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A National Model of Fuel Allocation — A Prototype.

E. W. HENRY AND S. SCOTT

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General Summary

USERS of fuels and electricity buy the kinds which suit them best: for some users the cheapest, for others the cleanest, for yet others the quickest and most convenient. Between Autumn 1973 and Autumn 1975, the import price of crude oil increased from about £9 to about £36 per metric tonne, with petroleum products keeping pace. This quadrupling of oil prices created severe problems at the national and household level, as Ireland imports more than three-quarters of its energy needs in the form of crude or refined oil. Since Autumn 1975 there have been further increases in oil prices and this is likely to continue. So, during the last few years, the users of fuels and electricity have been more conscious of the amounts used, for the obvious reason of saving costs. This in fact is the starting point for the authors of the present paper.

The Energy System

The authors have, for some time past, been investigating national economic aspects of supply, conversion and distribution of fuels within Ireland. They consider this supply, conversion and distribution as an energy system which takes as input all the imported fuels (crude and refined oils, coal and coke) as well as the native fuels (peat, coal and water power to generate electricity). All these inputs to the energy system may be denoted "primary energy". Many of these inputs are partly or wholly converted into secondary energy products, such as townsgas and electricity. Others remain in their original state such as coal and sod peat. Together these converted and the remaining unconverted fuels form the output of the energy system.

At least two economic aspects of the energy system can be studied:

(i) How the System Works

It takes in known quantities of fuels at given prices and gives out known quantities of usable fuels and electricity, also at known or given prices. This kind of study is historic in its nature and has been undertaken for 1973 (illustrated in Figure 1). The quantities have been expressed in a common unit measuring the heat content of the various fuels. The units used here are millions of gigajoules, written mGJ—(the authors could have used calories, kilowatt hours or tonnes of oil equivalent or any other heat measure, which would only alter the scale, not the proportions). The input to the energy system is 330 mGJ in all. Of this, 23 per cent is lost or used up in conversion processes (including 16 per cent used up in electric power stations), leaving 77 per cent available for delivery to final users. Of this amount, some 29 per cent is delivered to industry and agriculture, 39 per cent to domestic and commercial users and 22 per cent to transport. The remaining 10 per cent does not go to final users, but goes to exports, such as briquettes, and to stock increases.

(ii) How to Reduce Cost at the National Level

What is best or most convenient for the individual purchaser of energy may not be best for the nation. In order to analyse the energy system with a view to improving national economic aspects it is necessary to develop these ideas one step further: to move on from the concept of deliveries of usable fuels and electricity to the concept of final uses.

Final Uses of Energy

There are basically five final uses (as shown under the Final Uses heading on the right of Figure 1). These are:—

(i) space heating, taking some 41 per cent of deliveries to final users, and including water heating and cooking;

(ii) lighting, taking about 2 per cent of deliveries to final users, with phones, TV, radio and other electrical equipment.

(iii) process heat, taking about 21 per cent and including industrial heating such as required by cement making and bakeries.

(iv) motive power, taking some 6 per cent for flour mills, saw mills and so on.

(v) transport, by road, rail, sea and air taking the remaining 30 per cent of deliveries to final users.

Useful Energy

One further step is required to complete this analysis, that is, the consideration of useful energy produced by the fuels in final use.

The energy going to final uses, as outlined immediately above, can be further broken down into (a) useful energy, (b) waste energy (shown on the extreme right of Figure 1). It has been estimated that 112 mGJ of useful energy is realised from the 227 mGJ put to final uses, representing 49 per cent of deliveries to fuel users. The remaining 51 per cent goes to waste. The distinction between useful energy and waste energy is clearly illustrated by the case of space heat: if the combustion of peat results in 25 per cent of the heat reaching the surroundings and 75 per cent escaping up the chimney, then this particular final use is considered to give 25 per cent useful enrgy, i.e., to be 25 per cent efficient and 75 per cent wasteful.

Appendix Table A1 sets out these efficiencies in final use, giving the percentage of useful energy obtained from various final uses of various fuels. It is necessary to note at this point that the quoted efficiencies in final use are controversial figures especially for space heating and process heat, consequently the estimates of useful energy and waste energy might be unacceptable to some physicists and engineers. However, readers should appreciate that there do exist some firm guidelines, for example, in using a petrol-fed internal combustion engine there is no way of getting the conversion of heat into motive power to exceed some 25 per cent; but there is an obvious use for the waste heat: to heat the interior of the vehicle.

An Economic Model of the Energy System

In order to estimate a given national menu of useful energy at minimum cost to the nation a fuel allocation model is needed, the description of which occupies Chapter 3.

The model can be thought of as behaving like a computer. We give it a demand for specified quantities of each of the five kinds of useful energy, and ask it to say which combinations and processes will achieve this, (like specifying the right hand side of Figure 1 and then receiving a filled in diagram with computed figures for primary energy on the left). We are dealing with an annual period, thus the five kinds of useful energy are jointly required and any one of them by itself is not meaningful. In doing the calculations for us, it is to

(a) minimise the total national cost of providing the specified menu of useful energy;

(b) keep within specified upper and lower limits for outputs of peat bogs, oil refineries and electric power stations;

(c) keep within specified upper and lower limits, usually 50 per cent and 150 per cent of the actual 1973 levels of various fuels put to various final uses;

(d) include new possibilities of primary and secondary energy, such as Kinsale gas, combined heat and power from electric power stations and natural gas as input to such power stations;

(e) select the combination of primary energy and conversion processes which provides the specified amounts of useful energy at minimum national cost, and reject all other primary energy forms and conversion processes;

(f) avoid double-counting of costs; thus primary energy goes in at full cost and all subsequent processing or transport adds a value-added cost.

Experiments with the Model

Four major experiments have been undertaken with the model so far. 1973 technology for supply and conversion, (as implied in Figure 1) and 1973 levels of demands for useful energy have been used. Costs, where needed, are expressed in 1974 prices, in order to be representative of post 'fuel-crisis' conditions. Estimates were made for the price and technological structure for processes such as electricity generation from natural gas, which were not in existence in Ireland then, being due in 1978. The answers given by the model are true for the structures and relative prices used, *but not necessarily true for 1977 or any other year's prices.* More will be said about this in drawing conclusions below. These experiments were performed by computer, using a so-called 'Linear Programing' package.

> Experiment (1) was simply to get the lowest cost of supplying the specified 1973 useful energy amounts, by moving away from the 1973 actual energy supply to the permitted limits, upper or lower. At these extremes, the cheapest allocation given by the model would save the country some £40 million, that is 12 per cent of its energy bill, at 1974 prices. This would be achieved by sizeable changes in consumers' patterns of fuel use, which would require considerable time and planning. In particular there would be much greater use of fuel oil, implying the introduction of district heat schemes, an increase in the use of gas oil for space heat and greater use of diesel oil for transport, implying greater use of public transport. More machine peat would be used for heating and large quantities of briquettes would be exported, but other uses of peat would be reduced, in particular for electricity generation. The consumption of electricity and townsgas would be reduced and a higher proportion of the latter would be made from coal than at present. Consumers would still receive the same quantities of useful energy and there would be no change in the aggregate cost of imported fuels. Less crude but more refined oils would be imported.
>
> Experiment (2) was like the first, except that 270 million therms of Kinsale gas were assumed available to be either (i) converted into electricity, or (ii) piped to houses, or (iii) liquefied and exported, or (iv) shared between the three previous uses. The optimum result rejected the liquefaction for export. A comparison of results here with those in the previous experiment, shows that a net annual saving of £10 million in the nation's fuel bill can be attributed to the arrival of natural gas, matched by a net reduction of about £20 million in the aggregate cost of fuel imports (Table 7).
>
> Experiment (3) investigated how a gradual forced reduction of fuel imports by about a third, from the 1973 level of £198 million (expressed in 1974 prices) to £133 million, would affect the energy system and the price levels. This experiment was performed both with and without natural gas assumed available. Without natural gas, as the

gradual reduction occurred there was an early shift to increased output of milled peat (for electricity generation and briquette manufacture), then an increase in output of machine peat, and finally an increase in output of farmers' peat and native coal. Oil refinery output increased continuously throughout the reduction of total fuel imports, meaning a gradual change-over to imported crude oil, from imported refined oil and coal. The total *net* increase in energy cost to the nation was £26 million, because in 1974 native fuels were more expensive than imported fuels in providing the specified useful energy. Thus in saving £65 million on the cost of imported fuel we would pay £26 million extra for the same 1973 amounts of useful energy. With natural gas assumed available the results closely parallel those just described but at reduced overall cost.

Experiment (4) throws light on the employment aspects of the energy system. It is widely held that, where feasible, consumers should buy domestically produced goods in order to create employment. Indigenous fuel production, namely, of peat and coal, not only provides employment, but provides it in regions most in need of employment; it also helps to reduce the nation's dependence on foreign supplies. So in addition to providing energy, the native fuel industries fulfil other desirable objectives which are not strictly of an energy nature. So, of the wages and earnings paid in the native fuel industries, part could be viewed as a cost strictly to the indigenous energy sector, and the other part, the cost of achieving the non-energy objectives, could be viewed as not attributable to the energy sector. Meanwhile, we know from experiment (1) that some peat activities were not economic and were therefore reduced, but this happened because the indigenous energy sector was paying the full cost of the wages and earnings which included the costs of the non-energy objectives. The question is by how much would these full costs need to be reduced to make the indigenous fuels competitive with imported fuels. This experiment answers this question by showing what happens when there is a gradual reduction in wages and earnings attributable to the native fuel industries. There results a corresponding gradual substitution of indigenous for imported fuels, with corresponding rises in employment. When the attributable wages and earnings are roughly halved, machine peat, milled peat, with briquettes and electricity made from milled peat, and farmers' peat reach such levels as to provide about 500 more jobs than in 1973.

Conclusions

(1) The model has demonstrated that it can produce sensible results from the data supplied to it. All the answers make sense and there are no surprises.

(2) The model provides subsidiary information which would be difficult to get otherwise. For example, it gives the extra national cost of substituting one fuel for another.

(3) The model, as described in the paper, is at a prototype stage. It is also in ways too compact; for instance, house heating should be treated separately from commercial space heating and implications for new household equipment might be examined. But it is quite flexible, in being able to absorb any new processes of producing or converting energy, for example, a native oil well in place of imported crude oil.

(4) The model results may be sensitive to the prices of the various fuels and may be sensitive to the output limits specified. This means that the optimal results obtained by the experiments for 1973 amounts of useful heat at 1974 prices are not to be generalised. It is likely that in 1977 conditions, the various forms of peat (milled, sod and briquettes) would be much more competitive with oil than has appeared above for 1974 prices. The numerical results therefore are to be treated as particular to the year and price-system under analysis.

(5) Various government policies of fuel production and conversion can be examined by an enlarged version of the model, both directly and through the subsidiary information it produces. But for such policy exercises, great attention would need to be given to the upper and lower limits on outputs and also to the set of prices used to value the inputs and outputs. The basic framework of the model, however, has been shown to produce useful and plausible results.

Introduction

Why a Model of Fuel Allocation? Outline of the Paper

NATIONAL energy policy includes the following aims, according to the McAlister (1976) document:

- The optimum development of indigenous energy sources,
- Access to secure supplies for imported energy sources,
- Diversification of sources of energy supply,
- The promotion of economy in the use of fuels.

Only the last aim has been systematically researched recently, for example, by Henry (1976) and Minogue (1976). These studies examine the scope for energy conservation measures, such as improved thermal insulation, better maintenance of machines and the like, which reduce energy use at its point of final consumption. However, there should be an examination of the scope for economy in the actual allocation of fuels. For example, given that choice is permitted among oil, coal, peat, natural gas, the questions are which fuels should Ireland import, which indigenous fuels should it export, which should be consumed in their primary form and which should be converted to secondary form? The answer should take account of all the policy aims enumerated above.

In the past, market forces have played the major role in determining by whom, and for what end use, a fuel was purchased. One exception to this was the State's promotion of peat production and electricity generation from peat and coal. In general, however, consumers whether households, manufacturing or service industry, or energy converters, bought those fuels which were the best value for money for them.

The energy situation has now changed. To meet the challenge of recent price increases in fuels, new sources of energy and new technologies are emerging, providing more choices of action in energy policy. Meanwhile, our government is playing a more active role in the energy sector, in such areas as the allocation of new finds of indigenous fuels, decisions relating to oil refineries, allocating funds for research into alternative energy sources and alternative energy-using technologies. Also, it is now widely held that the government should intervene when national interests differ from sectoral interests. For example, an individual fuel supplier is interested in obtaining the cheapest inputs, while the nation is interested in meeting its energy needs with the cheapest mix of fuels, subject to the policy constraints enumerated above. From the nation's point of view and within a certain price range, a joule of energy supplied from indigenous sources is better than a joule supplied from abroad. Also from the nation's point of view there is a risk in depending heavily on one particular fuel, the supply of which can be used as a political weapon. Electric power stations, gas works, domestic and industrial consumers, transport users, all are at present predominantly dependent on oil. Finally, there is the question of how to use new indigenous fuels. Classical economic theory maintains that under perfect competition their best allocation would be ensured by selling these fuels to the highest bidder in a free market system. But the conditions for perfect competition are not operative. In addition, it is felt that the benefits to be gained from the advent of new indigenous fuels should be shared more fully by the nation as a whole.

In sum, the new energy situation is characterised by increased government involvement, large expenditures of state funds and increased complexity. The problems, therefore, require a more thorough analysis than before, and since there is the possibility of substitution between fuels, the analysis must cover the entire energy sector.

The prototype model described in this paper is a first step towards a systematic analysis of the whole energy sector, approached from the nation's point of view. The model aims to show which are the good fuels or the good uses of fuels, given that the nation's requirements must be met for heating, cooking, lighting, industrial process heat and motive power, and for transport. The model aims to satisfy these requirements at minimum cost to the nation, given that dependence on imports should be limited.

Chapter 1 describes the problems arising out of Ireland's present pattern of fuel consumption. This present pattern is illustrated in a flow chart. A discussion of 'waste' in the fuel sector and the possible uses for natural gas follow.

Chapter 2 describes how our information is expressed in a form suitable for quantitative analysis, as an Input-Output Table for 1973 at 1974 prices.

Chapter 3 describes the method of analysis which will indicate the best allocation of fuels. This method is a Linear Program based on the foregoing Input-Output Table.

Chapter 4 gives the results of an experiment with the model for 1973, and of an experiment where natural gas is assumed to be on stream.

Chapter 5 gives further analyses which throw light on various other issues—such as the increased costs entailed by reducing imports of fuels and by encouraging fuel industries which provide employment in Ireland. Other possible analyses and improvements to the model are discussed.

Chapter 6 has the summary and conclusions. The summary attempts an evaluation of the model and proposes that 'consensus runs' be undertaken with the model, that is, runs which use best estimates of price and technical data for the medium term future, agreed by representatives of the various fuel interests.

Chapter 1

The Energy Scene and Problem Outlined

SUPPLYING Ireland's energy needs is costly and import-intensive. In 1975 total primary energy costs amounted to about £276 million, that is 7·8 per cent of GNP. About 80 per cent of this was spent on foreign supplies. There is also heavy reliance on one particular fuel: oil, whose share amounted to 75 per cent of all primary energy. This reliance puts Ireland in a potentially vulnerable position, which caused some disquiet when the virtual monopoly powers of OPEC were revealed in Autumn 1973.

These then are the main features of the current energy picture. To some degree they all constitute problems. Another important feature is the role of indigenous fuels. These comprise peat, about 21 per cent of the coal consumed and a small amount of hydroelectricity. Together these indigenous fuels and the imported oil and coal form the inputs of primary energy to the energy sector. By 'primary energy' we mean fuels as they first arrive on the Irish scene, dug from the ground, shipped from abroad or, in the case of hydroelectricity, produced from water resources.

Where this energy goes and in what form it reaches its final destination is best seen from an energy flow diagram. Figure 1 gives the national energy flows for 1973, all expressed in a common unit, millions of gigajoules (mGJ). A gigajoule (GJ) is a common unit of energy, equal to 0·0239 tons of oil equivalent (OECD definition) or 277 7/9 kWh of electricity. A million gigajoules (mGJ) will be used frequently below as a unit. Inputs of primary energy are shown on the left hand side. Flows are drawn to scale so that relative sizes and the context can be seen at a glance. Flows go from left to right and at all stages their sum, that is including intermediate use and losses, is 330 mGJ. So at the final destination of energy on the right hand side, the sum is also 330 mGJ, though only 112 mGJ constitute useful energy, that is, actual heat felt by people in homes or offices, or power for pulling, grinding and so on.

In the middle of the diagram are three main breakdowns of energy which roughly correspond to stages in its journey to its final destination. The first stage, under the heading 'Energy Sector' shows some fuels being converted into secondary energy, namely, townsgas and electricity. The amount of energy entering a box from the left is the same as the amount, including losses, coming out on the right. So, for electricity the total energy made into electricity is 73·9 mGJ, made up of 47·2 of oil, 23·2 of peat, 1·2 of coal and 2·3 of added hydroelectricity. The output of electricity is 22·2 mGJ of which 8·7 go to industry and agriculture and 13·5 go to the domestic and commercial sectors. The remaining 51·7 mGJ is lost or used up in the manufacture of electricity. Over 70 per cent of fuels, shown at the top of this breakdown, remain in their primary forms as oil, coal and peat to be distributed by dealers to the final consumers. Refined oil products are included here with primary fuels because although they are the product of crude oil and could be termed secondary fuels, they are still basically oil.

The next breakdown, under the heading 'Final Users', shows the amounts of energy actually delivered to industry and agriculture, the domestic and commercial sectors, and to transport and fishing.

The following breakdown, under the heading 'Final Uses', shows what this energy is actually used for, broken down into five final uses. These are now described—space heat includes heating of homes, offices, factory areas as well as water heating and cooking. Light includes public lighting and the use of certain appliances such as X-Ray apparatus which can only reasonably be powered by electricity. Process heat refers mainly to industrial uses of heat such as melting, pottery firing, drying and so on. Motive power includes pumping, grinding, mixing, refrigeration and the like. Transport includes all forms of vehicle use for road, rail and air.

By far the biggest final use for energy is space heat, followed by transport then process heat. Motive power and light are fairly small uses. Associated with final use are various appliances, heaters, cookers, lamps, machines, boilers, engines and vehicles. All of these operate at certain levels of efficiency and cause some waste. For example, of the 93·8 mGJ of energy which is used for space heat, 48·8 is waste owing to the operation of various types of heater or fire in use. This was estimated by applying the efficiencies in final use (Appendix Table A1).

Running all along the lower half of the diagram is a flow of energy going to exports and to net stock appreciation, the latter being a very small amount during 1973.

Discussion of Waste

The most striking feature emerging from flow diagrams of this kind is the amount of waste energy. In our case, it is about 58 per cent of total energy in the system. The largest amount of this waste, 115 mGJ, emerges in the final uses of energy and represents about 50 per cent of the energy consumed by final users. Some 48 mGJ of this arise in combustion engines of transport etc., which transform only 29 per cent of their gross intake, 67·8 mGJ. Another large contribution to waste is 51·7 mGJ of energy used up in making electricity. This represents about 70 per cent of the 73·9 mGJ of energy input to the ESB. Also some 23 mGJ of primary fuels are lost before delivery to final users. This loss is about 9 per cent of the 244·4 mGJ of energy sent to final users in the form of primary fuels, and is mainly due to the energy needed to transport oil, peat and coal around the country.

It would be well at this stage to note that the word 'waste' is an ambiguous term. It is used for want of a better word and because it is in general usage in discussions and flow diagrams of energy. In fact, economic theory would

1. "Waste Energy" is a general term covering losses, reject heat and the use of intermediate energy e.g. for transporting energy products or for pumped storage etc. The latter categories are not strictly speaking "waste", but they do not constitute Final Useful Energy.

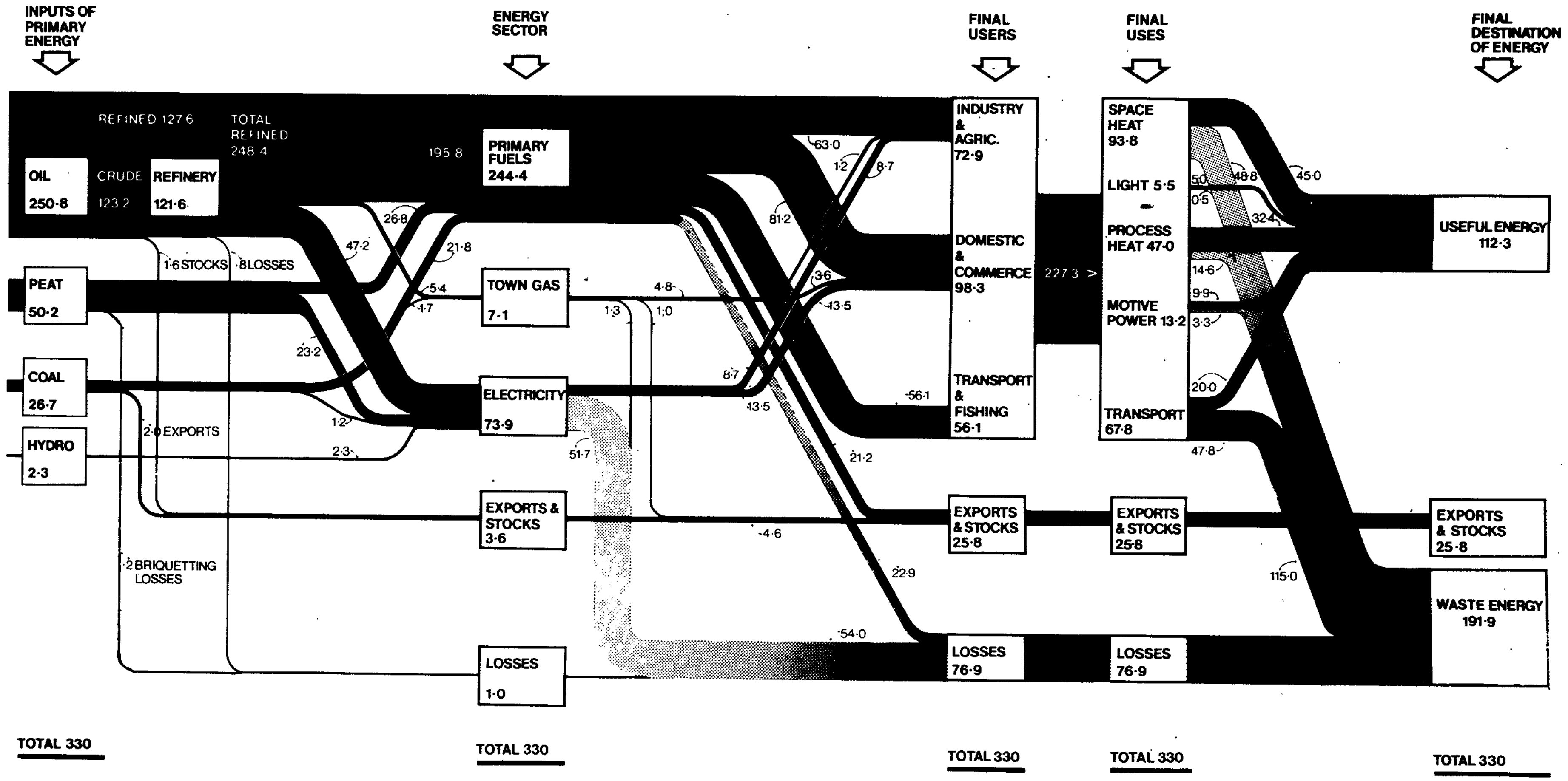
2. This diagram should be viewed in conjunction with Appendix Table A1 which sets out the Efficiencies in Final Use and from which were derived the losses at the Final Uses Stage.

3. Stock decreases are included on the left hand side as primary Energy, Stock increases are given on the right hand side under Final Destination of Energy, as "stocks".

4. Some of the figures are estimates.

FIGURE 1

National Energy Flows, Ireland 1973, in millions of Gigajoules



Source: Economic & Social Research Institute, Dublin.

maintain that waste can only exist under certain conditions. The first condition is that the benefits to be obtained from stopping the waste must outweigh the costs incurred in stopping the waste, taking into account people's or society's preferences. Secondly, people must be ignorant of these net benefits. For example, if a person did not know that his car was leaking petrol and needed a service, this might be a waste. However, if he did know about it, but decided not to have the car serviced because of the inconvenience of doing so, then this is not waste although physical waste is occurring. This also applies to electricity generation: the electricity produced amounts to only 30 per cent of power stations' energy input. Some 70 per cent is used up in the process of making electricity. It is an amount that people are willing to pay for the convenience of having electricity. The reject heat from electricity generation is only waste if it were economic to save it. If it *were* economic to save it, people would only not save it if they were ignorant. This amounts to saying that Ireland's energy system incurs no waste assuming that people are making informed choices when they select fuels and technologies. So the job of the energy economist is to spread knowledge of the full implications of choices in the energy field, and then, possibly, to suggest where the authorities might try to influence people's preferences.

Meanwhile, in the flow chart the word 'waste' is physical waste, regardless of whether it is economically feasible to save it. It includes all the energy which does not constitute useful energy to the final consumer. In so far as the purpose of the energy sector is to supply cheaply the useful energy which final consumers require, this may or may not entail reducing the amount of waste. One could substitute a larger but cheaper waste.

We can pursue our examination of waste by analysing the Danish energy sector. This is a useful exercise in itself because Denmark and Ireland have populations of the same order of magnitude. They both have open economies and had a strong agricultural tradition in the past, but Denmark's GDP per head is some 2·5 times that of Ireland. Denmark depends on foreign sources for 99·2 per cent of her energy supplies, compared with Ireland's 82 per cent, and Denmark's primary energy consumption per head is over 1·7 times that in Ireland. A comparison of the flow diagrams of the two countries gives the following information in percentages.

	Ireland	*Denmark*
Useful Energy	34·0	39·6
Exports, Stock Increases	7·8	19·6
Waste Energy	58·2	40·8
Total	100·0	100·0

By confining the analysis to useful and waste energy by excluding Exports and Stocks, which incur little waste, we have:

Useful Energy	36·9	49·3
Waste Energy	63·1	50·7
Total Energy	100·0	100·0

Before accurate comparisons can be made, much work needs to be done on the collection of international data to ensure the use of comparable definitions and conversion factors. However, in pure energy efficiency terms, that is quantity of output as a proportion of quantity of input, Denmark appears better. Close inspection of the structure of the Danish energy system reveals features which would support this view. Whereas the proportion of energy lost in the Danish transport sector is equivalent to that lost in Ireland (vehicles being fairly similar in different countries), the proportion lost in industry is somewhat lower, being 20 per cent compared to Ireland's 30 per cent. More striking is the space heating function where Denmark loses a remarkably small 25 per cent compared with Ireland's 52 per cent. About 20 per cent of the Danish energy input to buildings for space heating is channelled through district heating systems, which are highly efficient. The considerable outlay for setting up these systems was undertaken some years ago when in fact fuels were relatively cheap and savings therefore relatively small. In comparison with Ireland, Denmark's higher population density and colder winter climate might have been encouraging factors. Another feature of the Danish energy system is that while the proportion of primary energy going to making electricity is about the same as in Ireland at just over 20 per cent, at least an extra 11 per cent efficiency is achieved in the electricity sector by using some of the waste as associated district heat to be sent to buildings.

If energy were a homogeneous product, such that both Ireland and Denmark paid the same world prices for the energy they use, then Denmark is paying some 25 per cent less than Ireland is paying for each unit of useful energy. In fact, Ireland has a much larger share of coal and peat in her primary and final energy consumption. Their efficiencies in use are relatively low and their prices per useful GJ are relatively high; thus the Danes might be paying even less still for each unit of useful energy by comparison with Ireland. There are insufficient data for a complete weighted comparison between the two countries.

The Arrival of Natural Gas

To complete the description of Ireland's energy scene, mention should be made of the addition of natural gas from Kinsale in the near future. The flow diagram will have as an extra input of primary energy on the left hand side some 47·5 mGJ per annum, which is roughly equivalent in magnitude to the energy presently supplied each year by peat. There are four main options for its allocation: (1) it can be used in its existing form as gas and join the primary fuels in the diagram; (2) it can be used to make electricity; (3) it can be exported as liquid natural gas (LNG); (4) it can be used outside the energy system as in the case of the 40 per cent allocation to NET, as a chemical feed-stock. Holland, for example, whose large natural gas deposits supply 46 per cent of its total primary energy, exports nearly half its annual production of natural gas. One-quarter is piped to final users in its existing form; the remainder is divided evenly between electricity generation and chemical and industrial use, according to Bunyan's 1974 report. In Ireland the potential role of natural gas, at say, 13 to 15 per cent of total primary energy consumption, can be more closely compared with the Italian case. There, natural gas consumption is some 10 per cent of total energy consumption. Some of Italy's gas is imported. Nearly three-quarters of the gas is piped directly through a complex of pipelines which supplies all the most important centres of consumption in Italy. The remainder is divided between electricity generation and the chemical industry. Later in this paper we describe some experiments on the allocation of Ireland's natural gas, carried out by our energy model.

This then is an outline of Ireland's energy scene. If we want to solve some of the problems mentioned earlier, such as the high cost of energy or our large reliance on imports, we need to have the information given in the flow diagram in a form that can be manipulated quantitatively. So we construct an input-output table which shows the energy system in greater detail. The next chapter describes the input-output table and its construction.

Chapter 2

Description of the 1973 Energy Input-Output Transactions' Table

AN input-output (I-O) transactions' table of the Irish energy system during 1973 is shown as Table 1. Although this gives much more detailed information than the energy flow diagram of Figure 1, there is obviously a correspondence between the two which will be described later. The two are based on the same data sources except for a few instances, where the I-O tabular detail could be obtained only by using data referring to the financial year 1973/74 rather than to the calendar year 1973.

The I-O table shows the fuel and energy production and conversion complex broken down into 24 kinds of fully or partially home-produced fuel and energy and a further six kinds of totally imported fuel, thus giving 30 kinds in all. The 24 fully or partially home-produced kinds include one for aggregate electricity and one for aggregate townsgas. Information is given in physical units, namely, tonnes, thousand (10^3) kWh and thousand therms. The destinations and quantities of flows of each kind in 1973 are given along the row for that kind. The first 24 columns show inputs to home-produced fuels and energy, so that the full 30 rows and these 24 columns show the flows *between* energy sectors, such as fuels to electricity generation, to gas making, to oil refining. Detailed descriptive material on Table 1 is given in Appendix 1 and should be read for further insight on the table.

The total fuel and energy absorbed by Columns (1) to (24), that is by the production-conversion complex, is shown in Column (25), denoted Total Inter-Industry. Column (26) shows the domestic, i.e., native, amount produced and thus has zero-level entries for totally-imported items in Rows (25) to (30). Column (27) shows amounts imported: those in Rows (1) to (24) are similar to, or competing with, native products and those in Rows (25) to (30) are complementary to, or non-competing with, native products. Column (28) shows the total supply, given by the sum of entries in Columns (26) and (27). Column (29) shows the amount available for final uses (including losses in distribution) and is the total supply less amounts used by the energy complex, Columns (1) to (24).

Columns (30) to (35), also denoted (f1) to (f6), show the deliveries of fuel and energy to six Final Users, namely, Agriculture, Industry, Transport and Fishing, Domestic and Commercial, Exports and Re-Exports, Stock Increases and Losses. Column (36) has the Final User total amounts. The export and re-export amounts, Column (34), include estimated invisible exports, in the form of sales to foreign ships and aircraft, as well as merchandise transactions.

Columns (38) to (42) show a re-classification of deliveries to final users (f1) to (f4). This new classification shows five *Final Uses* denoted (d1) to (d5) to which these fuels are put, namely, Space and Water Heating and

Table 1: *Irish 1973 Input-Output Energy Model. 24-Sector Inter-Industry Transactions in Physical Units*

		Physical units ('000)	*Native coal* (1)	*Coke* (2)	*Milled peat* (3)	*Machine peat* (4)	*Briquettes of peat* (5)	*Farmers' peat* (6)	*Residual Fuel oil* (7)	*Gas/diesel oil* (8)	*Motor gasolene* (9)	*Jet fuel* (10)	*Naphta* (11)	*LPG* (12)	Row codes	*Refinery gas* (13)	*Total Refinery output* (14)	*Electr. hydro* (15)	*Electr. from coal* (16)	*Electr. from milled peat* (17)	*Electr. from machine peat* (18)	*Electr. from sod peat* (19)	*Electr. from oil* (20)	*†Total electr.* (21)	*T fr*
Native coal	(1)	tonnes													(1)				47.0						
Coke	(2)	,,													(2)										
Milled peat	(3)	,,					800.2								(3)					2,275.6					
Machine peat	(4)	,,													(4)						463.2				
Briquettes of peat	(5)	,,													(5)										
Farmers' peat	(6)	,,													(6)							43.9			
Residual fuel oil	(7)	,,			0.1										(7)					9.2			1,107.0		
Gas/diesel oil (incl. derv.)	(8)	,,	0.5		3.4	1.5	0.5		51.6	24.9	14.3	4.6	2.4	2.2	(8)				0.3				4.5	0.7	
Motor gasolene	(9)	,,	0.1		0.1	0.1									(9)					0.7	0.2		2.5		
Jet fuel	(10)	,,													(10)										
Naphta	(11)	,,													(11)										
LPG (butane/propane)	(12)	,,													(12)		28.0			0.1			0.2		
Column codes			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)		(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	
Refinery gas	(13)	,,													(13)		57.0								
Total refinery output	(14)	,,													(14)										
Electricity, hydro	(15)	'000 kwh													(15)			8.5						769.9	
Electricity from coal	(16)	,,													(16)				4.9					64.0	
Electricity from milled peat	(17)	,,													(17)					96.9				1,251.1	
Electricity from machine peat	(18)	,,													(18)						24.3			379.6	
Electricity from sod peat	(19)	,,													(19)							2.9		22.7	
Electricity from oil	(20)	,,													(20)								235.0	4,427.3	
Total Electricity†	(21)	,,	4.0		12.0	6.0	35.0								(21)		45.0	43.0							
Townsgas from coal	(22)	'000 therms													(22)										
Townsgas from oil	(23)	,,													(23)										
Total Gas*	(24)	,,													(24)										
Column codes			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)		(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	
Totally Imported:																									
Kerosenes (TVO + burning)	(25)	tonnes													(25)										
White spirit & SBP	(26)	,,													(26)										
Aviation gasolene	(27)	,,													(27)										
Lubricants	(28)	,,			0.3	0.1									(28)								0.1		
Coal (incl. anthracite)	(29)	,,													(29)										
Crude petroleum	(30)	,,													(30)		2,767.0								
Column codes			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)		(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	
Physical unit ('000)			tonnes	tonnes	tonnes	tonnes	tonnes	tonnes	tonnes	tonnes	tonnes	tonnes	tonnes	tonnes	Units ('000)	tonnes	tonnes	'000 kWh	'000 kWh	'000 kWh	'000 kWh	'000 kWh	'000 kWh	'000 kWh	'0
Domestic output (excl. by-products)			64.0		2,154.1	934.9	316.0	1,034.3							Domestic output		2,686.0	778.4	68.9	1,348.0	403.9	25.6	4,662.3	6,914.6	

†Outputs of sectors (15) to (20) combined, reduced by power station use; the components of the aggregate are shown as inputs to column (21), in rows (15) to (20).

*As for electricity, the sum of the two kinds of gas.

									Deliveries to final users							Deliveries to final uses (Distincts from users) for (f_1) to (f_4)							
wnsgas om coal (22)	Townsgas from oil (23)	*Total townsgas (24)	(a) Total Inter-industry (25)	Row codes	(b) Domestic output (26)	(c) Imports (27)	(d) Total supply (b)+(c) (28)	(e) Amount avail- for final use incl. losses (d) – (a) (29)	(f_1) Agriculture (30)	(f_2) Industry (31)	(f_3) Transport and fishing (32)	(f_4) Domestic and commercial (33)	(f_5) Exports and re-exports (34)	(f_6) Stock increases and losses (35)	Total for (f_1) to (f_6) (same as (e)) (36)	Row codes	Total for (f_1) to (f_4) (37)	(d_1) Space and water heating and cooking (38)	(d_2) Lighting and appliances (39)	(d_3) Process heat (40)	(d_4) Motive power (41)	(d_5) Transport (42)	Equivalence conversion factors: '000 Gigajoules per physical unit (43)
			47.0	(1)	64.0	nil	64.0	17.0						17.0	17.0	(1)							30.216
			0.0	(2)	35.0	13.0	48.0	48.0		11.7		2.3	34.0		48.0	(2)	14.0	2.3		11.7			30.216
			3,075.8	(3)	2,154.1	nil	2,154.1	- 921.7						– 921.7	– 921.7	(3)							8.267
			463.2	(4)	934.9	nil	934.9	471.7		3.0		476.5	nil	– 7.8	471.7	(4)	479.5	479.5					14.432
			0.0	(5)	316.0	nil	316.0	316.0		12.2		299.7	10.2	– 6.1	316.0	(5)	311.9	311.9					20.351
			43.9	(6)	1,034.3	nil	1,034.3	990.4				990.4			990.4	(6)	990.4	990.4					10.770
	160.0		1,132.3	(7)	1,270.0	1,607.0	2,877.0	1,744.7	20.0	1,033.0	10.0	134.0	479.0	68.7	1,744.7	(7)	1,197.0	123.0		1,054.0	10.0	10.0	40.930
0.1	1.0		112.5	(8)	693.0	696.0	1,389.0	1,276.5	173.0	137.0	262.0	449.0	64.0	191.5	1,276.5	(8)	1,021.0	472.0		23.0	46.0	480.0	45.637
	0.3		4.0	(9)	473.0	326.0	799.0	795.0			799.5		5.5	– 10.0	795.0	(9)	799.5					799.5	44.840
			0.0	(10)	79.0	179.0	258.0	258.0			123.0		155.0	– 20.0	258.0	(10)	123.0					123.0	Not applicable
	123.0		123.0	(11)	46.0	85.0	131.0	8.0						8.0	8.0	(11)							
	3.0		31.3	(12)	68.0	57.0	125.0	93.7	2.0	27.0		59.1	3.4	2.2	93.7	(12)	88.1	70.1		12.8	5.2		49.843
(22)	(23)	(24)	Inter		Dom. output	Imports	Tot. supply	Final	Agricul.	Industry	Trans. & Fishing	Dom. & Comm.	Exp. & Re-Exp.	Stock+ Losses	Final total		(f_1) to (f_4)	(d_1)	(d_2)	(d_3)	(d_4)	(d_5)	Equiv. C.F.
			57.0	(13)	57.0	nil	57.0	0.0							nil	(13)							
			0.0	(14)	2,686.0											(14)							
			778.4	(15)	778.4	nil	778.4	0.0							0.0	(15)							
			68.9	(16)	68.9	nil	68.9	0.0							0.0	(16)							
			1,348.0	(17)	1,348.0	nil	1,348.0	0.0							0.0	(17)							
			403.9	(18)	403.9	nil	403.9	0.0							0.0	(18)							
			25.6	(19)	25.6	nil	25.6	0.0							0.0	(19)							
			4,662.3	(20)	4,662.3	nil	4,662.3	0.0							0.0	(20)							
1.0	8.0		154.0	(21)	6,914.6	92.8	7,007.4	6,853.4	212.0	2,199.8	1.0	3,706.2	87.1	647.3	6,853.4	(21)	6,119.0	2,285.87	1,561.70	125.00	2,146.40	0.03	3.600
0.1587		3.9283	4.0870	(22)	4.0870	nil	4.0870	0.0							0.0	(22)							
	1.5078	45.5520	47.0598	(23)	47.0598	nil	47.0598	0.0							0.0	(23)							
		1.6665	1.6665	(24)	51.1468	nil	51.1468	49.4803		10.3166		34.9972	nil	4.1665	49.4803	(24)	45.3138	40.1555		5.1583			105.4
(22)	(23)	(24)	Inter		Dom. output	Imports	Tot. supply	Final	Agricul.	Industry	Trans. & Fishing	Dom. & Comm.	Exp. & Re-Exp.	Stock + Losses	Final total		(f_1) to (f_4)	(d_1)	(d_2)	(d_3)	(d_4)	(d_5)	Equiv. C. F.
												123.0	0.2	– 3.2	128.0	(25)	131.0	123.0				8.0	43.411
			0.0	(25)	nil	128.0	128.0	128.0	8.0						6.0	(26)	6.0						
			0.0	(26)	nil	6.0	6.0	6.0		6.0	2.0				2.0	(27)	2.0					2.0	not applicable
			0.0	(27)	nil	2.0	2.0	2.0			53.0	53.6	4.9		119.5	(28)	114.6						
			0.5	(28)	nil	120.0	120.0	119.5	2.0	6.0		682.0	71.0	– 50.0	753.0	(29)	732.0	707.0		25.0			30.216
58.0			58.0	(29)	nil	811.0	811.0	753.0		50.0			4.8	– 306.8	– 302.0	(30)							
			2,767.0	(30)	nil	2,465.0	2,465.0	– 302.0															
(22)	(23)	(24)	Inter																				
00 therms 4.0870	'000 therms 47.0598	'000 therms 51.1468		Units ('000)																			

Cooking, shown in Column (38), Lighting and Electric Appliances (39), Process Heat (40), Motive Power (41), Transport (42). The aggregate of these five uses is the same as the aggregate of entries in Columns (30) to (33) and is shown in Column (37). Our information on these final uses is scanty and fragmented. We still think that our estimates provide material for the means of obtaining interesting results through the model below, not possible without allowing for substitution between fuels and energies for some of the five defined final uses. This is the first time we have examined final uses in Ireland by means of an energy model; we are therefore breaking new ground and preparing the way for better data on uses, in coming times.

Column (43) is the final column of Table 1 and has the Equivalence Conversion Factors per physical unit of fuel or energy. As the word "equivalence" implies, these factors show the actual energy contained in a fuel, expressed in a common unit, thousands of gigajoules. There is no implied loss or efficiency; the fuel's energy is simply converted into its equivalent in terms of gigajoules.

We can now describe the correspondence between the input-output table (Table 1) and the energy flow diagram (Figure 1). Taking the flow diagram headings in turn and progressing from left to right, we start with Inputs of Primary Energy. These are two sorts, imported and domestic. Table 1 shows the imports in Rows (25) to (30) and Column (27) and domestic primary fuel production in Columns (1), (3) to (6) and (15), these being coal, peat and hydroelectricity. The next flow diagram heading is the Energy Sector which roughly corresponds with the inter-industry activities of Table 1, that is Columns (1) to (24). "Losses" in energy conversion and distribution do not appear explicitly in the table. They can, however, be calculated by comparing the inputs with the output for any column activity, using the relevant equivalence conversion factors of Column (43). The flow diagram's Final Users breakdown is given in Columns (30) to (36), and Final Uses in Columns (36) to (42). The "Final Destination of Energy" heading in the flow diagram does not appear in Table 1 except the exports and stocks as Column (34) and as some of Column (35). The "Useful Energy" item on the right hand side of the flow table is shown later as Table 2.

The input-output table provides the bulk of the quantitative information needed for our analysis. The problems of Ireland's energy sector, as we saw in the previous chapter, are that the current combination of fuels costs a large amount of money and is heavily dependent on imports. Given the technologies operating at present, and given the existing requirements of final useful energy, we want to know if there is any better or best combination of fuels, allowing for inter-fuel substitution. In order to discover this we require a technique for optimising the data. In the next chapter we describe the formulation of a Linear Programming model based on the Input-Output table.

Chapter 3

Description of the Fuel allocation Model: Constraint Equations, Activities, Objective Function to Minimise Costs

THE fuel allocation model is developed from the Input-Output table and flow diagram described in the previous chapters. It is formulated as a Linear Programming (LP) model; the essence of such a model is an objective function to be maximised or minimised subject to a set of constraints which are equations or inequalities involving the variables of the system linearly. To explain linear programming adequately requires a description far too long for the present chapter. Interested readers should consult a basic text such as O'Connor and Henry (1975), if they are not already familiar with LP procedures.

In this application to the problems of energy, some of the constraints are technological, based on the input-output table data. Additional constraints ensure that consumers' requirements are met, that a certain level of imports is not surpassed, and that gross outputs do not exceed realistic levels and so on. The variables or activities comprise domestic gross outputs, exports, imports and final deliveries, each of which has an associated cost to the nation, (or gain, in the case of exports). The objective is to minimise the total cost of energy to the nation, so the objective function is the sum of the activities weighted by their respective costs. In its solution, the model gives the minimum total cost and the level of all the activities.

The constraints, activities and objective function are each now described in turn. A summary schema of the model is given in Table 3 at the end of this chapter.

Groups of Constraints

There are seven groups of linear constraints:

1. Requirements of Final Useful Energy (5 constraints);
2. Technological (20 constraints);
3. Natural Gas (2 constraints for selected runs);
4. District Heating from Electricity generated by Oil (2 constraints for selected runs);
5. District Heating from Electricity generated by Natural Gas (2 constraints for selected runs);
6. Foreign Exchange (1 constraint);
7. Upper and lower limits on activity levels (65 constraints).

A list of all constraint statements is given in Appendix Table A.2. Each group of constraints is described now in detail.

1. *Requirements of Final Useful Energy*

The novel aspect of this model is the way in which the nation's energy requirements are specified. Rather than specifying that so many kWh of electricity or so many therms of gas are required by final users, we specify that so many *final uses* of energy, like heating and lighting, must be satisfied. In other words, what is defined is the fuel's use, not the fuel itself. Rough estimates of the nation's requirements of final useful energy have been made, broken down into 5 categories, u_1 to u_5, as follows:

u_1 Space heat and water heat (including cooking);
u_2 Lighting and electric appliances;
u_3 Process heat;
u_4 Motive power (mixing, grinding etc.);
u_5 Transport (excluding air transport).

Values of u for 1973 were estimated from Table 1, delivery Columns d_1 to d_5. These column entries were converted from their physical units to a common unit, thousands of gigajoules, with the aid of the energy equivalence conversion factors shown in Column (43) of Table 1. *The results then had to be converted into final useful energy,* that is the actual amount of space heat etc., which the consumer gets when using different types of burners, boilers, engines and so on, by applying *"Efficiencies in Final Use"* of the various fuels (given in Appendix Table A.1). Aggregation over each of these five uses then gave u_1 to u_5 as shown in Table 2. Readers are asked to please note carefully the difference between *"deliveries to final uses"* and *"final useful energy"*, the latter being smaller GJ quantities than the former and in what follows identified with the symbols u_1 to u_5. We treat air transport as a constant demand not subject to fuel substitution and so exclude it from Table 2. Final deliveries of fuels (various types of peat and oils, electricity, gas and coal) must then satisfy these requirements of final useful energy, u_1 to u_5.

Table 2: *Estimated final useful energy consumption in Ireland, in 1973 by five categories of final use*

Final Use	*Consumption, 10^3 Useful GJ*
Space heat and water heating (including cooking)	45,039 = u_1
Lighting and appliances	5,060 = u_2
Process heat	32,366 = u_3
Motive power	7,852 = u_4
Transport (excluding air transport)	17,179 = u_5
Total of the above items	107,496

This constitutes 5 constraint equations as follows:

Constraints for Final Useful Energy Requirements

$$Wy=u \tag{3.1}$$

where u: column vector of constraints, u_1 to u_5 described above (in 10^3 Useful GJ);
u has five rows and one column. The elements of u are constants, as shown in Table 2.

y: column vector of deliveries to final uses, in physical units, these quantities to be determined by the model;
y has 30 elements, which are the deliveries described in Appendix Table A.3.

W: a matrix of efficiencies in final use (in 10^3 Useful GJ per physical unit of the relevant fuel) calculated from Appendix Table A.1 and Table 1 (final column). W has 5 rows and 30 columns; each row is for a final use and each column for an element of vector y. For example, for i = space heat, j = LPG, then $w_{ij} = 32.4$. That is 32.4×10^3. Useful GJ is the useful space heat that can be obtained from deliveries of 1,000 tonnes of LPG, since LPG has the energy equivalent of 49.843 GJ per tonne and produces space heat at 65 per cent efficiency. (LPG means liquid petroleum gas).

The efficiencies in final use are highly contentious data. Alternative efficiences to those given in Appendix Table A.1 may be used in future runs of the model if better values become available.

Substitution between fuels is possible as there is a choice of fuels for each use, that is, many linear combinations of y-elements can satisfy the u values. This is a very important feature of the model and a novel approach in energy modelling, at least for this country. Forerunners of this approach can be found in Nordhaus (1973) and Hoffman (1974) and in Pickler (1971). In the latter report final useful energy requirements for Hungary are broken down into no less than 50 homogeneous categories e.g., process heat is disaggregated into blast furnaces, smelting furnaces, rolling mill furnaces etc. However, included in Pikler's categories of final use is electricity generation. That is, electricity demand is a predetermined constant, which allows limited scope for substitution—this treatment is possibly a hangover from the ideological emphasis on the development of heavy infra-structural industry, such as power stations. In the Hoffman report which covers the USA, many additional features are incorporated, including load-duration structures of electrical demands, environmental effects and a multi-time period treatment. Nordhaus' model covers the non-Communist world and a two-hundred-year time period. It incorporates five demand categories, similar to our final deliveries and the fuels include some still at development stage or involving speculative technology. The model gives the possible order and timing of introduction of new fuels and technologies based on existing technical and cost estimates. It also calculates the "correct" prices of fuels and the cost of meeting all US energy needs from domestic resources.

While differing in emphasis and matters of detail, these three works are all linear programming applications, allowing inter-fuel substitution. They all have the same objective, which is to minimise the cost of meeting demand.

2. *Technological Constraints*

There are 20 technological constraints in our model. They correspond to the rows in Table 1 except that for electricity and gas only the totals are needed for LP constraints.

We have seen above that the model determines what final deliveries of fuels and electricity there must be in order to satisfy final useful energy requirements. We now describe how these final deliveries are *produced:* what gross outputs of fuels are needed to supply final deliveries of peat, oil, electricity, gas, etc.

In Input-Output analysis gross output is regarded as follows for row i, meaning deliveries of fuel i:

Gross Output =	Intermediate flows +	Net exports +	Final Deliveries +	Stock
	(i.e., flows of fuel i to making other fuels)	of fuel i (i.e. exports-imports)	of fuel i	increases of fuel i

With minor adjustments in our case, the standard matrix notation gives:

$$Qx = Ax + z - m + By + s \tag{3.2}$$

where Q: matrix of technical output coefficients per unit of gross output activity x, having 20 rows and 18 columns.

x: vector of gross outputs of fuels and electricity (in physical units) having 18 elements; see Appendix Table A.3.

A: matrix of technical input coefficients mainly derived from the 1973 energy Input-Output Table (Table 1). Typical element a_{ij} gives the amount of fuel i required per unit gross output of fuel j. A has 20 rows and 18 columns, there being 20 constraints of a technological nature. See Appendix Table A2.

B: matrix of 20 rows and 30 columns, to aggregate the 30 y-elements into a column vector of 20 elements. Thus the elements of B are either unity or zero; for example row (7) of B has 4 entries of unity, because there are four y-elements for the different uses of residual fuel oil, as shown in Appendix Table A3.

z: vector of nine exports of fuels (in physical units) and also containing zero for eleven constraint rows, thus having 20 elements. The eleven zero elements are elements 1, 3, 4, 6, 13, 15 to 20. See Appendix Table A3.

m: vector of 13 imports of fuels (in physical units) and also containing zeros for seven rows, to make up 20 elements. The seven zero elements are elements 1, 3, 4, 5, 6, 13, 14.

y: vector of deliveries to final uses, described under (3.1) above, and having 30 elements.

s: vector of stock increases (in physical units), and having 20 elements, three of them zero, namely, elements 2, 6, 13.

As stated above, final deliveries y are determined by the model. Similarly, how these final deliveries are to be obtained from a combination of gross output, exports and of imports is also to be determined by the model. That is, y, x, z and m are endogenous. Stock increases are specified at their 1973 levels and constitute the right-hand sides of the constraints. This enables the optimum to be directly compared with the actual 1973 situation. After rearranging the equation (3.2) the technological constraints are as follows:

$$(Q-A)X - z + m - By = s \qquad (3.3)$$

3. *Natural Gas Constraints*

In some of the model runs we assume that natural gas is already on line and sells at the recently rumoured price of £20m for the annual flow of about 450 million therms. This is about 4.5 pence per therm. The model allows natural gas to be used in making electricity, or to be piped to houses in its primary form, or to be exported as liquid natural gas.

It is taken that 40 per cent of the gas will be used outside the energy sector, that is as feedstock to the fertiliser industry. This leaves 270 million therms to be distributed by the model between the above energy uses. The constraint equations are as follows:

$$x_{18} - 0.0853231\, x_{12} - 1.053\, x_{17} - 1.05263\, z_9 = 0 \qquad (3.4)$$

that is, the natural gas that is landed must be used up, and also

$$x_{18} \leqslant 270 \qquad (3.5)$$

This gives the upper limit. The activity levels of the xs are determined by the model. The unit of output is millions of therms. The variable x_{18} is landed natural gas, x_{12} is mkWh of electricity from natural gas, x_{17} townsgas from natural gas, z_9 exports of LNG. (The letters mkWh mean millions of kilowatt hours.)

4. *Constraints on District Heating from Electricity Generated by Oil*

In some runs, the model is allowed to operate district heating to households from the waste heat produced by electricity generating stations. For each mkWh of electricity produced in an oil-fired station there could be, in addition, over 1 mkWh-worth of heat output. After allowing for losses in distributing this heat to households through underground pipes, up to 1 mkWh of heat could be actually delivered to households. The area of Dublin for which such a scheme has been analysed (Chapman and O'Reilly 1975) consumes 687 mkWh-worth of heat per year, so that this is the upper limit to the level of district heat activity in our experiments. The constraint equations are:

$$y_{29} - x_{11} \leqslant 0 \tag{3.6}$$

$$y_{29} \leqslant 687 \tag{3.7}$$

The variable x_{11} is electricity generated by oil and y_{29} is district heating from such power stations.

5. *Constraints on District Heating from Electricity Generated by Natural Gas*

There is a similar set of constraint equations to allow for the possibility of operating district heating from stations generating electricity from natural gas. These equations appear in some of the model runs which assume natural gas to be on line.

6. *The Foreign Exchange Constraint*

It is considered desirable to limit the amount of imported fuels used. In these experiments with the model, expenditure on imports, net of exports, is constrained not to exceed the 1973 level expressed at 1974 prices, £197.7 million. Any limit to dependence on foreign supplies can be imposed. The foreign exchange constraint is:

$$p_m^1\, m - p_z^1\, z \leqslant 197.7 \tag{3.8}$$

where p_m^1, p_z^1: row vectors of import and export prices respectively;
m, z: column vectors of imports and exports, respectively, measured in physical units.

7. *Constraints imposing upper and lower limits on activity levels*

Arbitrary lower and upper limits of 50 and 150 per cent of 1973 levels are placed on many activities to prevent them from operating at unrealistic levels. One might prefer to leave a worthwhile activity unbounded. However, to do so would imply that choice of fuels is entirely based on economic criteria. In fact, people usually base their choice of fuels on a number of factors: convenience, noise in use, pollution, storage space needed, habit or patriotism, available or inherited combustion equipment and so on. There is therefore a limit to the amount of substitution possible and, without a detailed survey ascertaining why certain fuels are put to their current uses, it is necessary to use some arbitrary limits.

In addition, it is clear that the production functions ought to reflect any non-linearities in the energy industries. For example, the cost of supplying electricity declines as the load factor improves. As yet, the model does not reflect possibilities for economies of scale and so on. However, the inclusion of upper and lower limits, to some extent, prevents activities from operating at levels where the existing technological data is no longer valid.

Activities on which limits are imposed are the deliveries to final use y. Upper limits only are imposed on gross outputs x, and imports m.

Exceptions to these 50 per cent and 150 per cent are the nation's *total* consumption of refined oil products. The refinery at present can produce only half the nation's requirements. Thus the model can call extra refinery capacity into operation. There are difficulties in getting reliable data on costs, on which the model assesses the feasibility of calling in extra refining capacity. Further remarks on this problem appear in the section dealing with the Objective Function. The limit imposed on electricity generation by natural gas is the same as that imposed on electricity generation by oil, which in turn is 150 per cent of its 1973 level, namely, 6,993 million kWh. It is also assumed that hydroelectricity production was at its upper limit in 1973. Exports of coke are limited by the amount produced at gas works, similarly exports of refined oil products are limited by the amounts produced at the oil refinery.

A subsidiary run in which these limits are removed is described later in Chapter 5.

The Activities

A complete list of the model's activities is given in Appendix Table A3. These activities are variables to be determined by the model. They were indirectly described in the above section on constraints, but a few summary remarks should be made here.

There are 18 gross output activities, x_1 to x_{18}; fourteen of these are taken directly from the input-output structure (Table 1). Oil refining x_6 is included as one activity with all the refined products being produced in fixed proportions. Four of the gross output activities are new and data had to be estimated from various sources including Bunyan's (1974) study. These new activities are: electricity generated by natural gas, electricity generated by imported coal, townsgas using natural gas, and landed natural gas.

There are 30 activities of deliveries to final uses, denoted y_1 to y_{30}. Although these involve basically only about 14 fuels, the different uses of a fuel are included as separate activities. For example, deliveries of electricity can be used for some or all of the 5 final useful energy requirements, u_1 to u_5, such as space heating, lighting, process heat. Each of the latter is treated as a separate activity, since we want the model to avoid having to assume fixed proportions in the final uses of a fuel. Included in these delivery activities are two new activities, both being district space heating: one from oil-fired, the other from natural gas-fired electricity generating stations and denoted y_{29} and y_{30} respectively.

There are 9 Export activities z, and 13 Import activities m.

The Objective Function: Minimise Costs

Various objectives could have been chosen to represent national energy policy. One could minimise imports of fuels subject to limits on the total expenditure on energy; or one could minimise the waste energy in the system, subject to the requirements of Final Useful Energy being satisfied, by minimising the total cost of this waste valued at its primary energy input costs.

In our experiments we have used another alternative: the objective function (OF) minimises the national cost of meeting the requirements of final useful energy. This is probably the most realistic representation of the nation's, or indeed of any private individual's aims. It will ensure the saving of waste and the use of imports where it is economical to do so. The formulation is as follows, v being the objective function, to be minimised:

Minimise Total Cost

$$v = c_x^1\, x - c_z^1\, z + c_m^1\, m + c_y^1\, y \tag{3.9}$$

where x, z, m, y, are the variable activities: gross outputs, exports, imports and deliveries to final uses respectively, as discussed above and c_x, c_z, c_m, c_y are vectors of the respective costs or prices of the activities, at their 1974 levels of price. The cost coefficients c_x etc. are defined below and readers should please note that these coefficients are defined so as to exclude double counting. Appendix Table A3 gives the cost coefficients used in Experiments 1 and 2.

Pricing Problems

In many cases, these costs or prices were difficult to evaluate. First, it is the basic cost price of fuels that is required. Indirect taxes are principally a redistribution of money within the nation and so should not be included. Secondly, since final users' energy needs have to be satisfied, the price has to be that applicable at the point of final delivery. It would be inconsistent to use the price the householder pays for electricity, which is delivered to his house (he cannot collect it from a shop), and then to use the price of imported coal at its point of unloading at the docks. So for consistency, some transport and distribution margins were added, where necessary, to get products to their point of final use. In general, a 20 per cent margin was added to imported oil products etc.; this is rather arbitrary. Thirdly, care had to be taken to avoid double counting the costs. For example, if a gross output activity used inputs of native or imported fuels, then the costs of the native fuel and imported fuel would already appear elsewhere in the objective function. The cost coefficient for the gross output activity would need to exclude these input costs; it should be just the value added. This could sometimes only be estimated from the difference between the (estimated) total cost price and the cost of the inputs.

In the case of the oil refinery we estimated a value added of about £7 per tonne of output, over and above the cost of the crude oil input. This is 18 per cent of estimated total refinery costs, the other 82 per cent being due to fuel inputs. Then the same distribution margin was added as for imported oil products, that is, 20 per cent of the import price. No accurate information is available on the costs of the refinery and the official import prices of refined products have been questioned. It has been argued that the Trade Statistics figures are mere book entries which do not truly represent financial transactions, because the importers are multi-national companies. One can see therefore that there are possible difficulties for the model to compare validly or objectively the costs of home-refined and imported-refined products.

A fifth and final problem relates to the new activities. Cost prices had to be estimated for the hypothetical activities involving natural gas. We accepted the rumoured price of 4.5 pence per therm of landed natural gas. An estimate was made of the margin which should be added to pipe and distribute this gas to households, based on the UK selling price of 12 pence per therm. In fact, we assumed a higher selling price in Ireland of 14 pence per therm. This extra 16 per cent, we hoped, would take account of the smaller scope for economies of scale and would also pay for the higher financing expenses which Marathon might want to cover, resulting from a slower build-up of gas demand compared with demand by the ESB. The margin, then, is 9.5 pence per therm. This may be an over-pessimistic guess. For electricity generated by natural gas (x_{12}) we assumed the non-fuel costs to be the same as in oil-fired stations; these were calculated from the ESB annual reports. In the case of the activity for exporting liquid natural gas (LNG) the world market price appears to have been around 15 pence per therm of LNG, but Ireland might not want to liquefy the natural gas herself. Liquefaction is a highly capital intensive business and the plant and LNG carriers cost billions of dollars at present. So any liquefaction plant in Ireland would probably be a foreign operation. Ireland would sell the natural gas to the liquefaction plant, and the price, which we assume Ireland to charge, includes a 10 per cent profit margin added to the price of the raw natural gas. The model provides subsidiary information on this in the results. Other hypothetical activities requiring price coefficients were the district space heat activities from electricity generated by oil and by natural gas, y_{29} and y_{30} respectively. The values added to

Table 3: *Summary schema of the energy model*

Chapter 3 Constraint Statements	*Activities (physical units)* *Constraints*	*Gross output (x_1 to x_{18})*	*Exports (z_1 to z_9 and zero elements)*	*Imports (m_1 to m_{13} and zero elements)*	*Final deliveries (y_1 to y_{30})*	*Constraint constants (either vector or scalar)*
(3.1)	Requirements of final useful energy (5 constraints):				Wy	$=$ u ('000 useful GJ) (Table 1)
(3.3)	Technological constraints (20 constraints):	$(Q - A)x$	$- z$	$+ m$	$- By$	$=$ s (Stock changes in physical units in 1973)
(3.4) (3.5)	Natural gas constraints:	$x_{18} - g_{12}$ $x_{12} - g_{17}$ $x_{17} x_{18}$	$- g_9 z_9$			$= 0$ (m therms) $\leqslant 270$ (m therms)
	District space heat from					
(3.6)	—Electricity generated by oil:	$- x_{11}$			$+ y_{29}$	$\leqslant 0$ (mkwh)
(3.7)					y_{29}	$\leqslant 687$ (mkwh)
	– Electricity generated by natural gas:	$- x_{12}$			$+ y_{30}$	$\leqslant 0$ (mkwh)
					y_{30}	$\leqslant 687$ (mkwh)
(3.8)	Foreign exchange constraint:		$- p_z^1 z$	$+ p_m^1 m$		$\leqslant 197.7$ (£m)
	Upper limits on gross ouput:	x				$\leqslant$ 150 per cent of 1973 levels (physical units)
	Upper and lower limits on deliveries to final use:				y	$\leqslant$ 150 per cent of 1973 levels (physical units)
					y	$\geqslant$ 50 per cent of 1973 levels (physical units)
	Upper limits on imports:			m_1 m_2 m_6 m_8		$\leqslant$ 150 per cent of 1973 levels (physical units)
	Upper limits* on exports:					
	—of coke:	$-a_{1,15} x_{15}$	$+ z_1$			$\leqslant 0$ (physical units)
	—of refined oils:	$-a_{7,6} x_6$	$+ z_2$			$\leqslant 0$ (physical units)
		.	.			.
		.	.			.
		.	.			.
		$-a_{12,6} x_6$	$+ z_7$			$\leqslant 0$ (physical units)
(3.9)	Objective function: Minimise total cost of energy	$c_x^1 x$	$- c_z^1 z$	$+ c_m^1 m$	$+ c_y^1 y$	

*These exports, namely, coke and refined oils, are constrained not to exceed domestic output levels.

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(3.4) $x_{18} - g_{12} x_{12} - g_{17} x_{17} - g_9 z_9 = 0$ (m therms)

(3.5) $x_{18} \leqslant 270$ (m therms)

these activities are made up of the capital expenditure on pipe laying etc., and the administration and maintenance costs. These could be obtained from the estimated viable selling price of district heat given in the District Heating feasibility study by Chapman and O'Reilly (1975).

There is no doubt that some of the price data need improvement. In these experiments we have attempted to use average 1974 prices, but in times when prices of different fuels are rising in quite large steps at various intervals, it might be better to take 2-year or 3-year averages.

Summary Schema of the Model

A summary schema of the model is given in Table 3. The notation used is as follows:

Notation: Capital letters are matrices.

Small letters are vectors.

Vectors have variable elements, except on the right hand side where they are constants.

Row vectors have a prime (′) following their symbol and above it.

Letter subscripts denote sub-sections of the system e.g., c'_x means the row vector of OF coefficients for gross outputs x_1 to x_{18}.

Symbols without numerical subscripts represent matrices or vectors.

Symbols with numerical subscripts represent one specific activity or coefficient; these are described in Appendix Table A3 and in the present Chapter 3.

Chapter 4

Results of two experiments with the Model: Pre-Natural gas experiment: Optimum Structure in 1973; Post-Natural gas experiment: Optimum Structure in 1973 assuming natural gas to be on line

ALL the results described here depend entirely on the data used and on the options incorporated in the model as described in previous chapters. These data are for 1973 quantities at 1974 prices and are the best figures available to the authors at the time of writing. The authors invite suggestions of improvements from readers and are optimistic about improvements in certain fields of the published data.

The results therefore are not guidelines for policy action. However, the results do show that there may be ways of improving energy allocations with the aid of such a model. They also highlight areas for further investigations and provide useful subsidiary information; indeed, given reasonable estimates of data for the medium term future, the model would provide definite guidelines for policy.

Results of the Pre-Natural Gas Experiment: Optimum Structure in 1973

This experiment optimises the energy system in 1973 by minimising the nation's expenditure on energy.

Table 4 shows the structure of the nation's consumption of final useful energy, comparing the optimum pattern with the actual pattern. Because we imposed upper and lower limits (50 per cent and 150 per cent of 1973 levels respectively) on the final consumption of the different fuels for the various uses, the most interesting information to emerge is which fuels are at their upper and which are at their lower limits. This is more informative than the actual levels, which in many cases are simply the limits imposed.

As can be seen from Table 4, this experiment indicates that the worthwhile fuels for space heating are machine peat, residual fuel oil, and LPG. Gas/diesel oil and kerosene are also above their lower limits. For lighting, and essentially electric appliances, electricity is obviously necessary. For process heat, the optimum indicates a shift to residual fuel oil which would increase its already large allocation by about 4 per cent. For motive power there is a shift from electricity to the various oils. For transport, the optimum would prefer diesel oil to motor gasolene, and the use of electricity in battery powered vehicles is also chosen. At one mile per kWh, vehicles run on batteries are very efficient. Wright (1975) suggested that such vehicles be used for intra-city travel in Dublin in the year 2005. With low pollution and noise levels, their use would avoid the devastation following the expansion of existing traffic. By running on batteries charged at night, use of these vehicles, incidentally, helps to even the load on electricity generation. In fact, this

Table 4: *Results of the pre-natural gas experiment. Structure of consumption of final useful energy 1973 in 10^3 useful GJ*

Optimum consumption compared with actual consumption $(Wy_{optimum}$ *compared with* $Wy_{actual})$

Energy	*Space heating etc.*		*Lighting etc.*		*Process heat*		*Motive power*		*Transport*	
	Optimum	*Actual*	*Optimum*	*Actual*	*Optimum*	*Actual*	*Optimum*	*Actual*	*Optimum*	*Actual*
Coke	9.1 LL	17.4			61.3 LL	123.7				
Machine peat	2,595.0 UL	1,730.0								
Briquette peat	793.5 LL	1,587.0								
Farmers' peat	1,333.4 LL	2,666.8								
Resid. fuel oil	4,908.5 UL	3,272.4			31,295.6	30,198.2	245.5 UL	163.7	196.4 UL	131.0
Gas/diesel oil	18,688.9	14,001.4			251.0 LL	524.8	944.5 UL	629.8	10,514.7 UL	7,009.8
Motor gasolene	–	–			–	–	–	–	6,348.2	10,037.9
LPG	3,417.4 UL	2,271.1			223.3 LL	446.6	155.8 UL	103.7	119.4	–
Electricity	3,965.2 LL	7,930.5	5,060	5,060	213.7 LL	427.5	6,505.7	6,954.3	(0.14) UL	(0.09)
Townsgas	1,375.5 LL	2,751.1			188.5 LL	380.6				
Kerosene	5,282.3	3,470.7			–	–				
Imported coal	2,670.3 LL	5,340.7			132.1 LL	264.4				
Total final consumption (10^3 useful GJ)	45,039.1	45,039.1	5,060	5,060	32,365.8	32,365.8	7,851.5	7,851.5	17,178.8	17,178.8

An activity with LL or UL is at its lower or upper limit, respectively. Lower limits are 50% of the 1973 level and upper limits are 150%.

feature is not incorporated in the model. Pricing in the model might in future be made to reflect non-linear aspects such as the financial benefits of spreading electricity demand, or else there could be a link-up with a separate electricity model. As mentioned before, at present we have assumed uniform average costs for any levels of electricity production (within the production limits imposed) regardless of the timing of electricity consumption.

In general then, residual fuel oil appears a worthwhile fuel, and LPG and gas/diesel oil are also highly favoured, as well as machine peat. Electricity, gas and imported coal do not fare so well. Indeed, 1974 was probably one of the worst years for gas production, the price paid for naphta having risen in an exceptional manner, even by fuel price standards. According to the 1974 annual report of the Dublin Gas Company, the price of naphta increased by 350 per cent between October 1973 and January 1975.

An important omission is that any necessary change of, or adaptation to, users' equipment has not been incorporated in the calculations. So that, while this experiment suggests that it is worthwhile using more fuel oil or LPG, the cost to the consumer of buying a new appliance has not been taken into account. We are simply assuming that over the last ten years or so he would have been replacing his cooker, his car etc., so that any necessary adjustments to capital have happened as part of a normal on-going replacement process.

The full results for all the activity levels are given in Table 5. This shows the combination of levels of gross domestic output activities, import activities and export activities which would be required to supply the Final Deliveries of Table 4. The actual 1973 levels are shown alongside the model's optimum levels and, when relevant, information regarding the binding constraint or limit reached is given in the middle column. The costs of these two patterns is shown in the final columns. The optimum, that is, the cheapest allocation in 1973/74, saves the country some £40 million or 12 per cent of its energy bill. This is achieved, briefly, by reducing production of peat, electricity (except that generated by oil) and townsgas, and lowering oil refinery output. Imports of fuel oil, gas/diesel oil and kerosene are increased, and net imports of motor gasolene are reduced. That said, however, the most striking feature of the results is how close the large activities are to their actual 1973 levels.

In a variant of this experiment, it is assumed that district heating from oil-fired generating stations is already operational in 1973 in Dublin. The net saving to the nation's energy bill is just under £0.3 million. There are no savings in foreign exchange which remains at its upper limit. District heat replaces gas oil the decrease in which enables refinery output and, hence, imports of crude oil to fall. The gap in foreign exchange is then filled by a rise in imports of fuel oil and motor gasolene. In real life there might be less saving on the energy bill and more saving on foreign exchange. In the model there is great pressure to use all the allowed foreign exchange in the search to minimise the energy bill.

Table 5: *Results of pre-natural gas experiment: optimum levels of activity compared with Actual 1973 levels, and their respective costs*

Activities[1]	*Actual 1973 levels*	*Optimum levels*	*Main constraint*[2] *acting on the activity (where relevant)*	*Costs of actual 1973 levels*	*Costs of optimum levels*
				(£'000 at 1974 prices)	
Gross Output Activites:					
Native coal	64.0	17.0	LL on stocks	844.4	224.3
Milled peat	2,120.1	0	LL	7,388.5	0
Machine peat	920.1	707.9	(UL on final deliveries)	6,619.2	5,092.3
Briquette peat	311.0	358.3	(Made entirely from stocks of milled peat)	649.7	748.4
Farmers' peat	1,018.0	478.4	(LL on final deliveries)	7,850.8	3,758.8
Refinery Output	2,686.0	2,266.2		18,994.3	16,025.7
Electricity generated:					
by coal	68.9	0	LL	653.2	0
by milled peat	1,348.0	0	LL	11,249.1	0
by machine peat	403.9	0	LL	3,562.4	0
by farmers' peat	25.6	0	LL	494.7	0
by oil	4,662.3	4,878.9		32,193.2	33,689.0
by imported coal	0	0	LL	0	0
Hydroelectricity	778.4	778.4	UL	5,335.0	5,335.0
Gas made					
from coal	4.1	6.1	UL	1,019.7	1,522.0
from oil	47.1	21.6	(LL on final deliveries and stocks of townsgas)	3,529.5	1,622.5
Export Activities:					
Coke	34.0	45.2		–1,021.9	–1,359.8
Residual fuel oil	479.0	435.4		–12,990.0	–11,807.4
Gas/diesel oil	64.0	0	LL	–2,983.4	0
Motor gasolene	5.5	0	LL	–304.0	0
Jet fuel	155.0	0	LL	–6,802.5	0
Naphta	0	0	LL	0	0
LPG	3.4	0	LL	–116.5	0
Briquette peat	10.0	212.8	LL	–120.0	–2,553.2

Continued . . .

Table 5 *continued*

Activities[1]	*Actual 1973 levels*	*Optimum levels*	*Main constraint*[2] *acting on the activity (where relevant)*	*Costs of actual 1973 levels*	*Costs of optimum levels*
				(£'000 at 1974 prices)	
Import activities:					
Residual fuel oil	1,607.0	1,905.2		43,580.2	51,666.1
Gas/diesel oil	696.0	1,044.0	UL	32,444.7	48,667.1
Motor gasolene	326.0	99.4		18,019.0	5,494.7
Jet fuel	179.0	36.3		9,426.9	1,914.1
Naphta	85.0	25.7	LL	5,100.0	1,543.9
LPG	57.0	86.0	UL	1,952.8	2,946.3
Coke	13.0	0	LL	468.9	0
Kerosene	128.0	192.0	UL	7,857.0	11,785.5
W. spirit	6.0	6.0	C	368.3	368.3
Av. gasolene	2.0	2.0	C	131.4	131.4
Lubricants	120.0	119.7	C	14,518.2	14,479.8
Coal	811.0	402.6		14,042.5	6,970.5
Crude oil	2,465.0	2,027.4		79,410.0	65,313.3
Final deliveries:[3]					
Coke	14.0	7.0	See Table 4		
Machine peat	471.9	707.9	„		
Briquette peat	307.0	153.5	„		
Farmers' peat	974.8	487.4	„		
Residual fuel oil	1,197.0	1,306.8	„		
Gas/diesel	1,021.0	1,430.0	„	Total Delivery Costs	
Motor gasolene	799.5	505.6	„	27,983.7	28,158.3
LPG	87.4	128.6	„		
Electricity	6,152.0	4,791.6	„		
Gas	45.0	22.6	„		
Kerosene	123.0	187.2	„		
Imported coal	732.0	366.0	„		
Total costs				331,349.0	291,736.9

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1. Units of Measurement are given in Appendix Table A2.
2. LL and UL are Lower and Upper Limits respectively. C means that the activity was constrained at constant level.
3. These activities have been aggregated over final use in this table. The breakdown for Final Use is given in Table 4.

Useful subsidiary information is given in the shadow prices resulting from the model. For example, increasing the allowed amounts of fuel oil, diesel oil and electricity used for transport at the expense of other transport fuels would save the nation's energy bill a net £36.7 per tonne of fuel oil, £11.0 per tonne of diesel oil and £0.6 per thousand kWh of electricity. Per useful GJ of transport these are savings of £2.85, £1.913 and £.930 respectively per useful GJ used. On the other hand, increasing the amounts of gas and electricity for space heat or process heat at the expense of other fuels only results in a net increase in the nation's total energy bill, from between £1.55 to £3.41 per useful GJ.

Of further interest are the shadow prices of the five Final Useful Energy requirements space heating, lighting, process heat, motive power and transport. These are given in Table 6. They show the national cost of supplying a useful GJ when fuels are allocated in an optimal fashion. In view of the relative closeness of the optimal pattern to the actual 1973 pattern, these shadow prices are reasonable indications of the actual costs to the nation.

Table 6: *Shadow prices per useful GJ of energy, by type of final use, at 1974 prices*

Final Use:	*£ per Useful GJ*
Space heating, water heating and cooking	2.20
Lighting and electric appliances	4.80
Process heat	1.14
Motive power	4.80
Transport	5.28

So, to provide an extra Useful GJ of, say, motive power would cost about £4.80, at 1974 prices. Actually, the cost in 1974 would have been slightly higher in so far as the optimum would be cheaper. Meanwhile, any new fuel or technology which could provide final energy at or near these prices, would be highly competitive. If any new fuel or technology could be developed, for which the eventual cost could approach the shadow prices, it would be worthwhile spending public funds to develop these. However, it must be remembered that the cost of the users' appliances are not included in these shadow prices, as explained above.

The model provides other information in its marginal cost valuations of certain activities. Here these valuations indicate how much the nation's minimum energy bill would be increased by including an excluded activity. For example, using its purely financial criteria, based on 1973/74 conditions, the model does not consider it worthwhile to make electricity from either native coal, machine peat or from farmers' peat. To do so means substituting this electricity for cheaper electricity, and indeed substituting electricity for other cheaper fuels. This experiment evaluates the marginal cost of substituting electricity made from coal at 0.65p per kWh, of substituting electricity made from machine peat at 0.39p per kWh and of substituting electricity made from farmers' peat at 1.98p per kWh. Since the actual levels of electricity generated from these fuels in 1974 were 71 million, 317 million, and 26 million kWh respectively, the additional cost to the nation's fuel bill was about £2.2 million. For this sum, Ireland obtained some very desirable results: nearly 500 men were employed directly in the generating stations; in addition, a larger number were employed indirectly collecting the peat, and Ireland's dependence on foreign supplies was decreased. The £2.2 million could be seen as the implicit value which the nation puts on these results.

As for electricity made from milled peat, it only just misses being included, its marginal cost being 0.083p per kWh. Indeed in subsequent years the relatively slow rise in price of milled peat has made it the cheapest source of electricity.

Results of the Post-Natural Gas Experiment: 1973 Optimum Fuel Allocation, assuming Natural Gas to be on stream

In this experiment it is assumed that natural gas from the Kinsale field is already on line in 1973. Some 270 million therms, which is 60 per cent of the full supply, is available to the energy system annually; the remainder is assumed to have been allocated as a chemical feedstock outside the energy system. The model allows the natural gas three possible allocations: it can be converted into electricity, it can be piped to houses where it is used as townsgas, or it can be exported as liquid natural gas (LNG). The same upper and lower limits of 50 per cent and 150 per cent of 1973 deliveries of all other fuels are specified. The natural gas technical coefficients appear above in equation (3.4).

The model does not choose to export the gas as LNG unless there is at least 80 per cent profit on the price of the natural gas. That is, if the landed natural gas is being bought into the Irish energy sector at the price of 4.5 pence per therm, it would have to be sold to the liquefaction plant for at least 8.1 pence per therm for the model to consider it. Failing this, the optimum policy is to make what townsgas is needed from natural gas. The remaining natural gas is used to generate electricity, and the shortfall in electricity that is needed is made up by electricity generated from oil. Note that these activities only supply townsgas and electricity "that is needed"; that is, final deliveries of townsgas and electricity (except for motive power and a minute quantity for transport) remain at their lower limits of 50 per cent of the 1973 levels. The fact is that the various oils, at their 1974 prices used here, are still highly competitive and the pattern of final deliveries is practically identical to that shown in Table 4 for the pre natural gas experiment. Adjustments resulting from the advent of natural gas are therefore only to be found in the production and the foreign trade activities. Because townsgas is no longer made from coal or naphta, imports of coal are decreased and naphta from the oil refinery is exported; meanwhile exports of coke disappear. With the reduced amount of electricity generated from oil, imports of fuel oil are halved.

Overall then, the decrease in the nation's energy bill is a potential £10.6 million per year accompanied by a £27.7 million saving in foreign exchange compared with the pre-natural gas situation. However, this saving in foreign exchange could be reduced to £15.7 million if Marathon repatriates abroad all its income from the gas. These are the major findings of the post-natural gas experiment. (See Table 7).

A variant of the experiment was to allow two options. These options enabled oil-fired or natural gas-fired generating stations to supply district heat. Again the same scope and data, as outlined in the 1975 District Heating feasibility study by Chapman and O'Reilly (1975) were assumed. The model chooses district heat associated with natural gas-fired stations. The district heat replaces some gas oil which results in lower oil refinery output, less imports of crude oil and small increases in imports of refined oil products, notably fuel oil. Overall, this district heat option saves only £0.25 million per year on the energy bill, but saves over £2 million in foreign exchange.

Two other variants of this experiment were performed, to analyse two specific allocations of natural gas. Forcing the 270 million therms of natural gas to electricity generation raises total energy costs by £2.1 million and foreign exchange cost by £7.9 million compared with the optimum outlined above. Alternatively, forcing the actual 1973 level of townsgas deliveries to be supplied by natural gas raises total energy costs by £0.7 million and Foreign Exchange costs by £0.6 million. As this only uses a small part, about one-fifth of the 270 million therms of natural gas available annually, the remainder is used by electricity generation. If, however, it were decided to increase dramatically Ireland's use of townsgas such that all the available natural gas is used for townsgas, total energy costs rise by £5 million. One would not expect this high figure because the data used and the emergent shadow prices indicate that a larger amount of useful space heat and process heat can be obtained from the natural gas if it is used for townsgas rather than electricity. However, it arises because townsgas would be replacing oil for space heat and process heat, and the 1974 oil price data supplied to us makes oil the cheaper source of space heat. This more or less follows the argument: use oil where it is competitive, namely, for space and process heat, and since electricity is essential, at least for lighting and appliances, it may as well be cheap, that is, generated by natural gas. However, if the peat-fired electricity generating activities are not allowed to disappear, and if dependence on oil for space heat and process heat is to be reduced (or possibly if the relative price of oil rises) the model would choose to allocate the natural gas to townsgas.

A summary of results of all these experiments is set out in Table 7 below.

Table 7: *Summary of the results of the pre- and post-natural gas experiments*

	Ireland's total energy bill	*Net foreign exchange bill*
	(£m at 1974 prices)	
1973 Actual Situation:	331.3	197.7
Pre-natural gas experiment		
Optimum 1973	291.7	197.7 UL
With district heat option	291.5	197.7 ,,
Post-natural gas experiment		
Optimum 1973	281.1	170.0
With district heat option	280.8	167.8
And forcing all natural gas to electricity	283.0	175.7
Supplying existing 1973 levels of townsgas by natural gas	281.5	168.4
Forcing all natural gas to townsgas	286.5	170.7

Note: the net foreign exchange bill for the post-natural gas experiment could rise by up to £12 million if Marathon repatriated 100 per cent of its income from the gas, or by £8.5 million if Marathon repatriated 70 per cent which seems more probable.

It appears from these results that there is some scope for savings in expenditure on energy. However, any changes in this field would require alterations to capital equipment, so a degree of forward planning is needed. In order to undertake such planning with the aid of this model, it is essential that all interested parties submit their own estimates of fuel efficiencies, import and export prices, values added in converting to secondary fuels, margins for substitution between fuels, projections and so on, because their estimates are likely to be better than ours. That this would be a worthwhile exercise is indicated by the summary results in Table 7. While the numerical differences in Ireland's total energy bill may be based on trial data, they show some interesting possibilities: (a) that district heat from oil-fired stations may save money from the nation's point of view; (b) that more foreign exchange is saved by allocating some natural gas to townsgas rather than none because townsgas emerges as a substitute for oil; (c) that townsgas may be preferable to electricity for space and process heat but is threatened by the competition from oil. Much depends on the price of oil, unless one imposes rigid guidelines that dependence on it should be reduced.

Unfortunately, the results also show that a great deal more analysis is required. So far all values refer to Ireland's energy account, that is: how much our energy costs and how much of this is foreign exchange. This is only a start, although an essential start. Some of the questions which still need to be answered are: (1) How much extra fuel costs would Ireland be willing to pay in order to create jobs at home? (2) What is the actual number of jobs created at home taking account of indirect employment as well? (3) How much income does this create, that is, what are the multiplier effects? (4) How much capital investment is required for the alternative policies in the model? While the annual capital costs have been incorporated in the cost-price coefficients in the model, the scale and timing of the initial capital outlays are likely to hit constraints which we have not incorporated. Thus we may add a fifth query: (5) Will some of the capital equipment, in turn, have to be supplied from abroad?

Some of these problems are approached in the next chapter which discusses further actual and possible subsidiary runs of the model.

Chapter 5

Subsidiary Runs of the Model; Other possible Runs and Developments

IN this chapter we outline the results of a few subsidiary runs of the model. We also describe several further runs which could usefully be undertaken and note some improvements which should be made, hopefully with the aid of interested readers.

Subsidiary Runs of the Model

Three subsidiary runs were undertaken, both for the current situation and for the situation when natural gas is on stream. In the first we were interested to see what adjustments would be made if less imports are allowed to the energy sector. In the second we, in effect, added a bias favourable to those activities which cause employment. This reflects current aims to raise employment in the country. In the third, we removed all limits on final deliveries of individual fuels and allowed the model much greater freedom. While the latter experiment results in the model moving further away from any realistically possible situation, it gives a clearer idea of the model's pressures. The results of these three subsidiary runs will now be outlined in turn:

1. *Runs Allowing Less Imports to the Energy Sector*

Gradually cutting down the amount of foreign exchange available has the effect of restricting imports to the energy sector. Starting with the existing level of £198 million, this is stepwise reduced until two-thirds or £133 million of foreign exchange is allowed. The results are basically of two sorts. First, there are the effects on Final Deliveries, and secondly, the effects on production, that is, the ways in which the Final Deliveries are supplied.

We start with the existing optimum for the pre-natural gas experiment. For the first £20 million reduction in foreign exchange, there are very small alterations in Final Deliveries: gas oil replaces some kerosene for space heating, and LPG replaces some motor gasolene for transport. At the production end, refinery output rises 33 per cent thereby decreasing net imports or increasing net exports of refined oil products. However, the most interesting change is that production of milled peat starts and is used for electricity generation, replacing some electricity generated from oil. Production of briquettes increases and supplies exports for an assumed market abroad. The first £20 million reduction in foreign exchange increases the nation's energy bill by a mere £1.6 million. To put this another way, "buying Irish" to replace £20 million worth of energy imports costs an extra £1.6 million.

For the next £20 million reduction in foreign exchange, there is another small replacement of motor gasolene by LPG for transport, otherwise final deliveries remain the same. At the production end, oil refining doubles, thus further decreasing net imports or increasing net exports of refined oil products. Production of milled peat rises to its upper limit, and electricity production from milled peat rises again at the expense of oil-generated electricity. The nation's energy bill rises by a further £6.3 million.

For the remaining £25 million reduction in foreign exchange, the main shift in final deliveries is away from gas oil to farmers' peat which now makes its first appearance. Production of machine peat rises and electricity from machine peat starts at the expense of oil-generated electricity. Oil refining rises by another 87 per cent with further beneficial trade effects. Finally, coal production and electricity generation from native coal emerge, with electricity beginning to replace diesel oil and LPG for motive power. The final rise in energy costs is £17.9 million.

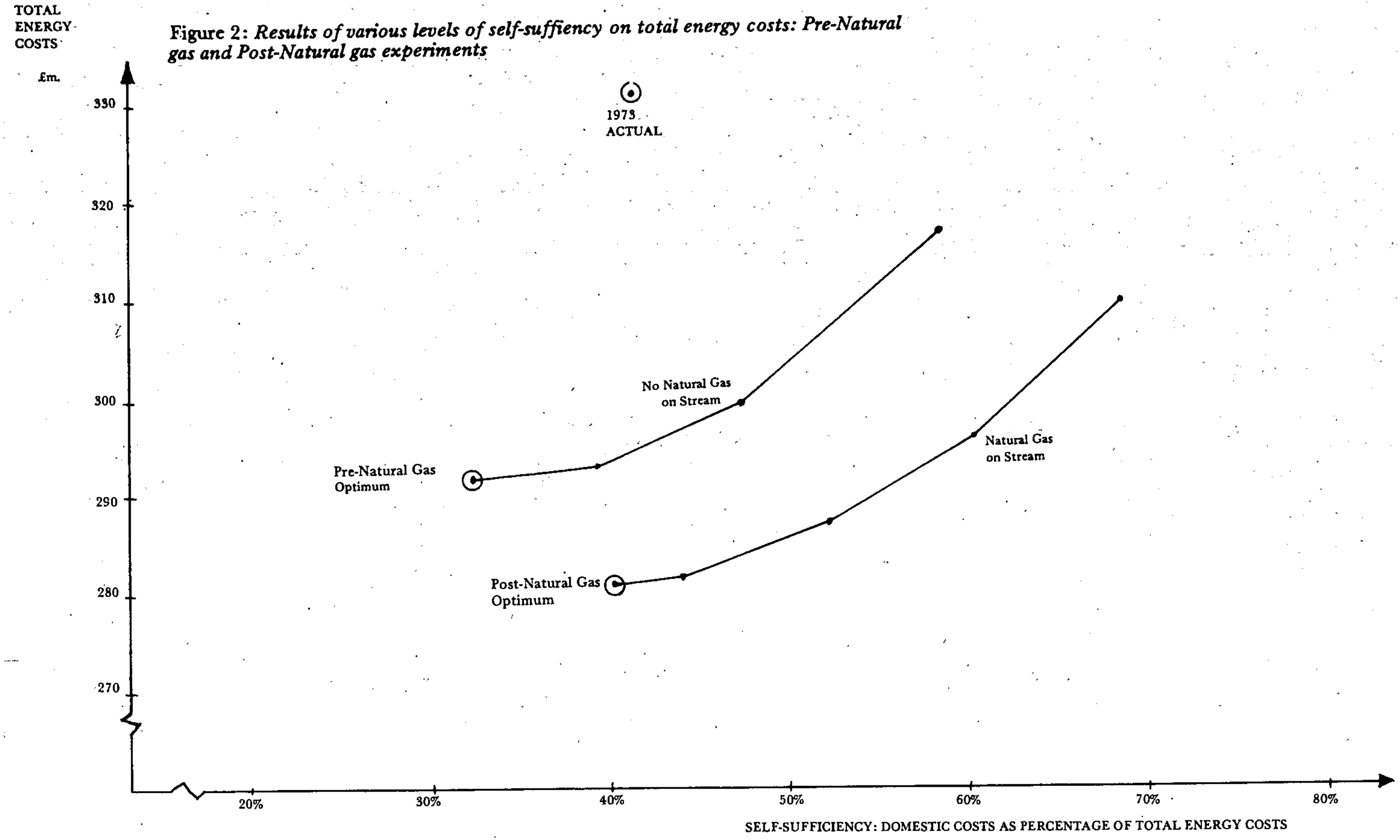
To summarise, there is a very early shift to milled peat, then machine peat rises; meanwhile refinery output continues to increase, and finally, farmers' peat and coal production emerge.

We then undertook the same procedure for the post-natural gas experiment. The initial amount of foreign exchange used in the optimum is £168 million. This is progressively reduced to £95 million. The sequence of events following cuts in foreign exchange is the same as for the situation of no natural gas, described above. However, when foreign exchange is effectively reduced by £25 million there is a switch in the allocation of the natural gas. Initially the natural gas is used for townsgas and electricity, but with the squeezing of foreign exchange, some natural gas is removed from electricity generation to be exported as liquid natural gas. The shortfall in electricity is made up by electricity generated by oil. As foreign exchange is further reduced, there is a progressive substitution by electricity generated by milled peat.

It will be noticed that for each incremental reduction in foreign exchange there is an increasing rise in the nation's total energy costs. This is because the model can substitute the cheaper of the indigenous fuels at first, but when further foreign exchange cuts are made the model has to resort to the more costly indigenous fuels. Figure 2 shows this graphically. Levels of foreign exchange have been expressed in terms of national self-sufficiency in energy, that is the percentage of total energy costs that is domestic cost, or not paid in foreign exchange. The Figure gives the costs of various levels of self-sufficiency for the two experiments, namely, the situations before and after the advent of natural gas.

The optimum points, described in the previous chapter, are at the bottom left hand end of the curves. The figure usually quoted for Ireland's dependency on foreign fuel sources is 80 per cent. This refers to primary fuels and puts self-sufficiency at 20 per cent. In our analysis, fuels are valued at the point of final delivery, that is including domestic value added. Thus, our measure for self-sufficiency is somewhat higher than that based on primary fuels only. As self-sufficiency is increased, total energy costs rise on average,

Figure 2: *Results of various levels of self-suffiency on total energy costs: Pre-Natural gas and Post-Natural gas experiments*



for the range examined, at just over £1 million per extra percentage point of self-sufficiency. At the beginning of the range it is much less, at about £0.2 million per extra percentage point in self-sufficiency; this is while milled peat is being introduced for electricity generation and for briquette production, etc., along with increased oil refinery operation. As the range approaches 60-70 per cent self-sufficiency, extra energy costs approaching £2 million per percentage point are incurred. At this stage, native coal and machine peat are introduced for electricity generation, with further rises in oil refining and substitution of gas oil by farmers' peat for space heating.

In terms of actual foreign exchange, energy costs rise on average about £0.4 million per £1 million of foreign exchange saved. This embraces a rate of about £0.1 million foreign exchange saved at the beginning, rising to about £0.8 million at the end of our range when £60 million to £70 million of foreign exchange has been saved. Readers are reminded here that these substitutions of imports by domestic fuels are made with different allocations of fuels and not by introducing new technologies or altering efficiencies.

2. *Runs with a Bias Favourable to Activities which Promote Employment*

As it stands, the model indicates the fuel allocations required to ensure the cheapest energy bill. It works on purely financial criteria and regards a pound spent outside the country as equivalent to a pound spent at home. However, while there is unemployed labour in this country, it is advocated that more money be spent on domestic goods in order to increase employment. If the model is to reflect this then the data relating to employment should be costed at labour's opportunity cost. This amounts to altering the cost coefficients in the objective function. These coefficients basically represent domestic value added to fuels. That part of value added which is composed of labour should now be costed at labour's opportunity cost. If labour were homogeneous, the existence of unemployment would imply that its opportunity cost were zero. Alternatively, if the labour component were disaggregated into different types of labour and if there existed a national model which could calculate opportunity costs for these types of labour, then these could be incorporated in the run. In the absence of this, we simply carried out a stepwise reduction from 100 per cent down to zero per cent of the actual remuneration to labour, in all the activities where labour is a component of cost. The model notifies us when and what activities change. Problems arose initially in trying to isolate the labour component in value added, as there is no information for each fuel in detail. So experimental estimates of the labour proportion in value added were derived from a national input-output table, to give a figure for the labour component. This component was then stepwise reduced.

The results are summarised in Table 8 below. The starting point is the optimum pre-natural gas allocation described in Chapter 4. Interest focuses mainly on the peat and coal production activities since these have implications for employment. In the optimum (run 1), only machine peat is in a strong position, being selected up to the upper limit on deliveries to final demand. There is no electricity generation by native fuels except of course hydroelectricity. As the opportunity cost of labour is lowered, milled peat and farmers' peat production rise by large amounts. Electricity generation by milled peat, by machine peat and by coal ensue. Farmers' peat is used for final demand but not for electricity generation. By the last run most native fuels are producing at their upper limits, most well before the opportunity cost of labour reaches zero.

Numbers employed in native fuel industries can only be estimated for the various model runs. Compared with the actual numbers employed in 1973, the optimum (run 1) would employ between 4,000 and 5,000 less people. However, by run 3, with a 50 per cent opportunity cost used for labour, numbers employed would be at least 500 more than in 1973 and by run 5, with zero opportunity cost at least 2,000 more.

When natural gas is on stream the starting point is the optimum post-natural gas allocation described in Chapter 4. Briefly, this involved natural gas being used for townsgas and electricity both of which were at their lower limits. When the opportunity cost of labour is lowered the pattern of events is practically identical with that described above for the pre-natural gas situation, with two additional effects. At a 31 per cent opportunity cost for labour, townsgas made from imported coal rises from its lower to its upper limit. At an 18 per cent opportunity cost for labour, townsgas from natural gas rises to its upper limit. The increased production goes to space heat at the expense of gas oil.

These results are tentative. It would be advisable to improve the data on labour content. It would also be more correct if opportunity costs were not uniform for all occupations or for all industries—as mentioned, labour is treated as homogeneous. However, as they stand these results support the policies which encourage domestic fuel production, such as peat. In so far as the peat activities enter the solution while the opportunity cost of labour is still positive, this shows that there is some economic justification rather than the purely regional, social and self-sufficiency justification for having people employed in peat production. The difference between the opportunity cost and the actual price could be regarded as the implicit value (like a subsidy) which the nation puts on the regional, social and self-sufficiency elements. So if milled peat enters when labour's opportunity cost is 83 per cent of labour's actual price, then the remaining 17 per cent can be regarded as the amount Ireland has been willing to pay to have a fuel which is indigenous, to have people employed in less populated regions and so on. Meanwhile, the increases in the total cost of energy are not large (until run 4 at least) and the saving in foreign exchange is considerable.

Table 8: *Results of introducing a bias favouring native fuel industries (by reducing the opportunity cost of labour)*

	Model runs	*Total cost of energy £m*	*Total foreign exchange £m*	*Main effects on levels of output of native fuels (each successive run is compared with the previous run)*[1]
1.	Optimum pre-natural gas situation	291.5	197.7	Base: 707,900 tons of machine peat supplying final demand (UL) 358,300 tons of briquettes made from stocks of milled peat and supplying final demand (LL) and exports 487,400 tons of farmers' peat supplying final demand (LL) No electricity generation by native fuels
2.	75% opportunity cost for labour	291.8	194.3	Extra 272,000 tons of milled peat supplies extra briquette production which is exported
3.	50% opportunity cost for labour	296.4	179.7	Extra 2,908,000 tons of milled peat (UL) supplies electricity generation which replaces some oil-generated electricity Extra 1,040,000 tons of farmers' peat (UL) supplies final demand replacing some LPG and Gas/diesel
4.	25% opportunity cost for labour	298.7	175.5	Extra 673,000 tons of machine peat (UL) supplies electricity generation which replaces some oil generated electricity
5.	0% opportunity cost for labour	316.2	154.2	Extra 70,000 tons of native coal supplies electricity generation by coal (UL) which replaces some oil generated electricity Extra oil refinery output (UL)

UL and LL mean Upper and Lower Limit imposed.

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[1] The effects described occur for values of labour's opportunity cost *within* the ranges between each successive model run, for example, in the last run electricity generation by native coal is introduced when labour's opportunity cost is 20 per cent.

3. *Runs with no Limits on Final Deliveries of Individual Fuels*

In these runs the upper and lower limits on final deliveries of individual fuels were removed. These limits had been 50 per cent and 150 per cent of the 1973 levels of final deliveries, and their purpose was to prevent unduly large swings and complete substitution of one fuel by another. In fact there is no comprehensive information on what scope exists for substitution between fuels, and it is difficult to find evidence from past experience because data on fuel consumption has not been disaggregated by end-use. However, some examples can be cited of large overall swings. For example, oil consumption in Ireland as a proportion of total energy consumption nearly quadrupled in the 20 years up to 1973, and consumption of natural gas in the Netherlands has risen from about 1 per cent to 30 per cent of total energy consumption in the ten years up to 1971. When the model is allowed to run unrestricted, it shows where its major pressures for change lie, thus providing a brief summary of the implications of the data used. The only remaining limits are upper limits on gross domestic outputs set at three times their 1973 levels.

The solutions to these runs reduce total energy costs by approximately one-third and foreign exchange usage by 18 per cent. Predictably, the low price of residual fuel oil makes it the preferred source of space heat and process heat and the main provider of transport and motive power, with small contributions from motor gasolene and LPG. Electricity is used only for lighting and appliances.

When natural gas is onstream, there is a further 1 per cent decrease in total energy costs and a further 17 per cent decrease in foreign exchange usage. Since electricity is needed for lighting, and a small stock of townsgas is specified, the natural gas is used by these activities, but the remaining natural gas is exported as LNG. With residual fuel oil being allowed to supply all space and process heat, townsgas from natural gas is not price-competitive.

These results show that if the prices used here are likely to represent a set of relative prices of fuels then it would be worthwhile to encourage a greater use of residual fuel oil. This would be even more the case if increased efficiences in use could be achieved, by district heating schemes which burn residual fuel oil. However, if one is interested in making long-term recommendations it would be advisable to include in the model a set of best long-term estimates of all prices.

Other possible Runs and Developments

There are many other possible runs which might be worth undertaking if adequate data became available. Some six experiments are suggested and outlined below:

1. Those having altered efficiencies of fuels in Final Use. The efficiencies in final use incorporated in the model runs described above are shown in Appendix Table A1. There is wide disagreement as to what these efficiencies

should be. For example, estimates of the efficiency of various oils used for space heat and process heat range from 33 per cent (Maher, USA) to 76 per cent (UK Department of Energy). We require estimates of average operating efficiencies in Ireland.

2. Those having altered costs in the Objective Function. The costs used in the model runs described above are listed in Appendix Table A3. These were already varied in the subsidiary runs which altered the shadow price of labour. Other variations might include different distribution costs of imported fuels, different margins added at the oil refinery; both of these items are estimates at present. Experiments with rises in the price of oil should also be undertaken.

3. Those having various schedules for the nation's requirements of Final Useful Energy. The model has to satisfy the nation's requirements of final useful energy, which in the above runs are the 1973 requirements shown in Table 2. Some attempts could be made at projecting these into the future. Certain types of usage, such as motive power, might expand rapidly. Because of conservation measures or cost considerations, demand for some fuels might contract. Policies making public transport more attractive or houses better insulated could reduce or hold static the nation's requirements of energy used for transport or space heat.

4. Those which incorporate different technologies. The output proportions of the oil refinery can be altered to a limited extent with existing oil refinery capacity, to a greater extent with new capacity. New technologies include systems with waste heat recovery, heat pumps, solar energy use, nuclear power etc. Final requirements of useful space heat should be separated into household and commercial use, if one wants to incorporate the possibility of integrated energy systems in firms. Also, process heat might be separated into low grade and high grade heat if one is to allow for the option of heat recovery from the latter. In order that new technologies be incorporated as possible activities in the model, readily usable data or relevant feasibility studies are necessary.

5. Those which include an explicit analysis of the implications for capital equipment. The model at present deals with capital equipment implicitly, since in the objective function each activity's cost coefficient is a reflection of the cost price of a unit of that activity at the point of final delivery. This cost price would automatically include depreciation or capital costs averaged over the lifespan of the activity. However, it might be desirable to treat separately the initial capital outlay of new activities or of those which represent new technologies. Apart from the speculative nature of these costs, caution must be exercised to net out any ongoing capital outlays arising out of ordinary replacement of equipment. Some attempt might also be made to examine the implications for users' equipment, for example, the adaptation required for transferring from existing townsgas to natural gas.

6. "Consensus runs". The greatest improvement that could be made to the model would be to obtain data agreed by a group of representatives from all the fuel interests. These representatives would have the best knowledge of likely trends relating to their fuels and might also be familiar with the model and linear programming. The best information could then be obtained on trends in costs, including distribution and value-added margins, in efficiencies, in the technologies of the model's existing activities and in new technologies. This would ensure a degree of realism, if a model based on this prototype is to be used to help in formulating policies in the future.

Chapter 6

Summary and Conclusions

THIS paper describes our attempts at analysing the Irish energy system and at developing a model which points the way to the best allocation of energy resources. We are satisfied that the background data for 1973, as given in Chapter 2, are fairly good, although the amount of detail could be increased. In particular, alternative product mixes of refinery output should be specified; gas/diesel oil and residual fuel oil could be disaggregated into various grades, as could coal, both imported and domestic. In particular, until an authoritative and generally accepted study of a gas grid is made, the data on natural gas distribution is speculative, but hopefully in the right order of magnitude.

Another important point concerning the model's structure is the amount of substitution allowed between fuels. This permitted substitution is one of the main features in the model. Unfortunately, however, there is no knowing how much substitution of one fuel for another fuel would be realistic in any given set of circumstances. We are only too well aware that "fuels have a number of attributes and heat content is but one" in the words of Webb and Pearce (1975). Here we treat this heat content as the only attribute, and as homogeneous within the ranges for substitution which we allowed (50 per cent to 150 per cent of the 1973 actual deliveries to final consumers). The only justification is that we know that when prices of fuels vary, substitution can and does take place. From recent observations we have seen the rise in sales of oil in the 1960s and the decrease in sales of townsgas in the 1970s, resulting from changes in their prices relative to other fuels. Estimates of UK cross-price elasticities of fuels for 1965 were made by Wigley (1968). All twelve cross-price elasticities for the four main fuels were positive and non-zero, half of them being greater than 0.5. Further information on the ranges of possible substitution as well as the changeover time applicable to Ireland would be highly desirable. Meanwhile, readers have to bear in mind these limitations when interpreting the results. If some readers feel that the model is invalidated because accurate data are unavailable, then they should be reminded that policy decisions are currently being made on precisely the same data but without the comprehensive framework provided by this model. Their argument therefore reduces to: no policies unless better data—an argument which is not completely invalid, although it may be difficult to justify in real-life situations.

As for the results of experiments with the model, one is obliged to ask whether these are of real practical use or of the all-too-frequent "theoretical interest only" kind. Certainly the results as summarised in Table 7 have not produced any surprises. It is common knowledge that oil is still highly competitive despite the price escalation, that LPG can be a good fuel for supplying motive power and transport, and that generating electricity from peat in 1973/74 was rather expensive if one is simply viewing it from the energy cost angle. The same applies to townsgas made from naphta whereas hydro-electricity generation is a very worthwhile activity. Meanwhile the introduction of systems distributing district heat from electricity generating stations is worthy of careful consideration; this requires close scrutiny of possible future world prices of fuel oil, value-added margins, capital costs and so on. These are some of the main results of the Pre-Natural Gas Experiment, which aimed at optimising the 1973 allocation of fuels. In the Post-Natural Gas Experiment, which assumes natural gas is onstream from Kinsale, the results are perhaps more interesting: in so far as townsgas and electricity have to be produced, the natural gas should be used for townsgas, and the remainder used for electricity. The shortfall in electricity is made up by electricity generated from oil. The dominant feature is the competition to electricity and townsgas presented by oil, given the 1974 price structure used here. Using natural gas to make electricity is the least favourable policy from the point of view of the nation's energy bill since the necessary townsgas has to be produced from naphta and this is expensive. This is not the usual reason raised by advocates of natural gas being used for townsgas.

Few people would disagree with these results, and one might wonder why one needs a model in order to demonstrate them. In reply one must first point out that as this model is in prototype stage, it is encouraging that the model has demonstrated that it can produce sensible results. This bodes well for any future refinements incorporated in the model. In the second place, the model provides subsidiary information which would be difficult to establish by any other method. For example, it gives for the nation's energy bill the marginal costs of substituting certain fuels for other fuels. This information helps put into perspective certain policies which, while not part of the computed optimum pattern, are considered to be in the national interest. Subsidiary runs show that foreign exchange can be saved from the optimum solution at fairly small extra cost to the energy bill (Figure 2) and that to encourage activities such as peat production, which provide employment in Ireland, results also in a moderately small increase in total energy costs. This certainly helps to show in more precise terms what is implied in the policy statement at the beginning of this paper—"the optimum development of indigenous energy sources". We have covered only some of the possibilities so far and there are numerous policies which can be examined with the help of subsidiary information from the model. So the results, so far, are good and the possibilities are also good.

We began this paper with the observation that the potential for energy *conservation* is already being investigated and that it would be worthwhile to analyse the scope for saving by *better* fuel allocation. We have now started to gain some idea of this scope as shown in the summary of results given in

Table 7. While the optimum levels for the two major experiments allow some socially desirable activities to disappear and therefore give an exaggerated level of savings, the results of the subsidiary runs which relate to *future* fuel allocations probably give a good idea of the relative savings or costs of individual policies. Compared with the pre-natural gas situation, the post-natural gas alternatives show savings in the five to ten million pound range for the nation's energy bill, and somewhat larger savings for foreign exchange.

These are the orders of magnitude based on 1973 technology and 1974 prices. Now the work must begin of obtaining consensus data relating to the medium-term future from all parties interested in fuel in Ireland. Fuel policy formulation will then have a comprehensive and systematic tool at its disposal.

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Appendix 1

Notes on Table 1

(1) *Row (2), Coke:* This is a by-product of townsgas made from coal (22) and for LP modelling appears as a negative input to column (22); it is thus being treated as a fixed proportion of such townsgas.

(2) *Row (3), Milled Peat:* The input to industry, milled peat for peat pots, has been omitted from the (f_2) column of row (3), because this peat is not for energy. There were large withdrawals of milled peat from stock, during 1973.

(3) *General remark about rows (7) to (14):* The refinery products, items (7) to (13) are treated for LP modelling as negative inputs to column (14), total refinery output; thus they are treated as fixed proportions of the latter. Total refinery output is defined to be the sum of items (7) to (13) and is not shown in detail along row (14). Row (7), residual fuel oil, is the residue remaining after petrol and gas/diesel has been produced from the crude.

(4) *General remark about rows (15) to (21):* Total electricity, row (21), is the sum of the outputs shown in rows (15) to (20) of column (21). Each of these entries in column (21) gives the amount of electricity leaving the power stations, that is exclusive of power station use (shown in row (15) of column (15) and so on) but inclusive of network losses. The latter appear in the (f_6) column of row (21), as a single aggregate. Row (21) shows electricity distributed as a single commodity, regardless of method of generation.

(5) *General remark about rows (22) to (24):* The treatment of gas corresponds closely to that of electricity. Row (24) output is the sum of total production of townsgas from coal, (22), and from oil, (23). Again the entry in the (f_6) column is for distribution network losses.

(6) *Rows (26) and (28):* Because white spirit and lubricants are not combustible sources of energy they are omitted from columns (a) to (d).

(7) *Row (30), Crude Petroleum:* Input to the refinery, column (14), has been taken to be 103 per cent of refinery output, in accordance with OECD 1975 practices, Table 10. This estimate of crude oil input has caused an apparent withdrawal from stocks, because imports were smaller than required refinery input.

(8) The row *"Domestic output (excl. by-products)"* has no entries for coke, column (2), or for refinery products, columns (7) to (13). The coke is defined to be a fixed proportion of townsgas from coal. Each oil product is defined to be a fixed proportion of total output of the refinery. Thus for the LP model the output of coke and of each refinery product is automatically determined by the level of output of another item.

(9) *General remark about Final User columns (f_1) to (f_6):* The entries here are based on severely limited information.

Appendix Table A1: *Efficiencies in final use, per cent of delivery to final use to give final useful energy*

	Final Uses				
	Space heating, water heating, cooking	*Lighting and appliances*	*Process heat*	*Motive power*	*Transport*
	Per Cent				
Coal	25		35		
Coke	25		35		
Machine peat	25				
Briquettes	25				
Farmers' peat	25				
Fuel oil	65		70	40	
Gas/diesel oil	65		50	30	32
Motor gasolene					28
LPG (butane, propane)	65		70	40	26
Electricity	95	90	95	90	85
Townsgas	65		70		
Kerosene	65				

Source: Institute for Industrial Research and Standards.

Note: A great deal more information would be desirable on the efficiency of oil-fired boilers in domestic use for space-heating etc.

Appendix Table A2: *List of constraint rows*

Names of Constraint Rows	*Units of Measurement*	*Nature of the Constraint: E = Equality; L = Less than; G = Greater than*
Requirements of Final Useful Energy:		
Space heating, water heating and cooking	10^3 useful GJ	E
Lighting and appliances	,,	E
Process heat	,,	E
Motive power	,,	E
Transport	,,	E
Technological Constraints:		
Native coal	10^3 tonnes	E
Coke	,,	E
Milled peat	10^3 long tons	E
Machine peat	,,	E
Briquette peat	,,	E
Farmers' peat	,,	E
Residual fuel oil	10^3 tonnes	E
Gas/diesel oil	,,	E
Motor gasolene	,,	E
Jet fuel	,,	E
Naphta	,,	E
LPG	,,	E
Total electricity	10^6 kWh	E
Total gas	10^6 therms	E
Kerosenes	10^3 tonnes	E
White spirit & SBP	,,	E
Aviation gasolene	,,	E
Lubricants	,,	E
Imported coal	,,	E
Crude petroleum	,,	E
Natural Gas Constraints:[1]		
Natural gas	10^6 therms	E
Upper limit natural gas	,,	L
Constraints on District Heat from Electricity:		
Generated by oil	10^6 kWh	L
Upper limit	,,	L
Generated by natural gas[1]	,,	L
Upper limit	,,	L
Foreign exchange constraint	10^6 £	L

Contd.

Table A2 – *contd.*

Names of Constraint Rows	*Units of Measurement*	*Nature of the Constraint: E = Equality; L = Less than; G = Greater than*
Upper Limits on Gross Output Activities:		
Native coal	10^3 tonnes	L
Milled peat	10^3 long tons	L
Machine peat	,,	L
Briquette peat	,,	L
Farmers' peat	,,	L
Refinery output	10^3 tonnes	L
Electricity generated by native coal	10^6 kWh	L
Electricity generated by milled peat	,,	L
Electricity generated by machine peat	,,	L
Electricity generated by farmers' peat	,,	L
Electricity generated by oil	,,	L
Electricity generated by natural gas[1]	,,	L
Electricity generated by imported coal	,,	L
Hydro-electricity	,,	L
Townsgas made from coal	10^6 therms	L
Townsgas made from oil	,,	L
Townsgas using natural gas[1]	,,	L
Upper and Lower Limits on Activities of deliveries to Final Use:		
Coke for space heating	10^3 tonnes	G
Coke for process heat	,,	G
Machine peat for space heating	10^3 long tons	G, L
Briquette peat for space heating	,,	G
Farmers' peat for space heating	,,	G
Residual fuel oil for space heating	10^3 tonnes	G, L
Residual fuel oil for process heat	,,	G, L
Residual fuel oil for motive power	,,	G, L
Residual fuel oil for transport	,,	G, L
Gas/diesel oil for space heating	,,	G, L
Gas/diesel oil for process heat	,,	G
Gas/diesel oil for motive power	10^3 tonnes	G, L
Gas/diesel oil for transport	,,	G, L
Motor gasolene for transport	,,	G
LPG for space heating	,,	G, L

Contd.

Table A2 – *contd.*

Names of Constraint Rows	*Units of Measurement*	*Nature of the Constraint: E = Equality; L = Less than; G = Greater than*
LPG for process heat	10^3 tonnes	G
LPG for motive power	,,	G, L
LPG for transport	,,	L
Electricity for space heating	10^6 kWh	G
Electricity for lighting	,,	G
Electricity for process heat	,,	G
Electricity for motive power	,,	G
Electricity for transport	,,	G
Gas for space heating	10^6 therms	G
Gas for process heat	,,	G
Kerosene for space heating	10^3 tonnes	G
Imported coal for space heating	,,	G
Imported coal for process heat	,,	G
Upper Limits on Import Activities:		
Residual fuel oil (m_1)	10^3 tonnes	L
Gas/diesel oil (m_2)	,,	L
LPG (m_6)	,,	L
Kerosene (m_8)	,,	L
Upper Limits on Export Activities (limited to domestic output levels):		
Coke	10^3 tonnes	L
Residual fuel oil	,,	L
Gas/diesel oil	,,	L
Motor gasolene	,,	L
Jet fuel	,,	L
Naphta	,,	L
LPG	,,	L

1. These contraints are only included for the experiments having natural gas assumed on stream.

Appendix Table A3: *List of the model's activities and objective function cost coefficients for experiments 1 and 2*

Activities	*Unit of measurement*	*Objective function coefficients: Cost per unit of activity*
Gross output activities ($x_1 \ldots x_{18}$):		£'000
Native coal (1)	10^3 tonnes	13.193
Milled peat (2)	10^3 long tons	3.485
Machine peat (3)	,,	7.194
Briquette peat (4)	,,	2.089
Farmers' peat (5)	,,	7.712
Refinery output (6)	10^3 tonnes	7.072
Electricity generated by coal (7)	10^6 kWh	9.480
Electricity generated by milled peat (8)	,,	8.345
Electricity generated by machine peat (9)	,,	8.820
Electricity generated by farmers' peat (10)	,,	19.325
Electricity generated by oil (11)	,,	6.905
Electricity generated by natural gas (12)	,,	6.905
Electricity generated by imported coal (13)	,,	9.537
Hydro-electricity (14)	,,	6.854
Townsgas made from coal (15)	10^6 therms	246.500
Townsgas made from oil (16)	,,	75.000
Townsgas using natural gas (17) (a)	,,	93.200
Landed natural gas (18) (a)	,,	45.107
Export activities ($z_1 \ldots z_9$):		
Coke (1)	10^3 tonnes	– 28.184
Residual fuel oil (2)	,,	– 23.497
Gas/diesel oil (3)	,,	– 47.956
Motor gasolene (4)	,,	– 59.175
Jet fuel (5)	,,	– 46.985
Naphta (6)	,,	– 60.00
LPG (7)	,,	– 31.217
Briquette peat (8)	10^3 long tons	– 12.000
Liquid natural gas (9) (a)	10^6 therms	– 150.000
Import activities ($m_1 \ldots m_{13}$):		
Similar imports		
Residual fuel oil (1)	10^3 tonnes	30.740
Gas/diesel oil (2)	,,	45.276
Motor gasolene (3)	,,	51.371
Jet fuel (4)	,,	48.946
Naphta (5)	,,	37.302
LPG (6)	,,	25.000
Coke (7)	,,	39.911
Complementary Imports activities:		
Kerosene (8)	,,	61.383

Continued . . .

Table A3 – *continued*

Activities	*Unit of measurement*	*Objective function coefficients: Cost per unit of activity*
White spirit (9)	10^3 tonnes	61.383
Aviation gasolene (10)	,,	65.700
Lubricants (11)	,,	120.985
Coal (12)	,,	17.315
Crude petroleum (13)	,,	32.215
Activities of deliveries ($y_1 \dots y_{30}$):		
Coke for space heating (1)	10^3 tonnes	..(b) (See footnotes)
,, ,, process heat (2)	,,	..(b)
Machine peat for space heating (3)	10^3 long tons	..(b)
Briquette peat for space heating (4)	,,	..(b)
Farmers' peat for space heating (5)	,,	..(b)
Residual fuel oil for space heating (6)	10^3 tonnes	6.150
,, ,, ,, ,, process heat (7)	,,	6.150
,, ,, ,, ,, motive power (8)	,,	6.150
,, ,, ,, ,, transport (9)	,,	6.150
Gas/diesel oil for space heating (10)	,,	9.055
,, ,, ,, process heat (11)	,,	9.055
,, ,, ,, motive power (12)	,,	9.055
,, ,, ,, transport (13)	,,	9.055
Motor gasolene for transport (14)	,,	10.274
LPG for space heating (15)	,,	7.461
,, ,, process heat (16)	,,	7.461
,, ,, motive power (17)	,,	7.461
,, ,, transport (18)	,,	7.461
Electricity for space heating (19)	10^6 kWh	..(b)
,, ,, lighting (20)	,,	..(b)
,, ,, process heat (21)	,,	..(b)
,, ,, motive power (22)	,,	..(b)
,, ,, transport (23)	,,	..(b)
Gas for space heating (24)	10^6 therms	..(b)
,, ,, process heat (25)	,,	..(b)
Kerosene for space heating (26)	10^3 tonnes	..(b)
Imported coal for space heating (27)	,,	3.463
Imported coal for process heat (28)	,,	3.463
District space heat from oil-fired electricity generating stations (29)	10^6 kWh	7.526
District space heat from natural gas-fired electricity generating stations (30) (a)	,,	7.526

(a) These activities apply only to experiments with natural gas assumed on stream.

(b) Delivery costs are already included in Gross Output Cost Coefficients.

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