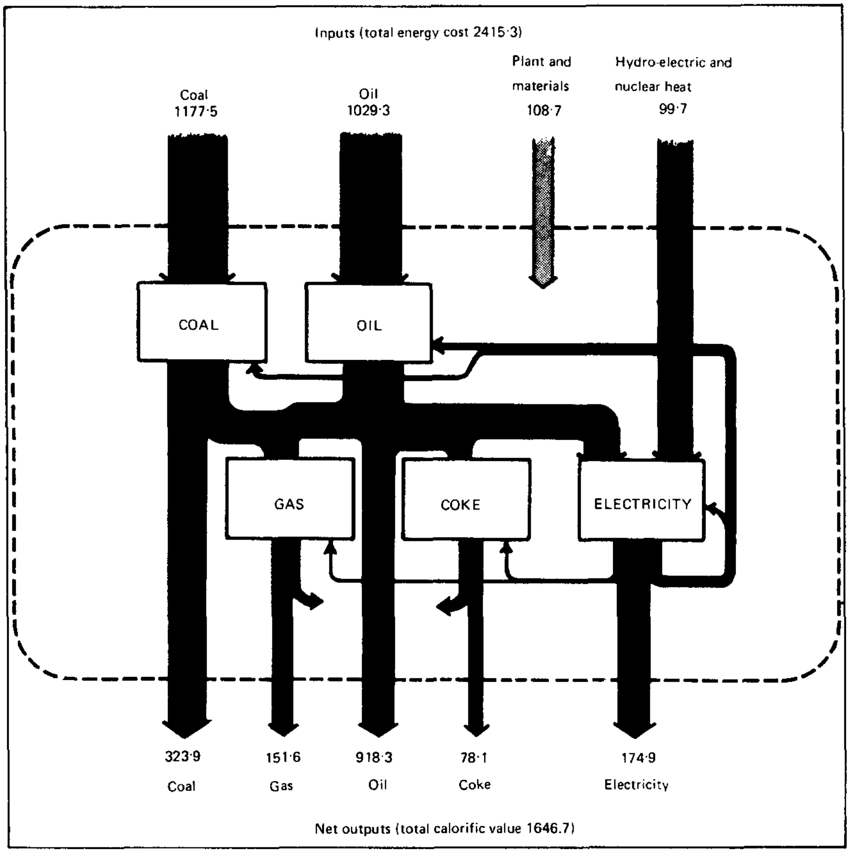
[7] T. Jackson and P.F. Chapman, 'Analysis of the 1963 Census of Production' (to be published)

Table 2. Efficiencies of energy industries

	1968		1963	1971/72
Industry	(from Table 1) (ϵ)	Efficiency (%) ($1/\epsilon$ x 100)	Efficiency (%)	Efficiency (%)
Coal	1·042	95·99	95·49	95·5
Coke (ϵ_c)	1·181	84·71	75·54	88·0*
Gas (ϵ_g)	1·390	71·92	64·74	81·1
Oil (ϵ_o)	1·134	88·21	80·82	89·6
Electricity (ϵ_c)	4·192	23·85	22·02	25·2

* This result is less accurate than others due to lack of data for coke-ovens 1971/72

Figure 2. A summary of the energy flows of the energy sector as a whole. Quantities in 10^9 kWh



UK Energy Statistics[8] for 1972. There is a number of important factors to bear in mind in interpreting these results.

Perhaps the most important is that the efficiency of a fuel industry should not be considered in isolation but in conjunction with typical efficiencies for utilising that energy. For example, a careful comparison of the overall energy efficiences of electric[9] and petrol[10] powered cars, summarised in Figure 3, shows electric cars to be only marginally less efficient. A similar comparison between oil-fired and electric-powered house heating (Figure 4) shows the oil system significantly more efficient. Thus the efficiency of the supply industry is only part of the overall 'energy efficiency'.

The second point to note is that the significant improvement in the efficiency of the gas industry in 1972 is, to a large degree, due to the use of natural gas as opposed to town gas. Although this probably reflects a true gain in efficiency the data available do not include all the exploration and drilling 'energy costs' of providing natural gas.

The overall efficiency of the electricity supply industry is much lower than the notional 33% assumed by many authors, presumably on the basis of modern power station efficiencies of 35%. There are three reasons for this. First, *most* of the power stations operating in the UK are not 'modern' and the overall thermal efficiency is still less than 29%.[11]

Figure 5 shows the steady, but slow, increase in 'overall thermal efficiency' achieved since 1932. Second, the transmission of electricity involves losses. In 1968 these amounted to 7·5% of the electricity generated.[4] A further 7·6% of the electricity generated[4]

[8] *United Kingdom Energy Statistics, 1973* (HMSO). Note this publication does not give full details of all purchases and the final results are less accurate than those based on refs 5 and 7

[9] D.P. Grimmer and K. Luszczynski, *Environment*, Vol 14 No 3, 1972, p 14

[10] G. Leach, *The motor car and natural resources* (OECD, Paris 1972); and G. Leach, 'The impact of the motor car on oil reserves, *Energy Policy*, Vol 1, No 2, 1973, p 195

[11] *Electricity supply statistics*, (Electricity Council, London, 1971)

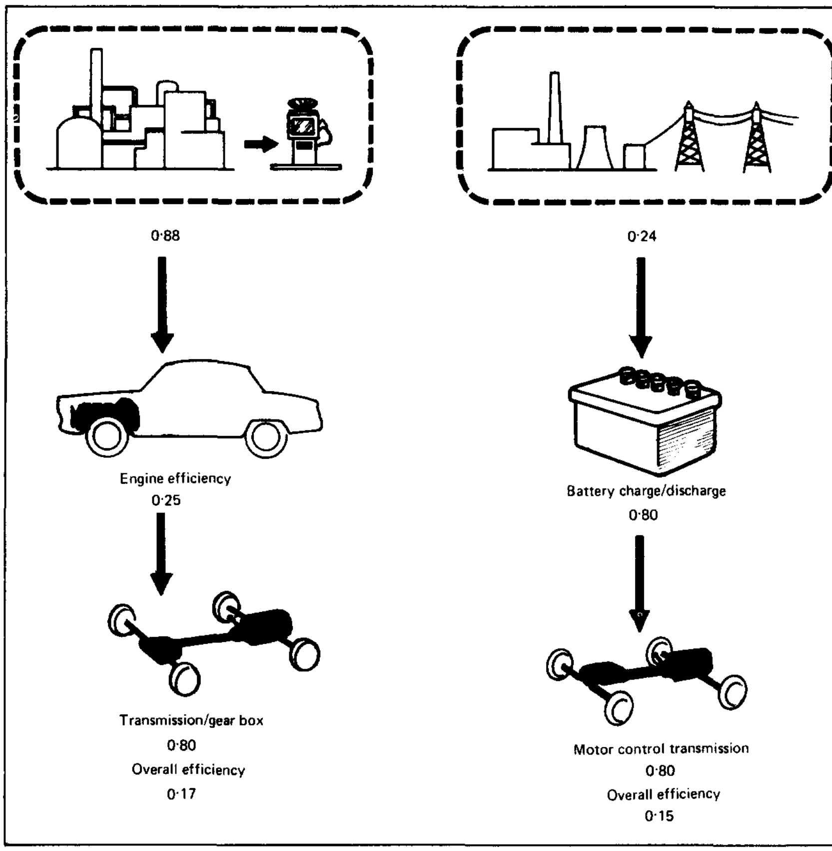


Figure 3. Comparison of the total efficiency of electric and petrol powered cars

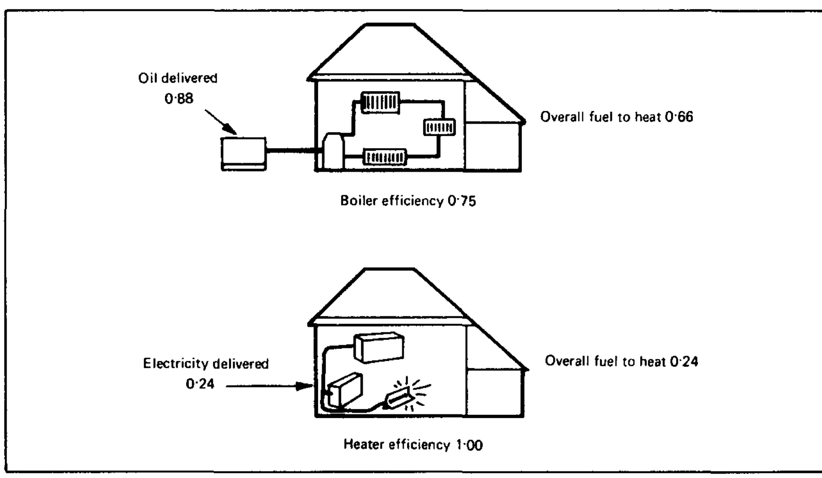


Figure 4. Comparison of the total efficiency of electric and oil-fired house heating

was used in electricity offices, works, showrooms etc. The third reason why the overall efficiency is lower than normally assumed is that this analysis has incorporated the energy costs of materials, plant, equipment etc, consumed by the industry, as well as the true energy costs of the fuels delivered to power stations.

These results in no way reflect the 'technical' efficiencies of the respective industries in the sense of showing what fraction of the potential energy is actually delivered to final consumers. For example, no account is taken of the oil left in a well when it ceases to be worked, nor of the coal not recovered from a deposit. Similarly, no account is taken of the theoretical energy available in a nuclear fuel rod, an energy which may be 100 times larger than that recovered in a burner reactor. To some degree it seems

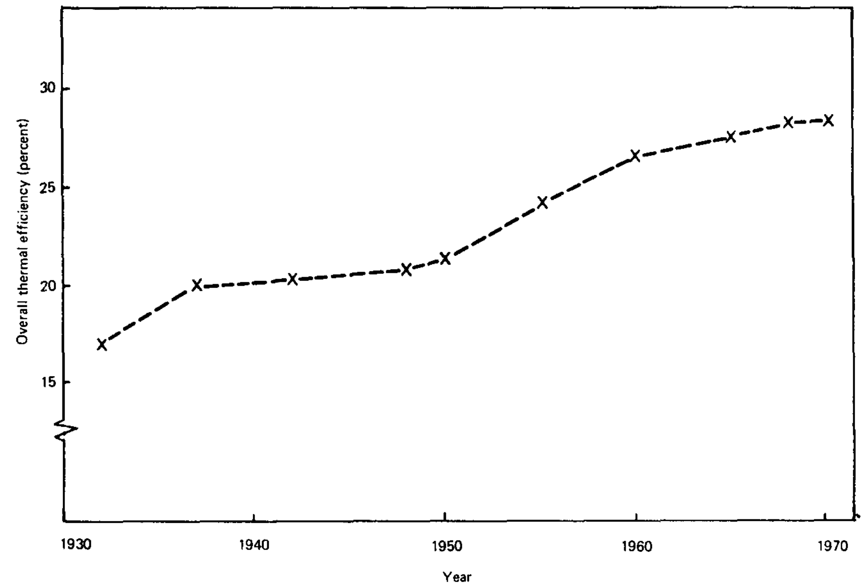


Figure 5. The overall thermal efficiency of the conventional steam stations in the UK. (Note this excludes hydro and nuclear power stations.)

inevitable that as more of the energy potentially available in a source is recovered, ie as the 'technical recovery efficiency' increases, then the 'energy cost efficiency' will decrease. This is a point taken up in the next section.

Table 3 summarises the energy costs of the fuel products as delivered to final consumers in the UK in 1968. These data are fundamental inputs to energy cost analysis, (as explained in reference 3). It should be mentioned that these results depend crucially on the conventions set out previously. Changing any one convention, such as counting nuclear electricity and not nuclear heat as an input, will alter all the values since they are derived from the interdependent relationships set out in Table 1.

The future

It is fairly safe to predict that over the next 20 years the energy cost of fuels will rise considerably because of three factors. First, easily recovered sources of fuel are steadily being replaced by 'difficult' sources: oil shales, North Sea oil and nuclear power require more direct energy expenditure for their production than previous sources such as Middle East oil. Second, many new energy technologies involve conversions from primary fuels to secondary fuels such as gasification or liquifaction of coal, and production of hydrogen electrolytically or chemically. The third factor is that as the rich sources of materials are exhausted, the energy cost of materials will rise considerably. Since the new fuel sources also require more materials input per unit output this factor may significantly increase the energy cost of the fuel production. Together these factors are inflationary. A rise in the energy cost of fuel will increase the energy cost of materials (since material production consumes fuel). The increase in energy cost of the materials is further increased by the lower grade of ore. In its turn this increased energy cost of materials increases the energy cost of the fuel production process – hence energy cost inflation. To date this inflationary effect has been counteracted by

Table 3. Energy costs of products of the fuel industries

	1968 (kWhth/ton)		1971/72 (kWhth/ton)	
Coal				
to iron and steel	8 056		8 100	
to chemicals	7 600		7 640	
to china and glass	8 608		8 650	
to cement	7 509		7 550	
industrial average	8 334		8 380	
Coke	9 340		8 990	
coke breeze	7 610		7 320	
other solid fuels	9 340		8 990	
Oil products	15 013	(49·9/ gall)	14 780	(49·1/ gall)
Motor spirit	14 547	(54·5/ gall)	14 330	(53·6/ gall)
Derv (diesel fuel)	13 718	(58·4/ gall)	13 510	(57·5/ gall)
Fuel oil	15 279		15 050	
Chemical feedstock				
Gas		40·73/ therm		36·1/ therm
Electricity		4·192/ kWh		3·97/ kWh

improvements in technical efficiency, but there is little room left for further improvements.

This energy cost inflation of obtaining future fuel supplies has serious policy implications so it is worth examining the basis of the argument in more detail.

The mining industry has developed impressive mechanised techniques for winning materials. This has been accompanied by decreasing financial costs but rising energy costs. In common with other industries financial savings have been made by decreasing labour costs using energy intensive technologies. For example, over the past 50 years the annual output tonnage of all US mines has increased by about 50% whereas the annual fuel consumption has increased by 600% in the past 25 years.[12] Figure 6 shows the expected increase in energy cost per kilogram of copper as the grade of ore decreases.[13] This type of variation will occur for all the relatively scarce metals such as zinc, lead, nickel, tin etc. For the relatively abundant metals, notably iron and aluminium, the increases are expected to be considerably less dramatic, but still significant.[14] The energy costs of plastics and petrochemicals are clearly directly tied to the energy cost of fuel sources (see below). The remaining materials used in significant quantities: glass, cement, bricks, etc, require substantial quantities of fuel for their production but are not subject to scarcity of raw materials.

Thus there is a trend towards greater energy costs associated with the production of materials from primary sources. The only obvious way of off-setting these increases is to increase the proportion of materials supplied by recycling. For metals the

[12] T.S. Lovering in *Resources and Man*, (W.H. Freeman & Co, San Fransisco, 1969), p 122

[13] P.F. Chapman, *Metals and Materials*, February 1974, p 107

[14] J.C. Bravard, *et al*, *Energy expenditures associated with the production and recycle of metals*, (ORNL-NSF-EP-24 Oak Ridge Tenn., USA, 1972)

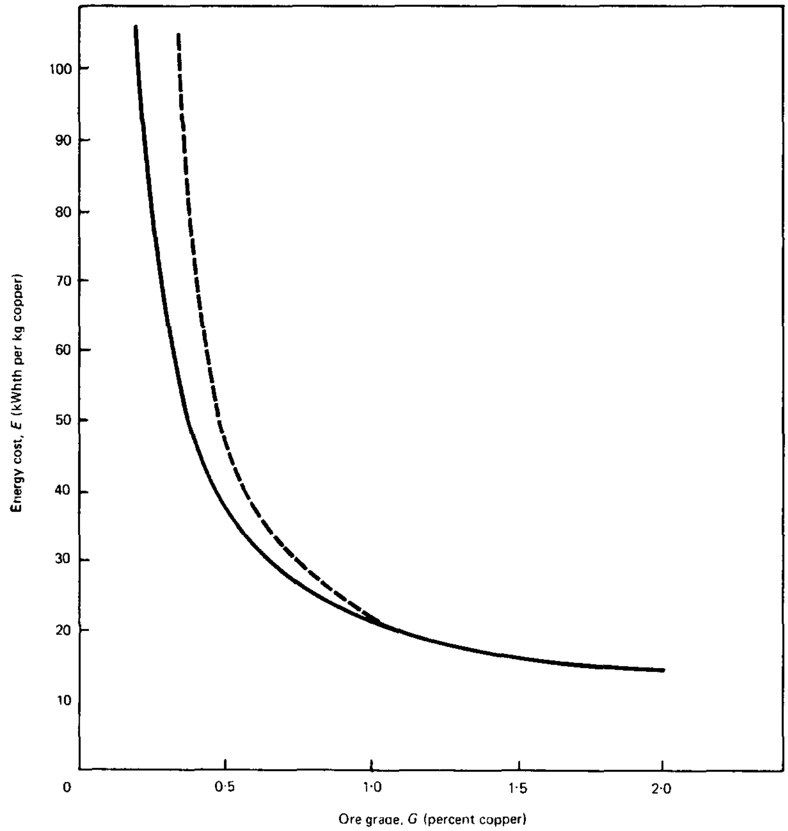


Figure 6. The energy cost per kg of copper as a function of ore grade. The solid curve is based on optimistic assumptions, the dashed curve on current technology

energy cost of recycling is generally an order of magnitude less than production from ores.[15]

While growth in total material consumption continues there are very stringent limits on the proportion of consumption that can be met by recycling. (This arises because the recycled material is a fraction of consumption some time in the past, which, under growth conditions, is less than present consumption.) So unless the rate of growth is *reduced* and the recovery of materials from scrap *increased,* the energy costs of materials will increase in the future.

There are presently a number of studies underway to try to evaluate the likely energy costs of future fuel supplies. To date only approximate data are available and these must be treated with caution. However, the trend is significant. The energy required to extract one ton of crude oil from a Middle East well has been estimated to be 500 kWhth/ton,[5] representing about 4% of the fuel energy obtained. Transportation to the UK absorbs a further 5% of the fuel[16], 4% as tanker fuel and 1% as loss in ballast. In comparison, the energy cost of an oil rig suitable for the North Sea represents about 10% of its total fuel output.[17] Assuming that the extraction costs represent a similar fraction as for the Middle East and that pumping ashore requires a further 4% of the fuel energy the total energy cost rises to about 18% of the fuel output. Thus an oil industry based on North Sea oil may have an efficiency as low as 80%, compared with the present 88%. And this estimate has not included energy costs associated with exploration, an activity involving considerably more material and fuels in the North Sea than in the Middle East.

[15] P.F. Chapman, *Metals and Materials,* June 1974

[16] G. Leach and M. Slesser, *Energy equivalents of network inputs to food producing processes,* (University of Strathclyde, Scotland, 1973)

[17] Based on cost estimate of rig and kWhth/£ value deduced from analysis of Census of Production. Pumping energy is large because secondary recovery process used from the start

In a similar way the net efficiency of the electricity industry may decrease as the proportion of nuclear power increases. The efficiency of future nuclear power stations may rise to 36%, the best efficiency so far achieved in a conventional station. However, the nuclear fuels used in burner reactors are very energy expensive. About 5% of the output of the power station is required to operate the gaseous diffusion plant for enriching uranium.[18] To mine the 0·7% U_3O_8 ores currently being developed will require a further 1-2% of the station output. Presumably, 15% of the output will be consumed as at present, in power stations, offices, showrooms and distribution losses. Furthermore, the energy cost of constructing the power station and appropriate proportions of the fuel preparation and reprocessing plants is equivalent to 1½ years' output of the power station. Assuming a 25-year lifetime, this represents a further loss of output equivalent to 6%. All these energy expenditures reduce the 36% station efficiency to an overall efficiency of 25·9% as shown in Figure 7. This, however, is not the end of the story. No account has been taken of the energy costs associated with research and development and, more importantly, those associated with waste disposal and protection. These are difficult items to incorporate in such an analysis, partly because suitable schemes have yet to be developed. (An energy cost point of view poses serious questions for proposals such as shooting wastes into the sun!) However, it seems likely that any suitable scheme will require husbanding these wastes for many, many years after the station has ceased operating – implying a continuing energy expenditure even after the source has ceased to supply energy.

Preliminary examinations of processes for extracting oil from shales or tar sands show these to be particularly energy expensive processes.[19] In summary, these current developments for obtaining

[18] N. Mortimer, (private communication based on approximate analysis of nuclear reactors)

[19] This is because in both cases significant quantities of rock have to be mined, crushed and processed to extract the oil. This involves considerably larger energy costs than drilling holes and pumping the oil up.

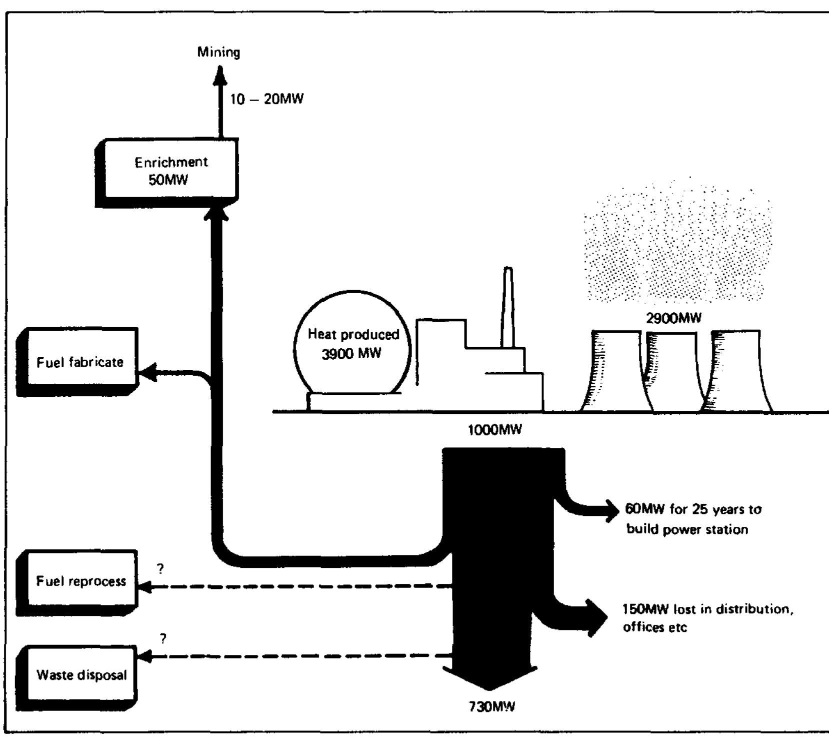


Figure 7. Approximate energy flows associated with a 1000 MW nuclear power station

increases in fuel supply do not offer the likelihood of reducing the energy cost of fuel; instead the energy costs may rise.

One serious consequence of any such rise is that it brings much closer the time when we have to concern ourselves with the climatic effects of heat release.[2] Virtually all the energy consumed ends up as heat in the atmosphere, only a small fraction being converted to (fixed) chemical energy. Thus if the energy costs of fuel and materials increase, the heat release associated with a given standard of material living will also increase. This will be further increased by any trend towards electricity as a major power source (since it has the lowest efficiency).

The climatic effects of heat release could be avoided by the development of technologies able to exploit the income, or renewable, energy resources. The use of wind, hydro, solar or geothermal power does not constitute an additional heat input to the atmosphere and could affect local climate only if energy were generated in one region and transported to another. It remains to be seen whether these income sources can be exploited for low energy costs. Preliminary calculations on the energy costs of solar cells[20] shows that the cell has to operate for about 10 years before the energy of fabrication is recovered. In contrast, the energy cost of windmills appears to be such that the energy of production is recovered in two or three years.

Conclusion

The energy cost of fuels should be an important consideration in formulating future energy policies. The analysis presented here has shown that at present the energy sector of the UK economy consumes more than 30% of the primary energy input. The discussion of future supplies of fuel and materials indicates that this proportion may be increased substantially as lower grade energy and materials sources have to be used. Together the energy costs of fuels and materials produce an inflationary tendency arising from the need to use more energy to obtain additional supplies of fuel. Serious consideration should therefore be given to 'deflationary' technologies such as increased materials recycling and increased development of the use of renewable energy sources.

[20] G. Turnbull and M. Slesser, (private communication)