A DYNAMIC PHYSICAL ENERGY MODEL OF THE UNITED KINGDOM

by DR. M. A. BARRETT

ERG.044

Energy Research Group,
The Open University,
Walton Hall,
Milton Keynes,
MK7 6AA,
England.

October 1982

ABSTRACT

This report describes the structure and simulation results of a dynamic physical model of the UK energy system. The model traces the hourly flows of energy from energy sources through various energy converters and stores to useful energy demands. Effects such as the temporal and climatic dependence of demands have been accounted for. Technical data has been collected so that it is possible to simulate the performance of the system as it was in 1976 or as it might be at some future date. The model has been validated against measured data and has been used to simulate the UK system with changed demands and new conservation and supply technologies.

Acknowledgements

It would have been much more difficult to have attempted the work described below without the support, advice and information given by a large number of people. In particular everyone in the Energy Research Group at the Open University has at one time or another helped or encouraged me in some way.

Help from the A.C.S. (Academic Computing Service) of the Open University was essential to the satisfactory development and use of the programmes written.

Last but not least I must thank my friends for making the expenditure of so much time psychologically bearable.

CONTENTS

COMPANION VOLUME

There is a companion volume, called "DYPHEMO output", to this report containing a description and samples of computer output from the model. This output is from the lineprinter and graphplotter.

LIST OF FIGURES

LIST OF TABLES

UNITS AND CONVERSIONS

Most physical measurements that constitute the database of the model are valued in System International (S.I.) units; there are some instances when other units are used to specify original source data.

Prefixes

k	kilo	10^3
M	mega	10^6
G	giga	10^9
T	tera	10^{12}
P	peta	10^{15}
E	exa	10^{18}

Energy

Energy is measured in Joules (J) or Watt-hours (Wh). (1 Wh = 3.6 kJ)

Power

Power is measured in Watts (W).

NOMENCLATURE

The nomenclature below lists the symbols frequently used in the report and a brief description of the variable to which they refer. In general they are also described in the text.

The common units for each variable are given in brackets after the description. Rather than use unique symbols I have opted for common, or mnemonic, symbols. This should not cause any confusion within any particular section.

A	- area	(m^2)
C	- storage capacity	(J)
D	- useful energy demand	(W)
D	- density	(kgm^{-3})
E	- energy	(J)
g	- gravity	($9.81\ ms^{-2}$)
G(t)	- incidental gains	(W)
H	- height	(m)
h	- hour	
I	- intensity	(Wm^{-2})
K	- constant	
L	- length	(m)
lf	- load factor	
M	- mass	(kg)
M	- flow rate	(kgs^{-1})
m	- month	
N	- efficiency	
N	- population	(millions)
P	- power	(W)
Q	- energy	(J)
S	- system efficiency	
S	- specific loss	(WC^{-1})
T	- transmittance	
T	- temperature	(C)

T	- period	(s.)
t	- time	
U(t)	- use pattern	
U	- U-value	($WC^{-1}m^{-2}$)
V	- volume	(m^3)
V	- speed	($m.s^{-1}$)
Y	- gigaseconds in year	(s.)

ABBREVIATIONS

ACE	Association for the Conservation of Energy
BGC	British Gas Corporation
BNOC	British National Oil Corporation
BRE	Building Research Establishment
CEGB	Central Electricity Generating Board
CHP	Combined Heat and Power
DYPHEMO	Dynamic Physical Energy Model
EAG	Economics Advisory Group
ECC	Electricity Consumer's Council
EP	Energy Paper
ERG	Energy Research Group (Open University) [1]
HMSO	Her Majesty's Stationery Office
IEA	International Energy Agency
IIED	International Institute for Environment and Development
NCB	National Coal Board
NCC	National Consumer's Council
NIES	Northern Ireland Electricity Service
NSHEB	North of Scotland Hydro Electricity Board
OU	Open University
OUERG	Open University Energy Research Group
SARU	Systems Analysis Research Unit
SMD	Simultaneous maximum demand
SSEB	South of Scotland Electricity Board

---

[1] Energy Research Group, Open University, Walton Hall, Milton Keynes, MK7 6AA.

1. INTRODUCTION

1.1 Layout of this report

Chapter 1 will briefly describe the problems of energy supply and motivations for producing an energy model. It will also give a first introduction to the scheme of the model and the sorts of questions which it might answer.

In chapter 2 a description of the layout and components of the UK energy system is given. The structure of the model, and its exogenous variables is subsequently detailed. A brief exposition of the theoretical background to the model is also given.

Chapter 3 gives a condensed flow chart of the model's calculations and some details of running it on the computer system. Sources of error and methods of eradicating them are discussed. Most importantly, a comparison of the actual performance of the UK energy system as measured is made with the simulated performance. The issue of validation is discussed.

In chapter 4 a procedure for hypothesising and assessing an energy system is suggested. The range of possible applications of the model is demonstrated by means of five types of application. These pertain to systems with changed demands, technical conservation, improved efficiency and allocation and new technologies.

Chapter 5 assesses the success of the research in attaining the aims of the programme. It discusses some of the limitations that have arisen and mentions future research that might arise from this programme.

The appendices detail the components of the system; namely demands, income sources, converters and natural and artificial stores.

1.2 Raison d'etre of model

This section proposes some reasons for contructing the type of model advanced in this report.

The dynamic physical energy model (DYPHEMO) which will be described in this report has been developed as a research tool. The aim is to develop a greater understanding of various physical and technical possibilities concerning the manipulation by society of energy flows in the UK. Since the classes of problems to be studied determine the type of research tool developed an account must be given of the types of problems one wishes to address. The following account gives the basic reasons for needing energy and discusses some of the constraints met in acquiring energy.

All life forms maintain their relatively ordered state by using useful energy (or available energy) in chemical form as food. This chemical energy is ultimately derived from the sun. The sun irradiates the earth with high temperature heat radiation. After some modification by the atmosphere the energy arrives at the earth's surface where it may be utilised by plants. Plants are called autotrophs; they can use solar energy to meet their energy demands, they do not ingest other living things. Plants convert solar energy into a form suitable for their own metabolism or energy needs by a process called photosynthesis. Essentially this involves the fixing of energy in sunlight of a suitable wavelength into biochemical energy in the plant. Photons are employed by chloroplasts in the plant to synthesise various biochemicals, these mainly being carbohydrates from carbon dioxide and water. This biochemical energy in plants can be used by the plant or it may be ingested by a heterotroph (a living being that derives energy from other living beings). This ecological system of autotrophs and heterotrophs survives by utilising its basic energy source (the sun) and distributing some of the energy collected by plants through food chains.

In addition to <u>vital</u> energy needs human society has developed a need for energy in excess of this vital supply; to the extent in fact that the demand for "non-vital" energy exceeds that for food by a factor of fifty (in the UK). The fuel (or energy) used to provide this useful energy is degraded by use to become more disordered chemical/biological waste or low temperature heat. Degraded energy in these forms constitutes pollution if it has the potential of changing the environment in some way detrimental to the well being of life forms. The physical problems can therefore be divided into two categories; the problem of meeting demand and the problem of pollution. There are other problems of a non-physical nature associated with demand and pollution, such as economics and social impacts.

1.2.1 The problem of meeting demands

Firstly, to survive, society must ensure an adequate supply of the vital energy supply - food. There are certain minimum requirements for food both in terms of available energy (calories) and in terms of the necessary nutritional mix of minerals and essential biochemicals.

Secondly, society in its present form relies on the supply of useful energy for many complex processes. The need for these processes arises from social requirements, they are not vital (except for those processes which are essential for the production of food and health care). It is therefore possible to reduce this second category of demand to zero, although unacceptable to most people.

The model DYPHEMO can be used to examine how changes in social energy demand, through behaviour changes or technologies, affects or constrains the energy supply technology: demand being investigated before supply. Various new technologies can be investigated using the model.

1.2.2 The problem of pollution

1.2.2.1 Directly harmful pollution

Directly harmful pollution consists of chemical and radioactive pollutants having a harmful effect on living things. In general the complexity of individual organisms of a species and the interaction between populations of different species in the ecosystem makes the estimation of damage difficult. This is especially so when the pollutant involved has some insidious effect on the genetically carried information. Damage from such pollutants (e.g. radioactive elements or certain chemicals) may take years to appear in an individual and possibly generations in a species. This is why it has taken so long to appreciate the damaging effects of such pollutants; they are only readily perceived in large doses or statistical samples. The model will be used to assess the potential role of technologies that seem to reduce or avoid such problems. Thus, conservation, higher efficiency and the use of ambient energy generally produce less pollution than contemporary technologies which achieve the same end.

1.2.2.2 Indirectly harmful pollution

Chemical and waste heat pollution can cause changes in the environment which may be harmful in a more indirect sense. These changes are mainly concerned with the heat flows in the ecosphere that do not directly concern animals or plants.

Chemicals can change the radiative and convective heat flows of the earth by altering the composition of the atmosphere, or more rarely by changing the physical processes at the earth's surface (e.g. by changing the earth's albedo). Waste heat is a direct extra input of heat to the environment (in excess of the "natural" flows of energy from solar, geothermal and tidal sources). Changes in terrestial flows will necessitate a thermodynamic re-equilibration of the earth. The system is so complicated that nobody presently can predict with confidence what a new equilibrium condition might be like.

There is a further type of pollution which might be termed mechanical pollution. This is due to the direct mechanical impact of technologies on the environment. For example, both wave and tidal machines alter the flows of materials and the movements of animals in the marine environment by direct physical intervention.

1.2.3 Resolving the problems

It can be argued that large changes in the thermal, chemical or radioactive state of the environment caused by human beings have largely unknown effects. As yet there is little agreement on many of the potentially important environmental changes that might arise because of pollutants such as carbon dioxide or sulphur dioxide. Since it is this environment that supports life at present, it is surely not advisable to change it in a way that might have unforeseen deleterious consequences. The overall aim, therefore, is to look at technologies that leave the environment as near as possible to what it would be if we were not here. The phrase "as near as possible" is the qualification of the overall aim that must come when human practicalities are considered; there are many reasons why environmentally sound technologies are not implemented such as cost, lack of manufacturing capacity and political forces. DYPHEMO should aid the investigation of technologies which warp " natural " energy and chemical flows to a smaller extent; obviously the actual implementation of these new technologies requires consideration of many non-technical factors. The economic, social and political aspects of energy technologies must necessarily be considered before any decisions to implement them are taken. A reduction in the human additions to the environmental pollution load can be effected by firstly conserving energy or reducing energy demand, and secondly by using "direct income sources" (i.e. solar, wind, wave, tide) wherever possible. Reliance on the natural stores of hydrocarbon chemical and fissile energy should be reduced since these are sources of direct and indirect pollution and are finite. However, this overall aim of reducing reliance on these sources must be tempered by consideration of economic and other factors. For example, the high capital costs of some ambient energy technologies makes their implementation on a large scale unlikely, despite the fact they may be environmentally desirable.

The problems of securing an adequate supply without excessive pollution should be tackled by society. Since these problems must be solved or avoided by investing social effort for future benefits an energy policy is required, be it explicit or implicit. The social upheaval caused by any large changes in the energy system is large; this is because the economic investment is large as are social effects on things such as employment or standards of energy use at home. At present energy policy in the UK is decided by a complex interplay between major national institutions (such as the Government, fuel industries) and international forces (such as the OPEC cartel , oil companies); the extent of consumer sovereignty in decisions about fuel is arguably not large. The common basis of all policies is that they must presume the same basic physical constraints. Furthermore there is a narrower set of constraints set by the technologies developed. Particular technologies are also "politically independent"; a particular aerogenerator will perform in the same way whoever operates it. Of course the types of technology actually developed and implemented are a result of social processes. It is possible to consider the domain of policy options increasingly constrained by physical, technological, environmental, socioeconomic and political criteria. This is illustrated in the diagram below.

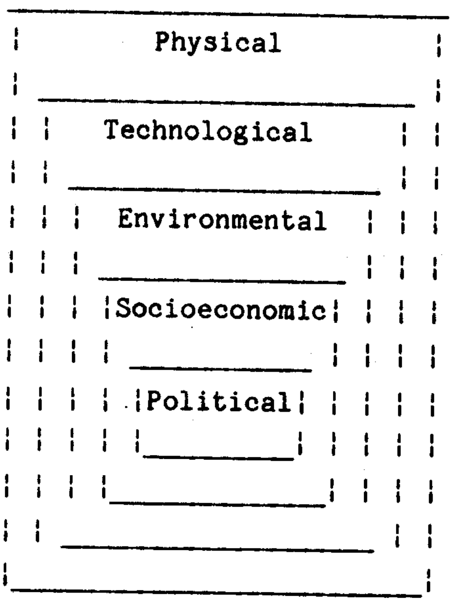


Figure 1.1 Domains of possibilities

Consider the question of how best to meet a specified electricity demand. There is a range of technologies which work and could meet the assumed demand. There are conventional thermal stations, and a variety of innovatory ambient technologies. On a physical and technical basis, there are many feasible alternatives. However, assessment according to environmental criteria could practically eliminate certain options. It could be decided, for example, that tidal schemes were too damaging to the estuarial environment. The options are further limited when socioeconomic criteria are applied. For example, it might be found that the capital costs of wave machines and fast breeder reactors are so large that other stations produce much cheaper electricity. It may further be considered important to support the coal industry, perhaps for reasons of employment and long term security for the industry; this would emphasise the option of coal burning stations. Finally political criteria might eliminate other options. Thus the option of oil burning stations might be rejected on the grounds that it increases dependency on imported oil supplies which could have undesirable political consequences.

This example illustrates how the assessment according to these criteria gradually narrows the range of options, hopefully to the point at which a decision to implement a technology, or not, can be taken. If the physical and technical aspects of an energy policy are made explicit, discussion can then be concentrated on the more important environmental, social or political implications and assumptions. There is still considerable argument about some technologies because they are still under development. However it is hoped that the model will aid the rapid understanding of purely technical problems. It will incorporate a fair range of technologies and conservation techniques and should therefore be useful for examining the technical feasibility of "alternative" low energy scenarios or "technical fix" policies.

1.3 An analogy with biology

An introduction to the method of simulating the UK energy system with a computer model of the type developed in this report can perhaps be gained by making an analogy between the energy flows in the human body and those in society.

The body requires energy to survive; this entails using energy derived from the sun via plants and animals. The energy in this food is used for:

(i) Tissue growth

(ii) Maintaining body temperature

(iii) Movement.

(iv) Internal body functions (e.g.circulation, nerve pulses).

Energy is mainly liberated from the food by oxidising the reduced carbon and hydrogen in food with oxygen from air. Carbon dioxide and water are the waste products of the oxidation of the carbon and hydrogen. There are other waste products associated with the liberation of energy. The body's demand for energy varies according to the individual demands (i) to (iv) above. The demand thus varies according to the person's age and sex, their activity level, their thermal environment, the time of day and so on. The body manages to control some of these demands (such as body heat loss) by various cunning devices. It also stores energy from times of surplus to times of deficit; a normal human being can probably expect to survive for 40 days without food. This implies an energy store of perhaps 350 MJ.

In a similar way society has demands for energy for analogous tasks, although they are not strictly speaking vital. It has demands which simply depend on the time of day or year and demands which depend on the climate just like the body. To date these demands have been mostly met by the same process of oxidising plant and animal matter, albeit in an inedible fossilised form. Like the human body, society breathes oxygen in and breathes carbon dioxide and water out. Furthermore, this "social body" also stores energy for times of high energy demand and many conservation methods are possible.

The simulation of energy flows by the model developed in this research will involve the description of the various social energy demands and their temporal and/or climatic dependence. Having some information about these social energy demands the model can be used to investigate ways of modifying demands and methods of supplying sufficient energy through conversion and storage systems.

The basic energy flows are shown schematically in the diagram below. Biomass includes fossilised biomass, i.e. fossil fuels. Sociomass is a jargon expression invented to describe the analogue to biomass; it would represent the fixing of energy in such things as plastics or reduced iron.

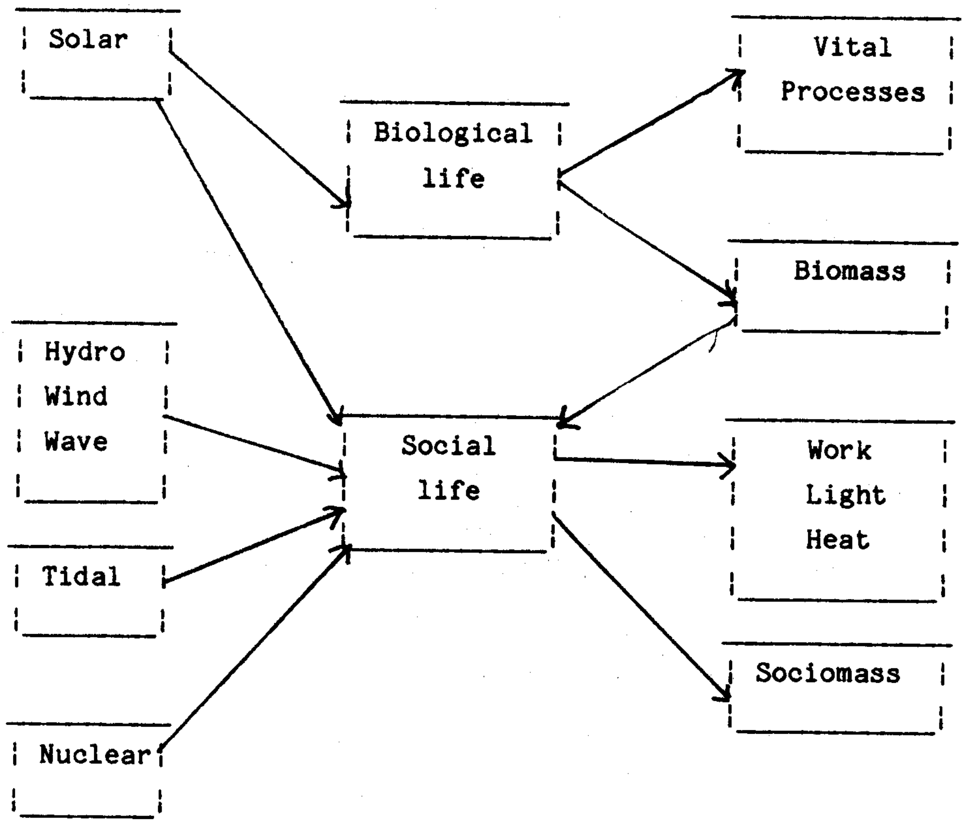


Figure 1.2 Basic energy system

1.4 Context of DYPHEMO

DYPHEMO has been developed over the last four years or so; the basic idea sprang from previous simulations of solar and heat pump systems. It became apparent that although many people were using computers to simulate the performance of many of the subsystems, nobody had developed a holistic dynamic physical model of the UK energy system. There has been some effort expended on energy modelling generally; a categorisation and description of the types of models is given on pages 423 to 453 of the " Annual Review of Energy" (Hollander, Simmons, 1976).

DYPHEMO is particularly aimed at answering questions which arise when an energy supply system with particular temporal characteristics is matched to a set of energy demands, also with particular temporal characteristics. At the time of publication there appears to be little work on the holistic dynamic modelling of the UK energy system; consequently the requirements for energy storage and other demand/supply matching techniques are only vaguely known. This view is substantiated by the following quote from page 104 of volume II of Energy Paper 39 (1979):

" In general, the renewable energy sources are being studied in the UK as isolated technologies. It has become clear, however, that the system effects of these sources need to be considered before the scope for their introduction in the UK can be evaluated with any degree of confidence. These system effects fall into three categories:

(a) Interaction between the renewable sources and centralised supplies of energy. For example, the extensive use of solar space and water heating systems would give the maximum savings in the summer, with the maximum call on back-up supplies in the winter. The load factor on demand required of conventional energy sources (mainly gas and electricity) would then be substantially reduced, leading to some increase in the cost of supply.

(b) Interactions within the electricity system. The renewable energy sources which might be developed to contribute to electricity grid supplies will have to be developed within the technical and economic constraints imposed by the system.

(c) Interactions essentially independent of centralised supplies of energy. These would be especially important in low energy scenarios. An example would be the use of an electric heat pump combined with a thermal energy store charged from non-firm power generated by, for example, wind energy. "

The general views expressed in this quote are reasonable, except that it is probably mistaken to apply them exclusively to renewable energy sources; there are very important system effects arising from conservation, increased efficiency or "new" technologies such as CHP.

Energy models of the whole or part of the UK energy system have either been of subsystems (some of these being dynamic physical models) or of the whole energy system (these being crude annual accounting models of energy flows). Therefore there are important system dynamic problems, such as peak loading or temporal matching of supply to demand, which are simply ignored or estimated crudely in existing models. Some of these models include non-physical variables such as money.

In contrast DYPHEMO is a holistic dynamic model which deals with physical energy flows only.

Holistic means that the entire system of energy demands and sources of energy in the UK is modelled. The energy flows and technologies included concern those that are currently in use and those which appear to be technolgically feasible.

The term dynamic is here used in its usual technical sense; the mathematical formulation of the model uses time as a parameter. The changes of state of the energy system with time can thereby be calculated. All energy flows and storage levels are calculated assuming a finite time step of one hour at most. Certain processes are calculated at shorter intervals, tidal power generation being such an example. Other physical models of energy subsystems, such as those of solar energy systems, are similarly dynamic. There are also energy/economic models which are dynamic, the time step of these models is usually at least one year in length. These models progress dynamically using assumptions about the values defining the initial state of the system and exogenous variables. Once started, the model projects the system's hypothetical future state. Energy/economic models (as opposed to purely physical models) usually incorporate a simple physical model which may be completely static or crudely dynamic. Some dynamic aspects of the physical system are described by means of assumed load shapes, load factors and so on. The model DYPHEMO will be used to simulate the hourly energy flows for periods of one day or one year so that important dynamic as well as annual total effects can be examined. The political, socio-economic or environmental features of these things do not appear explicitly in DYPHEMO. Any energy systems simulated with DYPHEMO are posited, although it is hoped that the hypothetical systems studied in this report are at least of interest in illustrating the wide range of technically feasible options.

From a search of published literature it appears that there have been no holistic, dynamic physical energy models of the UK constructed to date. However, there are other models which overlap with DYPHEMO in that similar data is used, or some of DYPHEMO's features are incorporated. There are energy models which deal with the UK energy system, such as that used by the Department of Energy (Hutber,1975) and ETSU (EP39,1979). However the former is mostly an econometric model, although there is a certain physical basis to it, but it certainly does not deal with current technologies in detail or dynamically and it excludes unorthodox technologies. In physical terms these models are largely accounting procedures; the annual demands and supplies of energy are balanced. There is little attention paid to seasonal or diurnal variations, because in relatively orthodox systems these are well known and it is easy to plan for them. The national scale modelling work of ETSU is also physically non-dynamic, and it also concentrates on orthodox technologies.

These models are used to explore orthodox energy policies or scenarios; for this reason the physical dynamics are less important because ambient sources are largely assumed to have a negligible role and the dynamics of orthodox future systems would be similar to those of today (because no large changes in the relative proportioning of energy demands and use patterns due to social changes or high conservation are envisaged). Apart from the general physically dynamic nature of DYPHEMO and its incorporation of ambient energy sources, DYPHEMO attempts to define the magnitudes, temperatures and time variations of useful energy demands. This is a step towards understanding the basic purposes for which energy is actually used. Many models do not explicitly define useful energy demand. For example, the SARU (1979) model employed in the projection of UK energy demand defines some useful demands for the domestic sector but uses general energy intensities for other sectors.

Perhaps the most similar precursor to this work is the IIED study (1979). DYPHEMO does not disaggregate energy demands as finely as the IIED study, but it treats supply in much more detail. The IIED study deals with annual magnitudes only; it is not dynamic. DYPHEMO includes technologies not considered by the IIED study. However, the research in this report owes a large debt to the IIED study, particularly for its detailed data on energy demands in the UK.

1.4.1 Aims of research

The aims of the research in this report are as follows.

(i) To develop a holistic, dynamic physical energy model of the technical workings of the UK energy system. The model is to simulate the hourly energy flows from income sources and natural stores to useful energy demands. The model is to be designed as a research tool for exploring changes in the UK energy system. It will be tested, where possible, against measured energy flows in the UK.

(ii) To illustrate the range of applications of DYPHEMO by simulating four hypothetical energy systems. These will demonstrate potential "improvements" to the 1976 energy system, namely reduced demands, conservation, improved efficiencies and matching and new technologies.

1.4.2 Applications of DYPHEMO

The types of question DYPHEMO can address are described below.

Consumer reduced useful energy demand

(i) Changes in energy demand brought about by changed consumer behaviour; such as sharing cars or controlling heating systems better. These changes require no technical change.

Technical conservation of energy

(i) Insulation and ventilation reduction in buildings.

(ii) Lighter vehicles with less aerodynamic and friction losses.

(iii) The adoption of different lighting levels in buildings.

(iv) Reduction of domestic hot water demand by reducing the volume and temperature of demand.

Improvements in user converter efficiencies and allocations

(i) The model can be used to estimate the effect of feasible improvements in energy converter efficiencies. The bulk of this technical data will be gleaned from studies such as the one by the IIED (1979). Almost all user converters [1] are susceptible to easily achieved increases in efficiency (with obvious exceptions such as electrical resistance heaters).

(ii) At present the UK allocations of user converters are such that problems arise due to a low primary to useful energy efficiency or due to large variations in the demand with time. Some technologies, such as solar water heaters, will save primary fuels but aggravate the winter: summer peak load ratio. The use of solid fuel space heaters with a high efficiency and an easily stored fuel would provide a steady demand for the coal industry and reduce the problems of load variation for the gas and electricity industries. The IIED (1979) study gives evidence of many feasible substantial improvements in the efficiencies of converters in the industrial and commercial sectors. The system effects of these improvements can be studied.

Improved supply technologies

(i) Due to the large quantities of fuel used by the energy supply industries there is an obvious emphasis on efficient conversion, provided the concomitant capital charges are not exorbitant. But the development in some supply technologies is leading to steady improvements in efficiency (e.g. power stations). Some of the potential changes in such technologies can be investigated.

----

[1] A user converter is a device operated at or near the point of demand that converts energy from one form into another, this is in distinction to a converter operated by an energy industry.

(i) Innovation in the domestic sector such as solar hot water heaters, active and passive solar houses, electric and gas driven heat pumps, combined heat and power district heating and electric cars can be investigated. The hourly load variation caused by these devices from ambient sources which also vary hourly causes problems relating to storage and "ambient collector" sizing (e.g., Barrett, Everett, 1977). [2] The model is particularly aimed at this kind of problem, since it uses meteorological and use pattern data to calculate the variations in demand and ambient source intensities.

(ii) The implementation of combined heat and power generation, aerogenerators, wave machines and a Severn estuary tidal scheme in the electrical supply system can be simulated.

(iii) The introduction of processes which convert coal and biomass into synthetic oil and gas can be assessed.

DYPHEMO is used to simulate the energy systems incorporating these changes. The hourly or monthly energy flows and their totals are calculated and output. Analysis of these flows enables peak flows, flow spectra and minimum storage requirements to be estimated. DYPHEMO can thus be used for the technical appraisal of different systems.

---

[2] This refers to the process of finding an optimum compromise between the size of an energy store (such as a tank or a battery) and the size of the device collecting the intermittent, unpredictable ambient energy source (such as a solar collector or aereogenerator). This problem is especially difficult when the storage level affects the performance of the collector, as for the solar collection and storage case.

2. GENERAL DESCRIPTION OF THE UK ENERGY SYSTEM AND MODEL

2.1 Characteristics of the model

2.1.1 Domain of model

The dynamic physical energy model (DYPHEMO) concerns itself solely with the flows of energy in the UK manipulated by society. It charts the energy flows embodied in primary and secondary fuels, income sources and useful energy demands. All the useful energy demands are for energy within a particular temperature range varying with time according to use patterns and possibly climatic data. In general primary and secondary fuels have a flame temperature higher or equal to that required for energy demands since fuels are often in the form of high grade energy (e.g. chemical energy in fossil fuels). There are exceptions such as the secondary fuel supply of hot water from a combined heat and power station. Most income sources are in the form of work (wind, wave, tidal) although solar energy (heat at about 6000 K) is a notable exception.

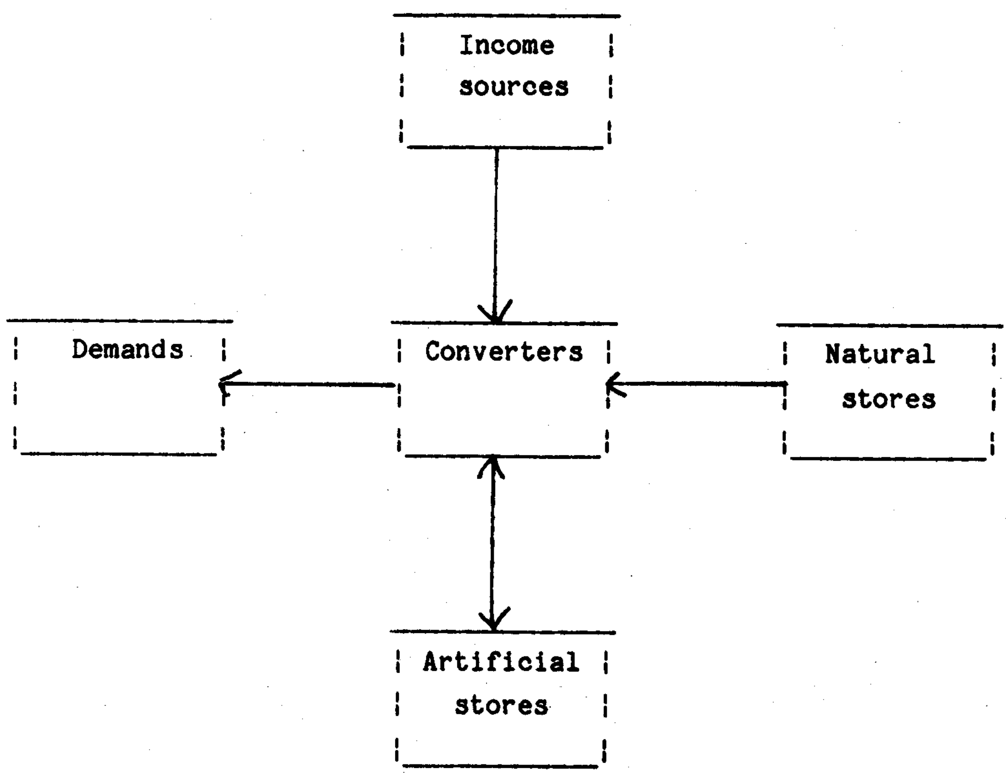
The domain of the model is restricted to physical processes and their control; values ascribed to its variables and parameters are expressed in S.I. units (for the physical processes) and logical conditions (for the control). For example, the electricity inputs and outputs from pumped storage scheme is controlled by reference to the instantaneous values of variables such as capacity of storage, quantity in storage, rate of change of electricity demand and the spare capacity (if any) of other electricity stores. The ultimate objective for the development of the model is to aid the investigation of future energy options where it might be dovetailed to economic (or other) analytical methods. However such considerations and evaluations would occur entirely exogenously to the model.

2.2 Description of the UK energy system

The UK energy system consists of energy consumers, energy technologies and primary energy sources. Energy flows from primary sources, through the energy technologies, to the final consumer. These energy flows may be thought to pass through different types of component in the model; namely sources, converters, stores and demands.

The energy system has been split into five different types of component with the possible direction of the energy flows between each of these components as indicated in the diagram below.

Figure 2.1 Basic layout of system components



The components may be described as follows.

2.3 Demand

2.3.1 Introduction

The demand component consists of demands for useful energy. Useful energy is the energy which is required for a particular task, be it light for reading this report by or high temperature heat for manufacturing steel. The concept of usefulness is subjective, although as there is often agreement between people as to what is useful the concept can usually be used in a meaningful way. But there are problems; for example the low temperature heat from a power station is commonly regarded as waste heat (i.e. not useful), but of course it may be useful for heating greenhouses or homes. Furthermore in the above example the efficiency will also change according to what is defined as useful; this is discussed in the section on converters. Useful energy is an important concept, but hard to define in a way to make it generally applicable to any demand. However, in most cases, a workable definition is often feasible since people use energy for similar purposes because of physiological and social reasons. Thus useful light is light having a particular range of wavelengths visible to the normal human eye, and useful work for industrial machining would be the amount of energy actually available at the cutting edge on a lathe.

A general definition of useful energy demand might be

Useful energy demand is the minimum amount and temperature of energy required to perform a certain task.

If more than this minimum energy were used energy would be wasted, this wasted energy would not by definition be useful energy. Occasionally it is possible to define this minimum rigorously and uncontrovertially (water heating for example). In general it is difficult to arrive at a reasonable definition. For example it is difficult to define the useful energy demand incurred in performing the task called transport. However, since useful energy demand is fundamental to the energy system it must always be defined, however crudely.

It is necessary to know the temperature, or "grade" of useful energy demand since no demand can be met directly by a lower temperature supply. Thus, if all UK demand were for work, thermal solar collectors could play no direct role in meeting it. It is possible to use thermal collectors indirectly by using the heat collected to run a heat engine.

The demand for useful energy varies according to the type and magnitude of energy required and the time at which it is needed. The magnitude required at a particular time for some demands is dependent on the climatic conditions at that moment of time. Thus in the example of artificially produced visible light, there is a negative correlation between the artificial intensity required and the intensity of natural light transmitted through the window.

2.3.2 Temperature of demand

The temperature or grade of demand is split into seven ranges (these being chosen to fit the categories that measured energy demands fall into):

(i) work

(ii) visible light

(iii) high temperature heat (120 to 3000 C)

(iv) cooking (20 to 300 C)

(v) low temperature heat (80 to 120 C)

(vi) hot water heat (5 to 60 C)

(vii) space heat (10 to 25 C)

Hot water heat has the range 5 to 60 C since the mains temperature is sometimes as low as 5 C and heat at any higher temperature can help meet useful water heat demand. The temperatures of demand are estimated from survey data (the data sources are given when demands are dealt with in detail). Note that the need for refrigeration results in the useful energy demand of heat largely in the range -50 C to 0 C. However, this demand is not well documented, and is probably relatively small. As refrigeration is usually accomplished using electricity this demand is accounted for by including it in the category of miscellaneous electricity demand.

This temperature analysis of demand is important since thermodynamically possible and desirable conversion paths such as heat pumping, cascading and using low temperature waste heat become more obvious; as well as clearly inefficient pathways in the present system.

2.3.3 Magnitude of demand

Each demand has a magnitude which is determined from data relating directly to demand (e.g. volume and temperature of hot water demand) or from actual measured consumption of delivered fuel and some assumed efficiency. This annual total demand is distributed over the hours of the day or year according to the relevant use pattern and other factors such as the weather.

2.3.4 Temporal patterns of demand

The patterns of energy demand arise from social behaviour such as domestic life, working habits and recreation. These use patterns critically determine the energy demands and the concomitant requirements for the energy supply system. The present inferred patterns may change significantly; the implications of unemployment, increased leisure or home based employment (through the use of microprocessors) for these patterns are not obvious.

2.3.5 Sectors of demand

Because of the nature of most statistical data the demands for useful energy will be divided into five sectors; domestic, commercial, industrial, iron and steel and feedstocks. Transport has been divided into three parts, each of which has been assigned to either the domestic, industrial or commercial sectors. These sectors are defined and described in the IIED (1979) study.

(i) Domestic sector includes all energy used in and delivered to dwellings.

Cars and taxis are included as domestic transport.

(ii) Industrial energy sector includes all demands usually classed as industrial, but excludes iron and steel. Agriculture, however is included in this sector.

Industrial transport demand is all diesel and similar transport.

(iii) Commercial sector includes all public administration, health care, selling goods, catering and banking. This sector of demand is dominated by energy use in commerical and institutional buildings.

Commercial transport includes ships, aeroplanes and electric trains.

(iv) Iron and Steel

(v) Feedstock demand includes all energy used in the production of chemicals for material feedstocks.

2.3.6 Summary of demands

Energy demand has been divided into about one hundred separate demands. In fact there are six demands in the domestic sector, seven in the industrial, seven in the commercial, four in Iron and Steel and three in feedstocks. However, each demand can be met by a range of user converters and these are separately accounted for in demands. For example, domestic space heating is one demand that can be met by many different user converters (twelve in the model). Each demand function contains parameters detailing the magnitude, temperature and use pattern of each demand, but note that many demands are assumed to have the same use pattern. Some demands are climate independent (e.g. heat for iron and steel manufacturing) whilst others are strongly climate dependent (e.g. space heating and lighting). Whenever this dependence is significant and calculable it has been included.

2.4 Income sources

Income sources are those natural sources of energy in the environment which may be converted to useful energy. Income means that these flows of energy are a long term input into the ecosphere (in fact most of them are to all intents and purposes inexhaustible). These sources are derived from three major stores of energy in the solar system; the sun, gravitational and geothermal energy.

2.4.1 Solar energy

The sun is a massive nuclear furnace which converts the potential energy held in the strong nuclear field of hydrogen ions into various particles and heat. The energy equivalent of the mass deficit realised by the lighter amount of products, largely helium produced by fusion is mostly lost to space by electromagnetic radiation. Although the temperature of the sun is estimated to be of the order of ten million degrees Kelvin at the centre, the thermal gradient is such that the temperature falls to around 6000 degrees Kelvin at the solar surface. The spectrum of this radiation closely approximates that of a black body radiator at this temperature. This radiation, which is largely visible has a nearly constant value of about 1.3 kWm^{-2} when it intercepts the earth's atmosphere. The intensity and spectral character of the solar radiation when it reaches some point on the earth's surface depends on the current astronomical configurations and various complex alterations and modulations of the radiation by the atmosphere. The intensity of the solar radiation at the surface of the earth can be calculated for any orientation of receiving plane at any time provided the actual recorded solar radiation data is available. The effect of the spectrum is small for most common solar thermal collectors and is therefore neglected.

Solar energy is recorded in detail at many UK locations.

2.4.2 Tidal energy

The gravitational and kinetic energies of the earth-moon-sun system cause tides. The gravitational forces move the surface water masses on the earth, the work done thereby is manifested as kinetic energy in the water. The kinetic energy is ultimately dissipated as potential energy stored in the earth's gravitational field or as frictional heat. The heat is eventually radiated into space. The kinetic or potential energy in tides represent a source of work. The basic forces involved are modified by the peculiarities of the basin holding the water mass and by the astronomical geometry at any particular time. The total tidal power dissipated on the earth is estimated to be of the order of 1100 GW (p 43, section 8,Considine, 1977).

Tidal variations are well recorded at many UK sites.

2.4.3 Geothermal energy

Geothermal energy is high temperature heat produced beneath the earth's surface . The heat arises from the decay of natural fissile materials and the dynamics of processes occurring within the earth, such as tectonic plate movements or "tides" in the molten core. Geothermal energy is only economically accessible at useful temperatures in limited areas of the world. It seems that there are some areas potentially suitable in the UK but much extensive surveying and analysis is required before it is possible to calculate the potential of supply from such sources (e.g. Garnish,1976). For this reason this source is presently omitted from the model.

Geothermal and tidal energy can be harnessed directly and converted to heat or work (with some conversion losses). Solar energy can also be used to provide heat or work directly but it also produces secondary sources of work ; namely wind, wave, and freshwater hydro power.

2.4.4 Wind

The unequal solar heating of the earth and atmosphere causes unequal temperature distributions in the atmosphere, this in turn causes pressure gradients which in combination with Coriolis' force and terrestial gravity cause winds. The basic wind velocities encountered high in the atmosphere are modified by local surface effects. Thus the wind is generally stronger at sea where it meets a smooth surface than on the land, where greater friction causes the more rapid conversion of kinetic energy into heat. Land formations can cause local acceleration of the general wind speed, such places are potentially most suitable for wind power. The hourly values for the wind speed are known for many sites in the UK, although great care must be taken if these data are to be used at a different site or at a different height to that where they were originally measured.

2.4.5 Waves

Frictional forces between the wind and the sea's surface cause a mechanical coupling, and some of the kinetic energy of the wind is transferred to the water, where it appears as waves. The mechanical power in the waves is manifested as mostly vertical oscillations of the surface of the water mass (although each particle of water follows a circular trajectory). This mechanical power can be partially extracted and converted to work or heat by means of a generator or generator and heat pump respectively.

The intensity of wave power at some locations can be estimated from measured values of the heights and periods of actual waves. Statistical data taken at three hour sampling intervals are available for some UK sites and time periods. In general, wave intensities are the least well recorded ambient energy source in the UK.

2.4.6 Hydro power

Solar radiation heats surface water and land masses and accelerates the evaporation of water into the atmosphere. Later atmospheric cooling causes condensation and rainfall. If the rainfall occurs on a land mass with catchment areas above sea level there is potential gravitational energy which can be exploited via hydroelectric schemes.

There are abundant sources of hourly rainfall data, but the hydroelectric potential of this rainfall may only be calculated by detailed consideration of the geographical and climatic properties of the catchment area.

2.4.7 Summary of income sources

Income, or ambient sources of energy included in the model presently consist of solar, wind, wave, freshwater hydro and tidal energy; geothermal power is omitted. Data for this latter source requires extensive collation and analysis if an accurate calculation of its contribution is to be made.

The UK is developing its geothermal research programme at the Camborne School of Mines (Cornwall). Data for waves are poor simply because of the difficulties in measuring them and the fact that in the past there has been no need for long term wave data. Solar, wind and tidal data are well recorded for long time periods and for many locations.

2.5 Converters

The primary sources of energy are income sources (solar, wind, wave, tidal) and natural stores (coal, oil, gas, uranium). The task of converters is to extract, distribute and transform these primary sources such that the demand for useful energy is met. Essentially this means that useful energy of the correct magnitude and temperature must be delivered at the right time and place. This implies the need for converters which change the primary sources of chemical energy (fossil fuels), nuclear energy (nuclear fuels), heat (solar radiation) and mechanical energy (wind, wave, tide) into the type of useful energy demanded; namely work, light and heat. Furthermore, these converters must ultimately provide this useful energy at the right time and place. It is convenient to include energy transmission and distribution systems as converters, particularly since these systems generally incur losses and therefore have a well defined efficiency.

For example, the production of useful energy in the form of heat from an electric heat pump may be produced by four conversions; coal mining, electricity generation, electricity transmission and the heat pump efficiency (or coefficient of performance). This illustrates the diverse nature of converters; from pipelines to heat engines , from heat exchangers to water turbines. Each converter will be described by at least one parameter, efficiency. The efficiency of a converter is defined as :

Efficiency = Useful energy output/energy input

A general definition is hard to arrive at mainly because the amount of energy output considered useful is subjectively measured. For example, a power station might produce about 0.25 units of electricity and 0.75 units of heat per unit of coal energy input. If only the electricity is regarded as useful, the efficiency is 0.25; if some of the heat (say 0.25 units as cooling water at 90 C) can be used the overall efficiency would be 0.5. Since the usefulness of a particular source of energy is conventionally manifested by its commercial value (i.e. if it can be sold it is useful) there is usually little problem arriving at some convention for the definition for a converter; arriving at some agreement as to what is the actual value of a particular efficiency is not so easy. Because of the subjective nature of efficiency one can not be sure that definitions appropriate now will be so in the future. The useful energy output of a device is that energy which can be used to meet a useful energy demand or as an input to another converter. If the output of one converter is used as an input to a second, the energy input of the second is the useful energy output of the first.

The energy input is also difficult to define generally since it ranges from fuels such as coal to income sources such as solar or wave energy. But note that in the electric heat pump example above the electrical energy delivered would be the input, the atmospheric heat being ignored in the efficiency calculation. This means that some efficiencies can be greater than unity.

This brief discussion emphasises the variation in the meaning of the terms useful energy output and energy input. A more precise meaning of efficiency for each particular energy converter is given in the relevant appendix.

The efficiency is a measure of energy losses incurred in a chain of conversions. Note that efficiency is generally a variable. Information is also required about the control and power characteristics of the converters. Many converters (e.g solar collectors) or conversion subsystems (e.g. the electricity supply network) require controls of varying sophistication in order that they supply sufficient energy in an efficient manner. The maximum power output of the converters must of course be sufficient to meet the demands imposed on them, although note that the use of storage can sometimes reduce the peak power requirements of converters.

Converters are devices which convert energy in one form at a certain location to another form and/or location, with some loss of energy. By this definition heat engines, gas boilers, pipelines and coal gasifiers are all included, although there are thermodynamic differences between many of these devices. The most important parameter defining converter performance is efficiency, which is often a variable and is defined by conventions detailed in the appendix relevant to the particular converter. Maximum power, control and other features are included where necessary.

2.6 Artificial stores

The problem is to match energy supplies to the varying useful energy demands. Artificial energy stores are used to either reduce the peak power requirements from a particular converter or to enhance the availability of income sources which may be mismatched to demand. At present the prime motivation for the introduction of storage is usually economic; the introduction of storage can produce a "lower cost solution". Logistical delivery problems can be diminished by storage and lower costs may thereby be attained. However there may be other reasons, for example the UK has strategic oil stocks to provide some security from politically motivated disruptions in imported (or possibly domestic) supplies.

Artificial stores are depositories for energy in three common forms; chemical, heat and gravitational forms. Car petrol tanks and coal stock piles are examples of storage in chemical form. Electric storage heaters and hot water tanks store energy as heat. Pumped storage stores energy by first converting electrical energy to kinetic energy (by pumping water) and then storing this kinetic energy as potential energy in the earth's gravitational field. Most artificial stores have a limited capacity and some lose energy, for example hot water tanks. Other stores, particularly chemical stores, lose practically negligible amounts during storage; a car petrol tank is a good example of such a store.

The energy inputs and outputs from the stores are determined by the control strategy, the most complex facet of modelling these stores. To this end algorithms dictating the flows through these stores have been produced. These algorithms are described for each store where appropriate in the relevant appendix. They vary from the control of simple single store systems, such as a domestic coal bunker, to subsystems incorporating many stores. For example off peak electric storage heaters, electric vehicle batteries and pumped storage (tidal and conventional) can be used to store surplus electricity. Surplus electricity here means the quantity of electricity produced by low or zero fuel cost generators in excess of instantaneous demand. In this example a more complicated algorithm is required, which, amongst other things, would put the stores into an order of priority; i.e. which gives or takes electricity first.

Artificial stores are widely used at present but their use will increase if converters having a high capital cost in terms of capital per installed capacity (e.g. nuclear power stations) or income sources having an intermittency, unpredictability or definite mismatch to demand (e.g. tidal, wave and solar respectively) are introduced into the system in the future.

Artificial stores are manufactured energy stores such as electric storage heaters, coal bunkers and pumped storage schemes. They are characterised by their storage capacity, in/output power and control. The in/out efficiency of stores is generally included here rather than in "converters" for convenience.

2.7 Natural stores

Natural stores of energy are deposits of primary energy resulting from natural processes. There are no immediate plans to exploit indigenous reserves of fissile materials in the UK, although surveys are being made. Natural stores therefore consist solely of coal, oil and gas. They are the fossilised remains of plants and animals living predominantly 300 million years ago. Essentially they represent the stockpiling of an income source, solar energy, by photosynthesis and later geological aging processes. These fossil fuels exist in a bewildering array of chemical mixtures and physical states. However they have the common property of burning in air (once ignited) and it is via combustion that the energy content of these primary fuels is usually measured.

The estimated reserves of fossil fuels in the UK (including the UK continental shelf) are given in the appendix on natural stores.

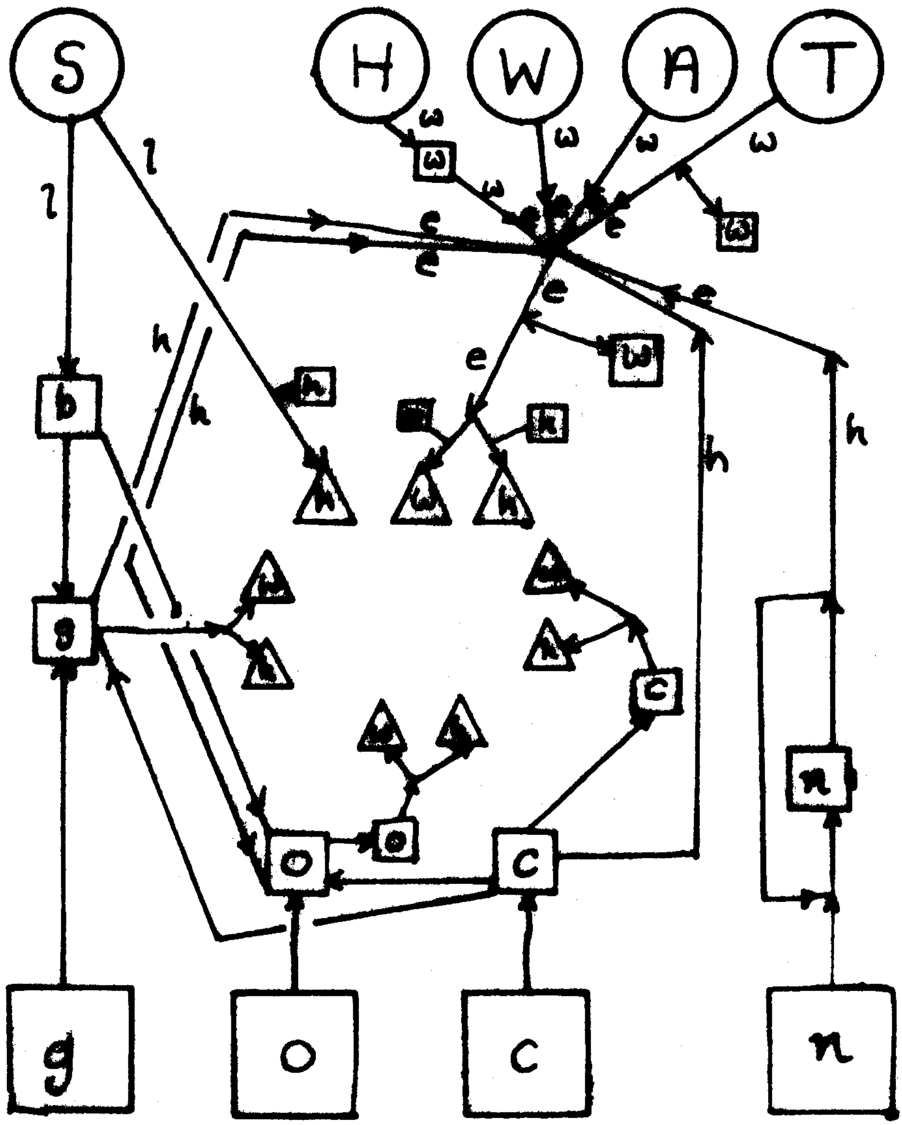
Natural stores are those stores of fossil and fissile fuel, i.e. coal, oil, gas and uranium deposits. They are defined by their size and overall extraction efficiency. Extraction efficiency is defined in the appendix on energy industry converters. These stores are included for completeness only since the model will only be used to simulate the performance of the energy system for periods of up to one year. The size of the reserves is so large compared with annual consumptions, all the primary reserves would last at least twenty years at present consumption rates. Therefore the change in reserves has no implications for flows of energy downstream in the system occurring in time spane of less than one year.

2.8 System diagrams

The two diagrams below, with their accompanying keys should clarify the layout of the energy system as modelled, and the categories into which the various technologies fall.

The first one shows the basic connections achieved by converters between the various stores, income sources and demands as modelled by DYPHEMO. It is not an attempt to show all the possible energy flows in a social energy system. The type of fuel or energy flow is also noted.

Figure 2.2 Energy flows by type through the system



The symbols in this diagram represent the following:

Triangle - demand
Circle - income source
Arrow - converter
Square - store

The letters in the diagram refer to the following energy types:

A ero

b iomass

c oal

e lectricity

f eedstocks

g as

h eat

H ydro

l ight

n uclear

o il

S olar

T idal

W ave

w ork

The diagram below shows in a different way the directions of energy flow and the types of component involved. The demand for work includes electricity used for miscellaneous purposes such as electrolysis and powering appliances.

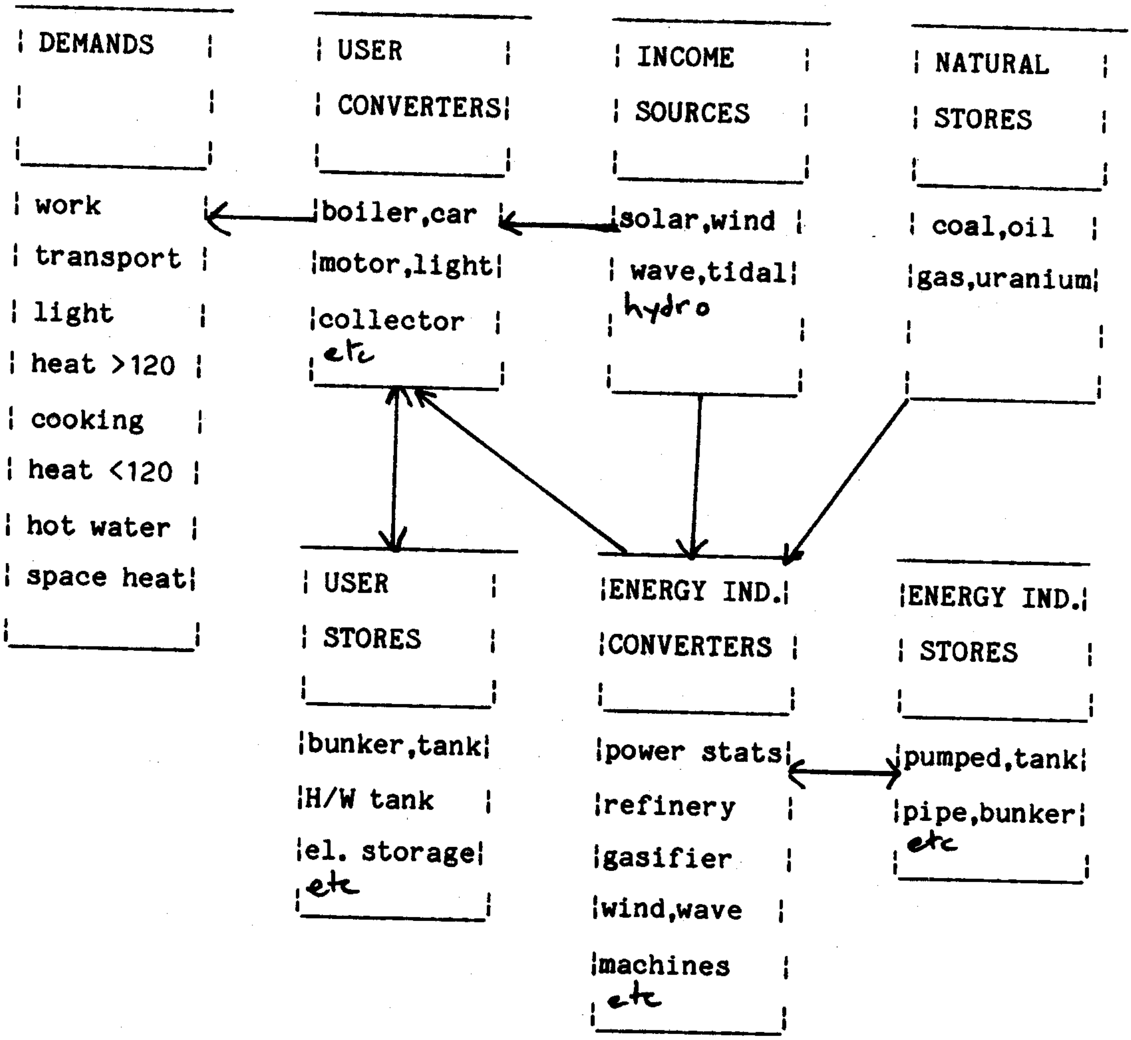


Figure 2.3 Detailed diagram of system components

Some definitions of the energy flows at different points in the system illustrated in the diagram are given below.

Income energy is the intensity of an income (or ambient) energy source integrated over some area and time.

Primary energy is defined as the energy content of fossil or nuclear material lying under or on the ground (i.e. natural stores).

Extracted energy is the quantity of primary energy extracted (mined) minus any losses incurred in extraction. In other words, extracted energy is the quantity of primary energy extracted times the extraction efficiency.

Delivered energy is the quantity of energy delivered to the final consumer.

Useful energy is the minimum quantity of energy required to accomplish some task.

2.9 Structure of the model DYPHEMO

The model is tailored for the simulation of the energy system described above. It is thus a sort of motorised Sankey diagram except that some additional parts of the system (mainly income sources and stores) not generally accounted for are included and the time dependence of the flows is explicitly dealt with. The large range of physical processes modelled made it difficult to make the model formally elegant and easy to understand. It was also difficult to predict the best final structure for the model whilst developing it.

The model simulates the system in three basic steps:

(i) Data defining the system components are input to the model.

(ii) The hourly energy flows through the system are calculated for the desired time period.

(iii) The energy flows and some analysis of these flows are output.

The physical structure of the UK energy system has been outlined. This section describes the structure of the model used to calculate the performance of the physical system.

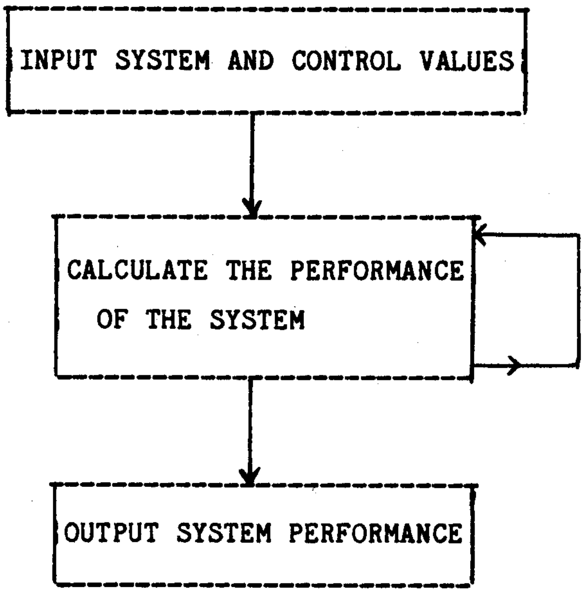
The basic structure of the model is fairly simple; it can be divided into three segments.

The first segment reads in the data describing the technical characteristics of the model and simulation control parameters which simply determine the time period which the model is to simulate and the output that is required. The values defining the technical characteristics of the system are output in a clear, comrehensible form.

The second segment is the core of the model. It is here that the flows of energy and storage levels calculated over the desired period of simulated time, namely one day or one year. It consists of four nested cycles pertaining to to spans of time of one hour, one day, one month and one year. All the flows of energy between the various components are calculated for each hour of simulated time. At the beginning and end of each of the time cycles ancillary calculations are performed. These either relate to variables in the energy system which vary over time periods greater than one hour (such as average monthly air temperature) or they relate to the summarising of flows into arrays prior to output. This calculation segment has a very simple basic looped linear structure. There are no complex interactions between modules which tend to occur in energy/economic models.

The third segment of the model conerns some analysis of the energy flows (such as load spectra) and output of the performance of the energy system simulated.

These three segments are shown below.



The details of each segment of the model and the calculations performed therein are to be found in the relevant appendices. The chart below should convey a picture of the overall structure of the model.

```
*************************************************************  *
* EXTERNAL DATA INPUT                                           *
*____________________________________________________________  *
*                                                               *
* USE PATTERNS                                                  *
* MERIT ORDER                                                   *
* SIMULATION CONTROL PARAMETERS                                 *
*                                                               *
*______________________________                                 *
* SYSTEM VALUES                                                 *
* DEMANDS AND USER CONVERTERS                                   *
* USER STORES                                                   *
* CONVENTIONAL ELECTRICITY GENERATION                           *
* AMBIENT ELECTRICITY GENERATION                                *
* ENERGY INDUSTRY STORES                                        *
* NATURAL STORES AND PRIMARY FUEL CONVERSIONS                   *
*                                                               *
* INITITIALISE DEMANDS                                          *
*      "      STORES                                            *
*      "      MERIT ODER                                        *
*      "      LOAD SPECTRA                                      *
*      "      CHP                                               *
*      "      WIND                                              *
*      "      WAVE                                              *
*      "      HYDRO                                             *
*      "      RANGERS                                           *
*____________________________________________________________  *
* OUTPUT SYSTEM VALUES                                          *
*                                                               *
* DEMANDS AND USER CONVERTERS                                   *
* USER STORES                                                   *
* CONVENTIONAL ELECTRICITY GENERATION                           *
* AMBIENT ELECTRICITY GENERATION                                *
* ENERGY INDUSTRY STORES                                        *
* NATURAL STORES AND PRIMARY FUEL CONVERSIONS                   *
*                                                               *
```

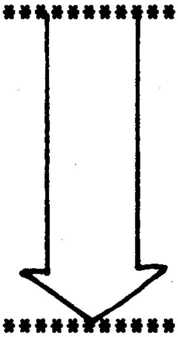
```
*-------------------------------------------------                          *
*                                                                           *
* READ AVERAGE MONTHLY AIR TEMPERATURES FOR YEAR                            *
*                                                                           *
*****************************************************************           *
```

```
*******************************************************************   *
* CALCULATION CONTROL SEGMENT                                         *
*-----------------------------------------------------------------    *
*                                                                     *
*-------------------------------------                                *
* MONTH CYCLE BEGINS                                                  *
*                                                                     *
*      CALCULATE CLIMATE                                              *
*          "      DOMESTIC TRANSPORT DEMAND LEVEL                     *
*          "      STORAGE CONTROL                                     *
*-------------------------------------                                *
* DAY CYCLE BEGINS                                                    *
*                                                                     *
*      CALCULATE WEEKEND                                              *
*                                                                     *
*-------------------------------------                                *
* HOUR CYCLE BEGINS                                                   *
*                                                                     *
*      CALCULATE CLIMATE (TA,WIND,WAVE,SOLAR)                         *
*          "        "    INTENSITIES                                  *
*-----------------------------------------------------------------    *
* USEFUL ENERGY DEMANDS FOR SECTORS                                   *
*-----------------------------------------------------------------    *
* DOMESTIC SECTOR                                                     *
*                                                                     *
* LIGHT                                                               *
* MISCELLANEOUS                                                       *
* COOKING                                                             *
* HOT WATER HEATING                                                   *
* SPACE HEATING                                                       *
* TRANSPORT                                                           *
*-----------------------                                              *
* INDUSTRIAL SECTOR                                                   *
*                                                                     *
* LIGHT                                                               *
```

```
* KINETIC                                                        *
* PROCESS HEAT > 120                                             *
* PROCESS HEAT < 120                                             *
* SPACE                                                          *
* WATER HEATING                                                  *
* TRANSPORT                                                      *
*____________________                                            *
* COMMERCIAL SECTOR                                              *
*                                                                *
* LIGHT                                                          *
* MISCELLANEOUS                                                  *
* PROCESS HEAT                                                   *
* SPACE                                                          *
* WATER HEATING                                                  *
* TRANSPORT                                                      *
*____________________                                            *
* IRON AND STEEL                                                 *
* FEEDSTOCKS                                                     *
*________________________________________________________        *
*                                                                *
*      CALCULATE COMBINED HEAT AND POWER                         *
* DOMESTIC                                                       *
* COAL                                                           *
* INDUSTRIAL CHP                                                 *
* GAS                                                            *
* OIL                                                            *
* COAL                                                           *
* COMMERCIAL CHP                                                 *
* GAS                                                            *
* OIL                                                            *
* COAL                                                           *
*________________________________________________________        *
*      CALCULATE DEMAND TO DELIVERED LIQUID AND SOLID FUELS      *
*________________________________________________________        *
* DOMESTIC                                                       *
* INDUSTRIAL                                                     *
```

```
* COMMERCIAL                                                                *
* IRON AND STEEL                                                            *
*-------------------------------------------------------------------        *
*      CALCULATE USER STORE LEVELS AND USER AMBIENT CONVERTERS              *
*-------------------------------------------------------------------        *
*                                                                           *
* DOMESTIC                                                                  *
* HOUSE OIL TANKS                                                           *
* HOUSE COAL BUNKERS                                                        *
* VEHICLE FUEL TANKS                                                        *
* OFF PEAK ELECTRIC HEATERS                                                 *
* ELECTRIC CAR BATTERIES                                                    *
* SOLAR HOT WATER HEATERS                                                   *
* ACTIVE SOLAR HOUSES                                                       *
* PASSIVE SOLAR HOUSES                                                      *
* INDUSTRIAL                                                                *
* OIL                                                                       *
* COAL                                                                      *
* COMMERCIAL                                                                *
* OIL                                                                       *
* COAL                                                                      *
*-------------------------------------------------------------------        *
*      CALCULATE DEMAND TO DELIVERED ELECTRICITY FOR ALL SECTORS            *
*      CALCULATE DEMAND TO DELIVERED GAS FOR ALL SECTORS                    *
*-------------------------------------------------------------------        *
*      CALCULATE ELECTRICITY SUPPLY                                         *
*                           :CHP (D,I,C)                                    *
*                           :AERO                                           *
*                           :WAVE                                           *
*                           :TIDE                                           *
*                           :HYDRO                                          *
*                           :PEAK SWITCHING                                 *
*                           :PUMPED OUT                                     *
*                           :PUMPED IN                                      *
*                           :GAS TURBINE                                    *
*                           :THERMAL - NUCLEAR                              *
```

```
*                                     - COAL                                    *
*                                     - OIL                                     *
*                                     - GAS                                     *
*      CALCULATE FUELS TO POWER STATIONS                                        *
*-------------------------------------------------------------                  *
*      CALCULATE ENERGY INDUSTRY STORE LEVELS AND FLOWS                         *
*-------------------------------------------------------------                  *
*      CALCULATE BIOMASS FORMATION                                              *
*          "        "    CONVERSION TO OIL AND GAS                              *
*-------------------------------------------------------------                  *
*      CALCULATE COAL TO OIL AND GAS                                            *
*-------------------------------------------------------------                  *
*      CALCULATE PRIMARY EXTRACTION                                             *
*-------------------------------------------------------------                  *
*      END OF DAY CYCLE                                                         *
*-------------------------------------------------------------                  *
*      CALCULATE ELECTRICITY SPECTRA                                            *
*      CALCULATE AVERAGE ELECTRCITY DIFFERENCE BETWEEN TOTAL                    *
*      DEMAND AND AMBIENT SUPPLY                                                *
*                                                                               *
*     END OF DAILY AND MONTHLY CYCLES                                           *
*****************************************************************               *
```



```
*****************************************************************               *
* OUTPUT SIMULATED PERFORMANCE OF SYSTEM                                        *
*-------------------------------------------------------------                  *
*                                                                               *
*   :HEADING                                                                    *
*   :DEMANDS                                                                    *
*   :FUEL/TYPE                                                                  *
*   :DELIVERIES                                                                 *
*   :USER STORES                                                                *
```

```
*    :ELECTRICITY                                                        *
*    :FUELS TO CONVERTERS                                                *
*    :SYSTEM STORES                                                      *
*    :PRIMARY EXTRACTION                                                 *
*    :SUMMARY - DEMANDS,DELIVERIES,ELEC,PRIMARY FUELS                    *
*                                                                        *
*    :PERFORMANCE ANALYSIS - ELECTRICITY SPECTRA, MAXIMA                 *
*****************************************************************        *
```

2.10 Variables in DYPHEMO

There are three types of variable employed in DYPHEMO.

First, there are variables which are used for the purposes of intermediate calculations in the model.

Second, there are variables defined internally. These are not accessible from outside the model. They are set to values which are normally held constant. Two examples are the Venturi sluice coefficient used to calculate water flows in tidal schemes and the angle of latitude used to calculate solar geometry.

Thirdly there are variables the value of which can be changed from outside the model. It is these variables which are used to define different energy systems. Input data are divided into two classes:

(i) Technical specification

The technical data relating to the performance and control of each component must be input. This includes such features as efficiency, capacity, population, specific loss and so on. The detail in which these are given relate to the level of detail manageable and the availability of such data.

(ii) Climatic data

The model works by calculating the energy flows for each hour of a given year. Since some of the energy demands and all of the ambient source intensities are determined by the climate in any hour, a large meteorological database has been assembled. At present the temporal variation of climatic parameters is calculated from functions based on long term recorded data rather than real hourly data recorded on magnetic tape. For example the hourly values for the ambient air temperature are calculated from functions approximating the average air temperatures recorded at different times of day and year over periods of several years. There are also the actual recorded hourly air temperatures for various sites stored on magnetic tape. However some weighting factors would have to be estimated for the combination of several sites so as to produce a "UK temperature" in a similar way to that done for Energy Trends. The appendix on income sources describes the details of these climate functions and their derivations. The average monthly air temperatures can be specified by by the person using the model. Thus the model can be used to simulate severe low temperature weather conditions so as to estimate peak capacity requirements.

The list below gives the FORTRAN names of the externally definable variables, the values assumed to be applicable to the present energy system, and an abbreviated description of what they are. The general constraints on the values of these variables are that they must not be negative and that efficiencies must be greater than 0.0 and less than 1.0 Further information concerning these variables is to be found the main text and appendices.

The order of the exogenously valued variables generally corresponds to the order in which they are output. The initial output from simulations, to be found in the companion volume, generally corresponds when reading left to right and top to bottom with the order in the list below.

Abbreviations used in the description of the variables are given below.

No	number
Eff	efficiency
Elec	electricity
Sol	solar
Pass	passive
Act	active
Ind	industrial

HT	high temperature
LT	low temperature
Comm	commercial
I&S	iron and steel
Sp	specific
Max	maximum
Min	minimum

DEMANDS AND USER CONVERTERS

DEMAND USE PATTERNS

The use patterns are arrays of numbers and are therefore not shown here; they can be found in the relevant appendices.

DUSE	[ ]	Domestic house use pattern.
COOK	[ ]	Domestic cooker use pattern.
DHW	[ ]	Domestic H/W use pattern.
TDUSE	[ ]	Domestic transport use pattern.
IUSE	[ ]	Industrial general use pattern.
TIUSE	[ ]	Industrial transport use pattern.
CUSE	[ ]	Commercial general use pattern.
TCUSE	[ ]	Commercial transport use pattern.

DOMESTIC

LDHO	[10.0]	Useful light per house (W)
LETA	[0.13]	Efficiency of incandescent light.
NHOUS	[19.5]	No of households (millions).
KDHO	[4800.0]	Miscellaneous domestic elec demand (MW)
MDECAP	[897.0]	Fridges & freezers; domestic load (MW)
COCAP	[23.5]	Average useful cooker power (W/cooker)
COGETA	[0.11]	Efficiency of gas cooker.
NGCO	[10.7]	No of gas cookers (mill).
COETA	[0.2]	Efficiency of electric cooker.
NECO	[8.8]	No of electric cookers (mill).
GHWETA	[0.43]	Eff of individual gas water heater
NDGHW	[4.11]	No of individual gas water heaters (mill).
TDHW	[55.0]	Domestic hot water demand temperature (C).
VDHW	[129.0]	Daily household hot water demand (l.).
GCHWET	[0.4]	Eff of gas c/h water heating.
NDGCHW	[3.80]	No of gas c/h hot water heaters (mill).
OHWETA	[0.5]	Base eff of oil hot water heater.
NDOHW	[0.19]	No of oil hot water heaters (mill).

```
CHWETA [     0.41] Eff of coal hot water heater.
NDCHW  [     5.19] No of coal hot water heaters (mill).
EHWETA [     0.72] Eff of electric immersion water heater.
NDEHW  [     6.18] No of elec immersion water heaters (mill).
NDSHW  [      0.0] No of solar water heaters (mill).
SHWT   [      0.0] Initial temp of solar HW tank (C)
ACHW   [      5.0] Area of solar water heater collector (m2).
VSHW   [    200.0] Volume of solar water heater tank (l.).
UASHW  [     20.0] Specific loss of solar water heater tank (W/C)
NDCHP  [      0.0] No of households served by CHP (mill).
NDGHPW [      0.0] No of gas heat pump water heaters (Mill).
NDEHPW [      0.0] No of electric heat pump water heaters (mill).
UAD    [    250.0] Fabric loss of average UK house  (W/C).
VENT   [     97.0] Ventilation loss of UK house (W/C).
TINT   [     16.5] Average occupied house temperature (C).
FUDGED [      0.9] Domestic incidental gain fudge factor.
GCHETA [     0.75] Base eff of gas c/h space heater.
NDGCH  [     4.16] No of gas c/h space heaters (mill).
GINETA [     0.50] Eff of individual gas space heater.
NDGIN  [     4.14] No of individual gas space heaters (mill).
OCHETA [     0.65] Base eff of oil c/h space heater.
NDOCH  [     3.45] No of oil c/h space heaters (mill).
CINETA [     0.25] Eff of individual coal space heater.
NDCIN  [     2.45] No of individual coal space heaters.
CCHETA [     0.65] Eff of coal c/h space heater.
NDCCH  [     2.72] No of coal c/h space heaters (mill).
NDEON  [     0.44] No of on peak electric space heaters (mill).
NDEOF  [     2.13] No of off peak electric space heaters (mill).
NDGHP  [      0.0] No of gas heat pump space heaters (mill).
NDEHP  [      0.0] No of electric heat pump space heaters (mill).
NDSOL  [      0.0] No of passive solar houses (mill).
ACSP   [     15.0] Area of south glazing of passive house (m2).
TAU    [      0.7] Transmittance of passive solar glazing.
UAPASD [    150.0] Daytime fabric loss of pass solar house (W/C).
UAPASN [    125.0] Nightime fabric loss of pass sol house (W/C).
VENTP  [     50.0] Ventilation loss of passive solar house (W/C).
```

NDSOA [0.0] No of active solar houses (mill).

ACSA [20.0] Collector area of active solar house (m2).

VSSP [40.0] Volume of active solar house water store (m3).

SSPINS [10.0] Depth of insulation on act sol house store (cm)

SSPT [0.0] Initial temp of active solar house store (C)

CARPOW [178.3] Average useful power output of car (W).

TDOETA [0.12] Efficiency of petrol car.

NOCAR [14.0] No of oil powered cars (mill).

TEETA [0.8] Eff of electric car drive.

NECAR [0.0] No of electric cars (mill).

INDUSTRIAL

LIWO [50.0] Useful light per industrial person (W).

LETAF [0.4] Efficiency of flourescent lights.

NWORK [10.50] No people working in industry (mill).

KIECAP [2140.0] Useful kinetic power demand from elec (MW).

KEETA [0.35] Indust eff of producing work from elec.

KIOCAP [332.0] Useful kinetic power demand from oil (MW).

TIOETA [0.17] Industrial eff of getting work from oil

QIGTCA [3069.0] Ind >120 C useful heat demand from gas (MW).

QIGTET [0.6] Eff converting gas into HT industrial heat.

QIOTCA [2933.0] Ind >120 C useful heat demand from oil (MW).

QIOTET [0.6] Eff converting oil into HT industrial heat.

QICTCA [1953.0] Ind >120C useful heat demand from coal (MW).

QICTET [0.6] Eff coal to >120C indutrial heat.

QIETCA [1763.0] Ind >120 C useful heat demand from elec (MW).

QIETET [1.0] Eff converting elec into >120 C ind heat

EECHPI [0.11] Efficiency indust CHP, fuel to elec.

EHCHPI [0.55] Efficiency indust CHP, fuel to heat.

QIHGTC [691.0] Ind >120 C useful demand from gas CHP.

QIHOTC [1243.0] Ind >120 C useful demand from oil CHP.

QIHCTC [368.0] Ind >120 C useful demand from coal CHP.

QIGCAP [2204.0] Ind <120 C ind useful heat demand from gas(MW)

QIGETA [0.6] Eff gas to <120C industrial heat.

QIOCAP [3399.0] Ind <120 C iuseful heat demand from oil (MW).

QIOETA [0.6] Eff oil to <120 C industrial heat.

QICCAP [932.0] Ind <120 C useful heat demand from coal (MW).

QICETA [0.6] Eff coal to <120C industrial useful heat

QIECAP [143.0] Ind <120 C useful heat demand from elec (MW)

QIHGCA [907.0] Ind < 120 C useful demand from gas CHP.

QIHOCA [1634.0] Ind < 120 C useful demand from oil CHP.

QIHCCA [484.0] Ind < 120 C useful demand from coal CHP.

UAI [55.0] Industrial fabric loss per worker (W/C).

VENTI [60.0] Industrial ventilation loss per person (W/C)

TINTI [16.5] Industrial internal building temperature(C).

FUDGEI [0.3] Industrial incidental gain fudge factor.

QIGSET [0.6] Eff industrial gas space heaters.

NIGS [1.85] No ind workers with gas space heating (mill).

QIOSET [0.60] Eff industrial oil soace heaters.

NIOS [5.31] No ind workers with oil sapce heating (mill)

QICSET [0.6] Eff industrial coal space heaters.

NICS [1.05] No ind workers with coal space heating (mill)

NIES [0.33] No ind workers with elec space heating (mill)

NIHGS [0.58] No ind workers with gas CHP space heat (mill)

NIHOS [1.05] No ind workers with oil CHP space heat (mill)

NIHCS [0.31] No ind workers with coal CHP space heat (mill)

WIGCAP [618.0] Ind useful water heat demand from gas (MW).

WILCAP [1772.0] Ind useful water heat demand from oil (MW).

WISCAP [351.0] Ind useful water heat demand from coal (MW).

WIECAP [111.0] Ind useful water heat demand from elec (MW).

WIHGCA [195.0] Ind useful water heat demand from gas CHP (MW)

WIHSCA [351.0] Ind useful water heat demand from oil CHP (MW)

WIHSCA [104.0] Ind water heat demand from solid CHP (MW)

TICAP [2324.0] Ind useful transport demand (MW).

TIOETA [0.17] Eff oil to useful power of diesel motor

COMMERCIAL

LCCAP [48.0] Useful light demand per comm worker (W).

KCECAP [1046.0] Miscellaneous comm electricity demand (MW)

QCGCAP [279.0] Comm useful cooking heat demand from gas (MW)

QCGETA [0.2] Eff gas to comm useful cooking heat.

QCOCAP [12.7] Comm useful cooking heat demand from oil (MW)

QCOETA [0.2] Eff oil to comm useful cooking heat.

QCCCAP [12.7] Comm useful cooking heat demand from coal (MW)

QCCETA [0.2] Eff coal to comm useful cooking heat.

QCECAP [108.0] Comm useful cooking heat from elec (MW)

QCEETA [0.4] Eff comm elec cooking.

UAC [15.0] Comm fabric loss per worker (W/C)

VENTC [35.0] Comm ventilation loss per worker (W/C)

TINTC [17.0] Comm internal building temperature (C)

FUDGEC [0.4] Commercial incidental gain fudge factor.

QCGSET [0.6] Eff gas to comm space heat.

NCGS [4.86] No of comercial workers heated by gas (mill)

QCOSET [0.6] Eff oil to comm space heat.

NCOS [15.39] No of commercial workers heated by oil (mill)

QCCSET [0.60] Eff coal to comm space heat.

NCCS [4.05] No of comm people heated by coal (mill)

NCES [2.28] No of com people heated by elec.

EECHPC [0.11] Efficiency comm CHP, fuel to elec.

EHCHPC [0.55] Efficiency comm CHP, fuel to heat.

NCHGS [0.0] No com workers with gas CHP space heat (mill)

NCHOS [0.0] No comm workers with oil CHP space heat (mill)

NCHCS [0.0] No comm workers with coal CHP space heat (mill)

CWGCAP [571.0] Comm useful water heat demand from gas (MW)

CWLCAP [1300.0] Comm useful water heat demand from oil (MW)

CWSCAP [279.0] Comm useful water heat demand from coal (MW)

CWECAP [254.0] Comm useful water heat demand from elec (MW)

WCHGCA [0.0] Comm useful water heat demand from gas CHP (MW)

WCHLCA [0.0] Comm useful water heat demand from oil CHP (MW)

WCHSCA [0.0] Comm water heat demand from solid CHP (MW)

TCOCAP [2511.0] Useful trans demand from oil in sh,pl (MW)

TCOETA [0.20] Eff oil to useful power in ships,planes.

TCECAP [228.0] Capacity elec trains (MW).

TCEETA [0.8] Eff elec trains.

IRON AND STEEL

QSGCAP [1211.0] HT useful heat demand for I&S from gas (MW)

SGETA [0.78] Eff getting HT I&S heat from gas.

QSOCAP [2312.0] HT useful heat demand for I&S from oil (MW)

SOETA [0.54] Eff getting HT I&S heat from oil.

QSCCAP [5850.0] HT useful heat demand for I&S from oil (MW).

SCETA [0.43] Eff getting HT I&S heat from coal.

QSECAP [447.0] HT useful heat demand for I&S from elec (MW).

SEETA [0.30] Eff getting HT I&S heat from elec.

FEEDSTOCKS

FGASCA [3076.0] Rate of gas use for feedstocks (MW).

FLIQCA [14871.0] Rate of oil use for feedstocks (MW).

FCOLCA [159.0] Rate of coal use for feedstocks (MW).

USER STORES

DOMESTIC

OILCAP [11194.4] Capacity of domestic oil tank (kWh).

PETCAP [444.4] Capacity of petrol tank of car (kWh).

BUNCAP [17055.6] Capacity of domestic coal bunker (kWh).

ESTPOT [7500.0] Max input power /set of elec store heaters (W)

ESTT [200.0] Initítial temp of elec storage heaters (C)

ESTM [85.0] Sp thermal capacity storage heater (Wh/C)

UAEST [4.0] Sp loss of set of storage heaters (W/C)

BATPOW [10000.0] Max input power to elec car batts (W).

BATETA [0.8] Eff charging elec car batteries.

BATCAP [55000.0] Capacity elec car batts (Wh)

INDUSTRIAL

IS1OC [30700000.0] Capacity industrial oil stores (MWh)

IS1CC [15800000.0] Capacity industrial coal stores (MWh)

COMMERCIAL

CS1OC [14400000.0] Capacity commercial oilstores (MWh)
CS1CC [168000.0] Capacity commercial coal stores (MWh)

ELECTRICITY SYSTEM

CONVENTIONAL

CHPCET [0.25] Eff coal to electricity of CHP.
PPOW [1000.0] Max electrical in/out power pumped store (MW)
PPIN [1000.0] Elec power <PPUMSW pumped store filled (MW)
PUMETA [0.85] Eff in/out mechanical<>elec of pumped store
PUSTM [29100.0] Max potential energy storage of pumped (MWhm)
PUST [10000.0] Initial pumped storage level (MWhm)
ETETA [0.92] Eff transmission of electricity.
PSPOW1 [3.0] Available nuclear power (GW)
PSC1(1)[0.29] Max efficiency nuclear plant (zero load).
PSC2(1)[0.23] (<PSC1(1)) Min eff nuclear (full load).
PSPOW2 [35.0] Available coal power (GW)
PSC1(2)[0.35] Max efficiency coal plant (zero load).
PSC2(2)[0.11] (<PSC1(2)) Min eff coal (full load).
PSPOW3 [12.0] Available oil power (GW)
PSC1(3)[0.34] Max efficiency oil plant (zero load).
PSC2(3)[0.18] (<PSC1(3)) Min eff oil (full load).
PSPOW4 [1.0] Available gas power (GW)
PSC1(4)[0.35] Max efficiency gas plant (zero load).
PSC2(4)[0.1] (<PSC1(4)) Min eff gas (full load).
PSPOW5 [2.0] Available gas turbine power (GW)
PPSW [2500.0] d(LOAD)/dt at which gas peaking used (MW/hr)

AMBIENT

NAMACH [0.0] No of aerogenerators.
VCUT [3.0] Rated wind speed of aerogenerators (ms-1)
VRAT [20.0] Cut in wind speed of aerogenerators (ms-1).

WALAPS [5.0] (<10.0) Hours lapse of wave after wind weather

LWMACH [0.0] Length of wave machines (km.).

DWMACH [10.0] Diameter of wave machine (m.)

WOUTM [50.0] Max mechanical output of wave machine (kWm-1)

WHMAX [3.0] Wave height at which power is maximum (m)

POWHL [0.0] Elec H to L power tidal pumps/turbs (GW)

POWSH [0.0] Elec S to H power tidal pumps/turbs (GW)

HRESL [5.0] Initial height of low reservoir (m)

HRESH [12.0] Initial height of high reservoir (m)

HHMAX [15.0] Max height of high reservoir (m)

AREARL [0.0] Area low reservoir of tidal scheme (km2)

AREARH [0.0] Area high resevoir of tidal scheme (km2)

TIDETA [0.87] Base efficiency of tidal turbo machinery.

HEAD [2.0] Minimum head at which turbines operated (m)

PHYDMX [1165.0] Max elec power of freshwater hydro (MW)

HEANN [3204.0] Annual elec output freshwater hydro (GWhe)

PRIMARY FUEL EXTRACTION, CONVERSION, STORAGE AND DISTRIBUTION

GEXPOW [120000.0] Max rate of primary gas extraction (MW)

GST2M [228000.0] Capacity gas system storage (MWh)

GTETA [0.97] Eff of gas transmission.

OEXPOW [133200.0] Max rate of primary oil extraction (MW)

OST2M [262000000.0] Capacity oil system storage (MWh)

OTETA [0.99] Eff of oil transmission.

CEXPOW [99600.0] Max rate of primary coal extraction (MW)

CST2M [260000000.0] Capacity of coal system storage (MWh)

CTETA [0.97] Eff of coal distribution.

NEXPOW [20000.0] Max rate of nuclear fuel production (MW)

NST2M [1000000.0] Capacity of nuclear fuel storage (MWh)

PLETA [0.01] Eff solar energy to dry biomass.

BIAREA [0.0] Area land devoted to biomass production (km2)

BIGETA [0.55] Eff converting dry biomass to gas.

BIOETA [0.50] Eff converting dry biomass to oil.

GASTOT [15332.0] Size of gas reserves (TWh)

GEXET [0.96] Eff of extracting natural gas.

CGETA [0.70] Eff coal to gas conversion.

CGPOW [0.0] Output power coal to gas converters (MW)

OILTOT [17279.0] Size of UK oil reserves (TWh)

OEXET [0.96] Oil extraction efficiency.

OREFET [0.94] Eff of oil refining.

COCETA [0.70] Eff coal to oil conversion.

COPOW [0.0] Output power of coal to oil converters (MW)

COLTOT [563889.0] Size of UK coal reserves (TWh)

CEXET [0.95] Eff of coal extraction.

URATOT [50000.0] Size of hypothetical UK uranium reserves (TWh)

NEXET [0.5] Eff making fuel from nuclear ore and waste.

AVERAGE MONTHLY AIR TEMPERATURES (1976 SHOWN)

TAJAN [5.90] JAN's average ambient air temperature (C)

TAFEB [4.80] FEB's average ambient air temperature (C)

TAMAR [5.00] MAR's average ambient air temperature (C)

TAAPR [8.00] APR's average ambient air temperature (C)

TAMAY [11.8] MAY's average ambient air temperature (C)

TAJUN [16.7] JUN's average ambient air temperature (C)

TAJUL [18.3] JUL's average ambient air temperature (C)

TAAUG [17.3] AUG's average ambient air temperature (C)

TASEP [13.4] SEP's average ambient air temperature (C)

TAOCT [10.7] OCT's average ambient air temperature (C)

TANOV [6.20] NOV's average ambient air temperature (C)

TADEC [2.2] DEC's average ambient air temperature (C)

2.11 Stability and sensitivity

It is important to know whether the model is generally stable and whether its results are especially sensitive to the values of particular variables. DYPHEMO does not have complex sensitive feedback loops and so problems of stability and sensitivity are less severe than for many energy/economic models. In fact, the only variables whose values in one time interval affects the energy flows in a subsequent period are storage levels.

All the the changes of state that the model calculates are either constrained to lie within certain limits or they are subject to negative feedback. For example, all the efficiencies of the converters, whether constant or variable, are positive and less than 1.0. (This is only the case when <u>all</u> energy inputs and outputs to the converter are considered. In the case of heat pumps utilising atmospheric heat with a zero commercial cost, the atmospheric heat is ignored and an efficiency greater than 1.0 can result.) As an example of negative feedback consider the heating of a solar storage tank with solar energy. As energy is collected the temperature of the tank increases. As the temperature of the tank increases so the efficiency of the solar collector falls. As time increases the temperature of the solar tank therefore tends towards a stable value. The calculations performed by the model are stable unless an improper value is specified for a variable such as specifying an efficiency to be greater than 1.0 or less than or equal to 0.0

The sensitivity of a model is defined by the magnitude of change of an output variable caused by a certain change in the magnitude of an input variable. This general definition of sensitivity must be made more precise. First, which different values of input parameter should be tried and how many? Supposing the original value of the input variable to be I; would it be sufficient to try the values 1.1 I and 0.9 I, or would it be necessary to use twenty values between 0.0 I and 2.0 I ? Secondly, when varying the input value of one variable, what should the values of the other input variables be? Thirdly, is it necessary to calculate the sensitivity of all the output parameters to each of the different permutations of input parameters? Fourthly, supposing that three output values corresponding to three input values are calculated. What if the change in output is not a simple linear function of the change in input? The sensitivity would then be a function of the change in input within an certain range; it would not be possible to formulate the sensitivity in simple terms such as a 10 % increase in input results in a 10 % increase in output. There are therefore problems in defining exactly what is meant by sensitivity. Suppose that there are m inputs to the model, I_i (i = 1,m) and n outputs from the model O_j (j=1,n). Then the sensitivity, S_{ij}, of the output O_j to the input I_i might be defined:

$$S_{ij} = \frac{\triangle O_j . I_i}{\triangle I_i \; O_j}$$

The change in output $\triangle$ O is found by running the model with two values of I (to obtain $\triangle$I) and finding the two corresponding values of O. Thus the input values of I_i are assumed, as are the values of all the other inputs (I_k: k=1,m; k≠i). This sensitivity would be 0.0 when the output is insensitive (i.e. independent) of the value of an input. If a 10 % change of input caused a 10 % change of output the sensitivity is 1.0. Note that this sensitivity is only defined for the range of I specified and the values of all the other inputs that is assumed.

The specification and control of the energy system as modelled by DYPHEMO are defined by the values of 259 externally valued variables. The model simulates the system and outputs approximately 2900 and 3200 different calculated numbers for the simulation of a year and a day respectively. Even if it were assumed reasonable to vary each value by ± 10 % whilst keeping all the other input values constant there would be between (259)(2900) and (259)(3200) sensitivities. If two or more values for each input variable are assumed, and permutations are considered the number of sensitivities exceeds 10^{80}. It is therefore necessary to study the general forms of the functions in the model and the general effects of changes in input on output in order to assess the sensitivity of DYPHEMO.

This general assessment will compartmentalise the model into three sections: demand, conversion and storage.

Demands are all simple linear functions of use patterns with three exceptions:

- instantaneous light demand is a linear function of the intensity of natural light as well as the use pattern.

- hot water demand in the domestic sector is a linear function of mains supply temperature as well as use pattern.

- Instantaneous space heat demand is a linear function of ambient air temperature and incidental gains as well as use pattern.

All demands are zero or positive with with upper bounds determined by the range of values allowed their parameters. Thus given values for the fabric loss, internal temperature, incidental gains and use pattern the ambient temperature minimum sets a maximum possible value for space heat demand.

All converter efficiencies are either constant or some well defined function constrained to lie within a certain range (between minimum and maximum efficiency).

The quantity of energy in a non-heat store is constrained to be greater than or equal to zero and less than or equal to the maximum capacity of the store. The quantity of heat in a heat store is a linear function of its temperature. If the specific heat loss coefficient of the store is set to a realistic value the temperature of the store will reach a maximum value within the simulated time period. These constraints on storage levels are important since these levels represent the only information passed from the calculations in one period to the next.

Thus in general, all the processes calculated by the model are either explicitly constrained linear functions or processes involving negative feedback. During the development and applications of DYPHEMO no output was found to be highly sensitive to input. For example most annual demands simply show a 10 % increase if the input value is increased by 10%. Space heat demand, although being a linear function at any instant in time, is not generally linearly related to its determinant parameters over a year. Although a small change in one of its parameters (internal temperature, specific loss) from their present values causes an approximate proportionate change in demand, this is not the case when annual space heat demand approaches zero. Thus, in the case of very highly insulated dwellings, the larger relative contribution of incidental gains shortens the heating season and the consequent space heat load in a non-linear way. If insulation levels are extremely high, the net space heat demand will be zero, even though the values of the input parameters are not. However, in this, and other similar cases, the functions defining the energy flow are simple and constrained. The results do not contradict intuitive judgment. For example, when the space heat demand section of the model was being constructed many different values were assumed for the determinants of space heating. It was found that unless extreme values were input the sensitivity of space heat demand to its determinants was close to 1.0 if the determinants are varied by 10%. Indeed, in the case where the specific loss of the buildings is reduced by 40 % the space heat demand is reduced by 50 %; thus the sensitivity is stable over fairly large ranges.

If the output of the model is simply related to the input, the question of why the model was developed might arise. The model was not developed on the basis of fundamental new insights or for the illustration of previously unseen phenomena. It would be theoretically simple to calculate the SMD on a winter's day using the assumptions in DYPHEMO. In practice it would be extremely time consuming, to the extent that it is rarely attempted. This is despite the fact that important policy issues might be explored with such calculations. A common example is the question of whether it is best to invest in insulation or electricity supply. DYPHEMO could quickly show the effect of insulation on SMD, thus enabling a analysis of the relative capital costs of insulation as opposed to generation plant. The calculations required to estimate the effects of insulation, income sources and so forth on seasonal supply could also be done manually, but the cost in human time would be prohibitive. With DYPHEMO, the results of these calculations might be available within a day of posing the question and defining the input data.

2.12 Theoretical background

Implicitly the theoretical base of the model is the laws of thermodynamics. Although they determine the basic constraints and relationships that must exist in the model, they do not greatly help our understanding of an energy system such as that in the UK except that the first law (the quantity of energy remains constant) does tell us what the basic balance must be. This is because the flows of energy are mostly determined by complex socio-economic and technological factors, within the thermodynamic constraints. Thus, although physical reasoning enables us to calculate the minimum energy required to meet the demands for useful energy of various grades, it does not enable us to estimate the practical or socially acceptable minimum; such an estimation is without the domain of physics.

Despite these reservations it is probably worthwhile giving a brief general account of the results of the underlying physical theory for two reasons. First it tells us how to find what the absolute minimum energy consumption might be, given some demand. Secondly it expresses the flows of energy in the common currency of energy, without the complicating issue of fuel types. This encourages an overview, albeit a view which must be used carefully since not all fuels are substitutable for technical reasons.

Phenomenonological thermodynamics deals with energy in macroscopic systems in thermal equilibrium. From its four laws we can derive the basic conditions which energy processes must obey in the energy system being considered, although note that the restriction to systems in thermal equilibrium strictly rules out all real temporal processes of interest.

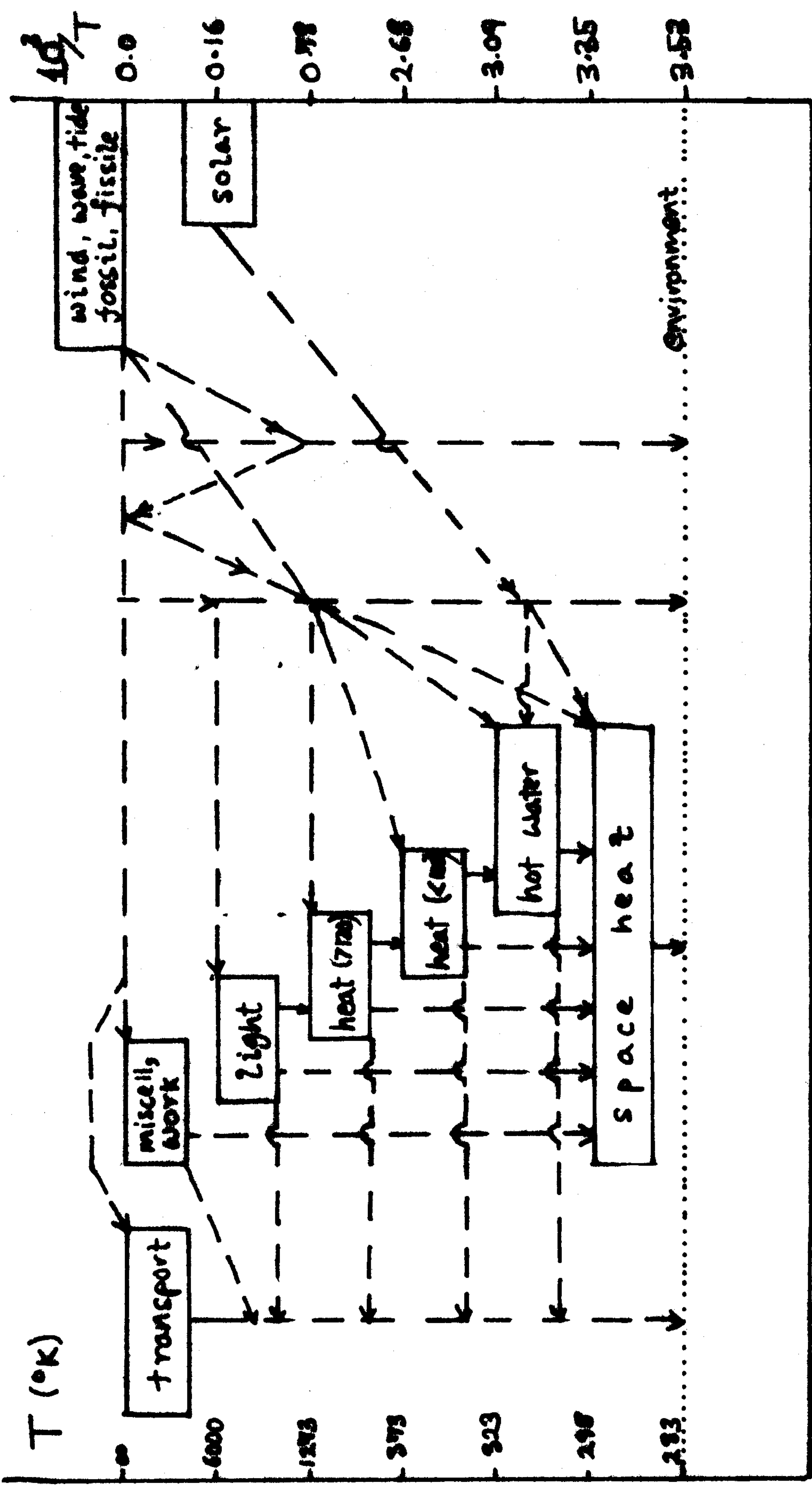
The model will differentiate between heat energy and other types of energy. In general these other types of energy will be labelled "work". This label will applied to chemical energy (Gibb's free energy), gravitational energy and kinetic energy. The reason for this is that theoretically these types of energy can be converted into mechanical work at 100 % efficiency provided they are not converted into heat at any stage in their conversion. Thus chemical energy in coal can be converted into electricity (work) via a fuel cell or a power station; since the latter conversion involves heat at a low temperature the theoretical efficiency is fairly low, unlike the fuel cell.

Appendix 1 describes in greater detail the thermodynamics of the processes encountered in energy systems, it might be appropriate for the reader to refer to this now.

It is assumed that there are two types of energy; work and heat. The technologies described in the model serve to either convert work and heat to different forms or to store it. Thermodynamics tells us the essential limitations which will be met by these technologies.

The diagram below is an energy temperature map of a social energy system. It shows the temperatures/grades of demands and potential supplies.

Figure 2.4 An energy/temperature map of a social energy system



This type of energy temperature chart displays the flows of energy from source to demand, and ultimately to the environment. It is more interesting than a simple energy quantity chart; it shows where energy is degraded by flowing through the system, because temperature is included.

Such charts are useful for analysing social energy systems. They can be used to spot wasteful energy degradation. Furthermore, if quantified, such charts may be used to calculate the minimum negative entropy required to balance entropy increases due to demands.

DYPHEMO presently accounts for the temperatures of demands and supplies by simply splitting the demands into temperature ranges and ensuring that any supplies are at an adequate temperature and of a sufficient magnitude.

The demands for energy are characterised by their variation with time (t), their magnitudes (D) and their temperatures (T). Let $D_{T_i}(t)$ represent the i th. demand at a particular temperature. We may suppose that these $D_T(t)$ are met by a set of supplies $S_T(t)$. Then the condition of supply equalling demand, as constrained thermodynamically, may be expressed

$$S_{T_i}(t) = D_{T_i}(t) \qquad \text{(J)}$$

for all i and t, and the temperature of each supply must be greater than or equal to the temperature of demand.

This implies that

$$\sum(\int(S_{T_i}(t)\,dt)) = \sum(\int(D_{T_i}(t)\,dt)) \qquad \text{(J)}$$

Both sides of this equation may be expanded. The supplies $S_T(t)$ are drawn from stores (dQ) and income sources (intensity I) via converters (efficiency η).

Thus

SUPPLY = Energy from stores - Energy to stores + Energy from incomes

$$\sum S_{T_i}(t) = \sum \{ \eta_j \, dQ_j - \eta_k \, dQ_k + \eta_l \, A_l \, I_l(t) \} \qquad (J)$$

where η_j is the efficiency out of store j

dQ_j is the energy taken from store j

η_k is the efficiency out of store k

dQ_k is th energy put into store k

η_l is the collector efficiency of income l

A_l is the collector area of income l

$I_l(t)$ is the intensity of income source l

Again one must note that the temperatures in the stores and the collected income energy must not be less than the demand temperature. It is of course easy to find the energy "wasted" during these flows simply by using the factor $(1-\eta)$ instead of η.

The demand functions of the model are derived from measured data. They are all functions of time; some are also functions of climate and other demands. Thus either

$$D_{T_i}(t) = K_i \, F_i(t) \qquad (J)$$

or

$$D_{T_i}(t) = K_i \, F_i(t,c,d) \qquad (J)$$

where K are constants.

t is time

F are the actual demand functions

c is a set of climatic parameters, such as ambient air temperature or insolation.

d is a set of demands cascading into D_T (such as incidental gains from other demands cascading into space heating)

Although these equations for the constraints are simple, the detailed simulation of the energy flows in time requires more complex mathematics. Therefore the above equations serve only as an overview of the system. However, it is in principle possible to calculate the minimum energy (or more properly exergy) required to meet a given set of energy demands. Such a calculation might have more than just intellectual interest.

The energy flows in the UK energy system are simulated by calculations coded in a computer programme. The basic set of calculations is repeated at hourly (simulated) time intervals.

3. RUNNING AND CHECKING THE MODEL

3.1 Computing

3.1.1 Calculation flow chart

The hourly calculations of the energy flows performed by DYPHEMO are illustrated summarily in the flow chart below. The chart is a simplified version of the model's structure described in the preceding chapter.

Calculation flow chart

```
                 -------
                 |START|
                 -------
                    |
      ------------------------------
      |Climate and income intensities|
      ------------------------------
                    |
                ---------
                |Demands|
                ---------
                    |
        -------------------------
        |Oil and solid conversion|
        -------------------------
                    |
      ------------------------------
      |User stores, income converters|
      ------------------------------
                    |
       -----------------------------
```

```
  |Gas & electricity conversion|
   --------------------------
                |
--------------------------------
|Electricity generation, storage|
--------------------------------
                |
     -----------------------
     |Energy industry stores|
     -----------------------
                |
 ------------------------------
 |Biomass formation, conversion|
 ------------------------------
                |
      --------------------
      |Coal to gas and oil|
      --------------------
                |
    -------------------------
    |Primary fuel extraction |
    -------------------------
                |
              ------
              |STOP|
              ------
```

The extra calculations involved over longer periods of time mostly involve summing and averaging hourly quantities. There are also calculations which analyse the system performance (such as load factors).

This sequence of calculations will be illustrated by tracing the flows of energy to meet useful domestic space heating (with solar heating) and industrial work (via an electric motor). The sections (i) to (x) refer to the boxes in the calculation flow chart after " START ".

(i) Firstly the ambient temperature (which partially determines the useful space heat demand) and the solar intensity (which determines solar collection) and other ambient variables are calculated.

(ii) The domestic space heat demand for active solar houses (dependent on the use pattern, population, specific loss, internal temperature and incidental gains) and the industrial work demand (dependent on use pattern and assumed average demand) are determined.

(iii) Oil and solid fuel deliveries are calculated from the demands and the relevant efficiencies.

(iv) The solar energy collected (if any) and the change in store temperature are calculated. If the latter is sufficiently high, the space heat demand is met from the solar tank; if not auxiliary gas heat will be required. It is arbitrarily assumed that all domestic solar systems use gas as an auxiliary fuel. The reasoning is that oil and gas will be more expensive and solid fuel is not suitable in terms of resposiveness and self-starting. The industrial work demand (from electricity) is divided by the efficiency of the electric motor to give the delivered electricity requirement. The new user store levels are calculated.

(v) Gas and electricity deliveries are calculated from demands and efficiencies. The total delivered energy requirements for each use and sector are then calculated and summed.

(vi) The industrial electricity demand is added to the other electricity deliveries; this total is divided by the transmission efficiency to obtain the total required from power stations. The calculated output from the stations as they are "switched on" (CHP, wind, wave, tidal, hydro, pumped, nuclear, coal, oil and gas) is increased until sufficient electricity is output. Any surplus electricity is stored if possible. The fuels required for electricity production are calculated.

(vii) The delivered energy requirements for coal, oil and gas are divided by the relevant distribution efficiency and subtracted from the energy industry stores to give the new levels.

(viii) Biomass formation, and its conversion into synthetic gas and oil are determined (any of the latter being added to energy industry stores).

(ix) Conversions of coal to oil and gas are treated similarly to biomass.

(x) The flows of primary energy from the ground to energy industry stores are calculated, the amount extracted being subtracted from the natural store, multiplied by the extraction efficiency and added to the energy industry store.

3.1.2 Running the programmes

The computing described in this report employs the Open University DEC-20 computer. Data and programmes are stored on disc and magnetic tape and are accessed from O. U. terminals. Character output goes to either an Open University terminal or the O. U. Student Computing Service line printer. Graphical output is available at the S. C. S. graph plotter or a suitable graphics terminal.

The programmes are compiled and stored as load modules. The data is stored on disc. To initiate a simulation the datasets defining the energy system and controlling the time period and type of output are changed as desired. The modules are then loaded and the data is read into the programme. Calculations of the energy flows are done, some analysis of the flows is done, and the results output to the printer or the plotter.

3.2 Output Description

3.2.1 Introduction

Output from the model is in two parts. The first is simply a description of the system as defined by the input values. The second section of output from the computer simulation consists of the hourly or monthly values of certain variables and their average or total over a day or year. Some analysis of the system performance may also be output (such as load spectra). The energy flows are charted at various points in the system between income sources and natural stores and the point of useful demand.

3.2.2 Output for intervals and periods

The intervals of output are of length one hour or one month; the periods of output for one day or one year. The output types are as follows:

(i) Climate (CLI)

These are the values of the solar intensity, wind speed, wave power, tidal height and ambient air temperature.

(ii) Useful energy demands (DEM)

These are 100 useful energy demands aggregated into 40 categories (e.g. cooking, light, motive power) over the sectors of demand. The totals for each type of demand are given, where the energy demand is split into five temperature ranges; work, light, high and low temperature heats and space and hot water heat.

(iii)Useful energy per fuel (FUL)

These are the total useful demands met by each fuel. The fuel types are coal, oil, gas, electricity, CHP and solar energy.

(iv) Delivered fuels (FSEC)

These are the amounts of fuels actually delivered to the consumer before final conversion into useful energy; the types are gas, oil, coal, electrictity, CHP, solar energy and oil and electricity for transport.

(v) User stores (UST)

The storage levels for the user stores. These include the temperatures of electrical and solar heat stores and the solar gain of passive solar houses.

(vi) Electrical generation (ELC)

This output is the values of the electricity generated from CHP, aerogeneration, wave power, tidal power, freshwater hydro, pumped storage and nuclear, coal, oil and gas power stations. Surplus electricity from the ambient sources is not included unless stored. The total demanded and supplied is also given.

(vii) Primary fuels in system (GOC)

These are the flows of coal, oil, gas and nuclear fuels from the natural stores to the energy industry stores. Coal and biomass for conversion to oil and gas are included.

(viii) System stores (SYST)

These are the storage levels for energy industry system stores of gas, oil, coal, nuclear and biomass.

(ix) Primary fuels extracted (PRI)

These are the amounts of nuclear, coal, oil and gas extracted from natural stores in any interval.

Examples of simulation output and further description are to be found in the companion volume "DYPHEMO output".

3.3 Testing the model

Of fundamental importance to the use of any computer model is that it works as expected and that its accuracy and realism are sufficient to enable it to be used with confidence. Simulation involves the collection of data, the construction of a theoretical model on this foundation and the use of the computer to calculate the hourly energy flows as determined by the mathematical model. These phases are all subject to errors and uncertainties, many of which are eradicable. The section below will briefly describe these sources of errors and methods for excising them. The subsequent section will describe how the model was tested against measured behaviour. Energy Trends [1] is a good statistical source to

---

[1] Energy Trends is a monthly summary of energy statistics for the UK. It is prepared by the Economics and Statistica Division of the Department of Energy.

compare and test the monthly flows of primary and secondary fuels.

3.4 Sources of error and their correction

The data defining the physical performance and control of some components of the system may be incomplete and/or inaccurate. The only resolution to this problem is a careful search for independent measurements and surveys relating to the same part of the system. However, despite such searches certain parts of the system such as industrial demands and converters remain coarse in detail and at best approximate.

The theoretical model based on this data may contain straightforward mistakes in mathematical or logical reasoning. Such mistakes are eradicated by testing individual parts or modules of the model and comparing the theoretical results against the published data (such as they are). The model may also cause errors because it is simply too crude. These errors are best corrected by comparing computed and actual performances and subsequently refining or "tuning" the parts of the model which are obviously inadequate. Since the mathematical model proceeds iteratively by finite steps there occurs a source of error called "truncation error". For example, there is an error in estimating the final temperature of an electric storage heater if hourly time steps and a simple linear approximation are used rather than the analytic solution using Newton's law of cooling. The estimation of the errors caused by truncation is not generally possible in practice with large complex programmes/models.

The theoretical model is transcribed from the languages of mathematics and logic to a high level computer language, FORTRAN. Since the resultant programme is large and complicated extensive checking for simple coding mistakes is required.

The running of the programme on the computer can cause errors due to the inherent limitations of the machine. Certain iterated calculations or manipulations can cause large innaccuracies. Rounding errors arise from the necessarily finite accuracy of the computer (unless it is dealing with "small" integer calculations). This limitation is expressed by the number of significant digits in the length of the mantissa of the computer word representing each real number or integer. This, coupled with the method of floating point arithmetic commonly employed in modern computers, means that undesirable errors may arise. Various methods can be used to assess and minimise these errors. A discussion of these numerical and computational limitations is to be found in Fox and Mayers (1968).

The errors in modelling can be reduced or eliminated in the following ways.

First, one can compare the results of iterative calculations as opposed to a single calculation from an analytic (rather than finite difference) function; this is sometimes possible for small independent subprogrammes.

Secondly, and most importantly, the calculated and measured performances can be compared. This criterion is only applicable to the extant, measured parts of the energy system. Thus new technologies, control strategies or types of energy demand can not be so tested. Furthermore, certain new combinations of conditions could take the present system outside of the domain of conditions under which it has been tested.

Finally it must be said that errors might cancel and accurate results might be produced from incorrect modelling or wrong data. It is not always easy to discover this type of error. It is a major problem in this kind of exercise.

3.5 Comparison of actual and simulated behaviour in 1976

The problem of validation has been discussed. The best method of validation appears to be to compare real and simulated behaviour of the UK energy system. Discrepancies will appear if either

(i) the system is incorrectly specified and modelled.

(ii) the average monthly climatic data used in conjunction with the functions for calculating daily and hourly temperatures is very different to the actual hourly temperatures to which the UK system responded in 1976.

If the measured data is sufficiently comprehensive the sources of error may be traced to category (i) or (ii) above.

The following sections deal with testing the simulated performance against the actual performance of the UK energy system as it was in 1976.

The detailed output of the simulated performance is in the companion volume.

3.6 Energy flows: actual and simulated

This section compares measured data for the "base" year, which mostly pertains to 1976, with the simulation results. Since the statistical data relates to 1976 and 1975, there are bound to be some discrepancies between measured and simulated performance. Data from 1975 and 1976 are used because there are no more recent years for which it is possible to collect a complete set of data. Fuel flows for the fuel industries are available very rapidly and are detailed. However there is little information on demand for other years. In particular, the IIED (1979) study of energy demand generally and the ETSU study of industrial energy demand have not been repeated more recently. It should be mentioned here that it would take little work to prepare more recent data for use with DYPHEMO, provided it is in the correct form, that is one of the reasons for developing the model.

The table below summarises the fuel flows for different parts of UK in and 1975 and 1976 (from IIED, 1979). These are combined to give a base dataset for comparing the simulation results with.

Table 3.1 Actual annual fuel flows in the UK

Energy in PJ

	Coal	Oil	Gas	Elec	Heat
Dom (1975)	458	151	622	321	
Ind (1976)	255(62)	843(203)	463(111)	304(42)	209
Com (1975)	73	292	143	147	
I & S (1976)	429	135	49	47	
Feed (1976)	5	469	97		
Tran (1976)	2	1484		10	
Pow stat (1976)	1880	310	21		345(n)
BASE TOT	3102	3684	1395	829(42)	
Losses	103	330	70	84	
BASE TOT	3205	4014	1465	913(42)	

In the table above the numbers in brackets refer to the fuel used and the heat and electricity produced by industrial CHP. (n) refers to the heat produced fron nuclear fuels for electricity generation.

The key below expands the abbreviations used in tables.

Dom	–	Domestic
Ind	–	Industrial
Com	–	Commercial
I & S	–	Iron and Steel
Feed	–	Feedstocks
Tran	–	Transport
Pow stat	–	Power stations
BASE TOT	–	BASE YEAR TOTAL

The table below shows the base year figures from the table above compared with the figures from the simulation of the 1976 system (see companion volume for details). Rows referring to the base year are annotated (B), those for the simulation with (S).

Table 3.2 Actual and simulated annual UK fuel flows

Energy in TWh

	Coal	Oil	Gas	Elec	Heat
Dom (B)	127	42	173	89	
Dom (S)	130	53	175	88	
Ind (B)	71(17)	218(56)	129(31)	81(12)	58
Ind (S)	78(16)	226(56)	122(31)	84(12)	58
Com (B)	20	81	40	41	
Com (S)	21	83	40	39	
I & S (B)	119	38	14	13	
I & S (S)	119	38	14	13	
Feed (B)	1	130	27		
Feed (S)	1	130	27		
Tran (B)	1	412		3	
Tran (S)		411		2	
Pow stat (B)	522	86	6		90(n)
Pow stat (S)	522	89	4		95(n)
BASE TOT (B)	861	1023	389	231(12)	
BASE TOT (S)	872	1030	382	223(12)	
Losses (B)	29	92	19	25	
Losses (S)	29	92	28	26	
BASE TOT (B)	890	1115	408	256(12)	
BASE TOT (S)	916	1165	411	249(12)	

Note: figures in brackets () are quantities of fuel used by or electricity produced by industrial CHP.

The annual fuel flows simulated by the model are in good agreement with those for the base year.

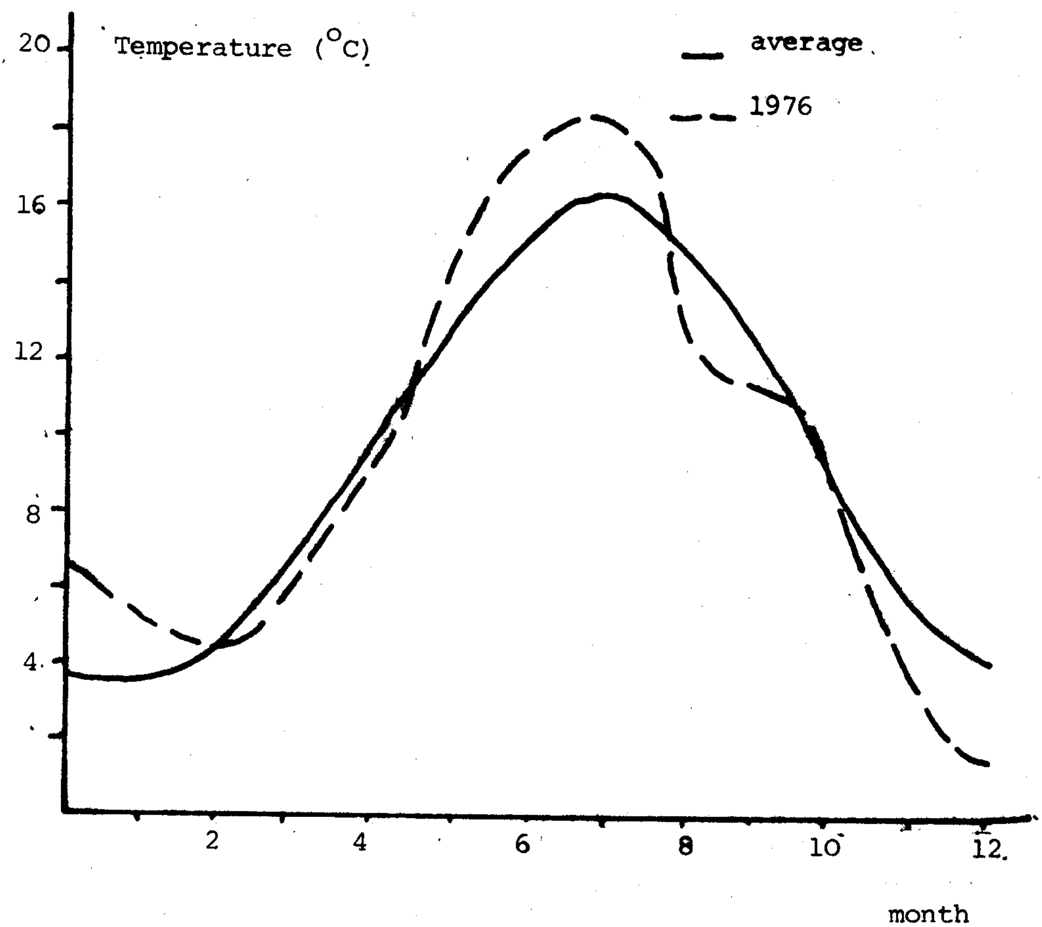
3.6.1 Climate

The climate in 1976 was unusual, or more accurately, more unusual than most years. This is to say that in 1976 the values (totals, averages, distributions) of certain climatic variables were very different from the long term averages. Using a more typical year would be better from the point of view of climatic effect, but the database for other parts of the system would be worse or refer the system in the too distant past. It is best to model the system as it was in the recent past to make it more relevant to the present system.

3.6.1.1 Ambient temperature

The graph below compares the average weighted long term and 1976 monthly temperatures.

Figure 3.1 UK monthly ambient temperatures



These monthly values are given below.

Values for 1976

J	F	M	A	M	J	J	A	S	O	N	D
3.6	3.9	5.7	8.5	11.3	14.4	15.9	15.7	13.7	10.8	6.8	4.7

Average = 9.58 C

Standard deviation = 4.45 C

The long term average UK temperatures are given below.

J	F	M	A	M	J	J	A	S	O	N	D
5.9	4.8	5.0	8.0	11.8	16.7	18.3	17.3	13.4	10.7	6.2	2.2

Average = 10.02 C

Standard deviation = 5.2

These latter are the weighted temperatures used in Energy Trends.

Although the average temperature for 1976 was high and the summer temperatures were exceptional, the winter of 1976 (Jan, Feb, Mar & Oct, Nov, Dec) had an average temperature of 5.9 C which is close to the long term average of 5.8 C. Since the main temperature effect of the present system is on space heating, the 1976 seasonal load curves should be expected to be similar to the average (ceteris paribus).

3.6.1.2 Solar radiation

This had a small direct impact on the 1976 energy system since there was no widespread use of solar energy then except for lighting and some incidental space heating. The use for lighting is accounted for in the model, albeit indirectly.

Solar energy will provide some free heat gains for space heating. This is discussed in the relevant appendix.

3.6.1.3 Wind

No effect in 1976; the ventilation loss rate of buildings are presumed to be independent of wind speed; this is discussed in the appendix on domestic space heating.

3.6.1.4 Waves

There were no wave machines operational in 1976; hence waves may be neglected for 1976.

3.6.2 Electricity

The electricity load curves shown below are derived as follows. The CEGB, who supply 87 % of the UK's electricity, have provided the basic summer and winter's weekday load curves. It is assumed that the curves for the UK are the same shape, but that the demand any time is a factor 1/0.87 larger than that for the CEGB (who serve England and Wales).

These "real" curves representing system behaviour are compared with curves generated by the model.

3.6.2.1 Summer's day

The figures below compare the actual and simulated summer's day load curves for the various sectors. The average ambient temperature is assumed to be 23 C.

Figure 3.2 Summer's day domestic electricity load curves

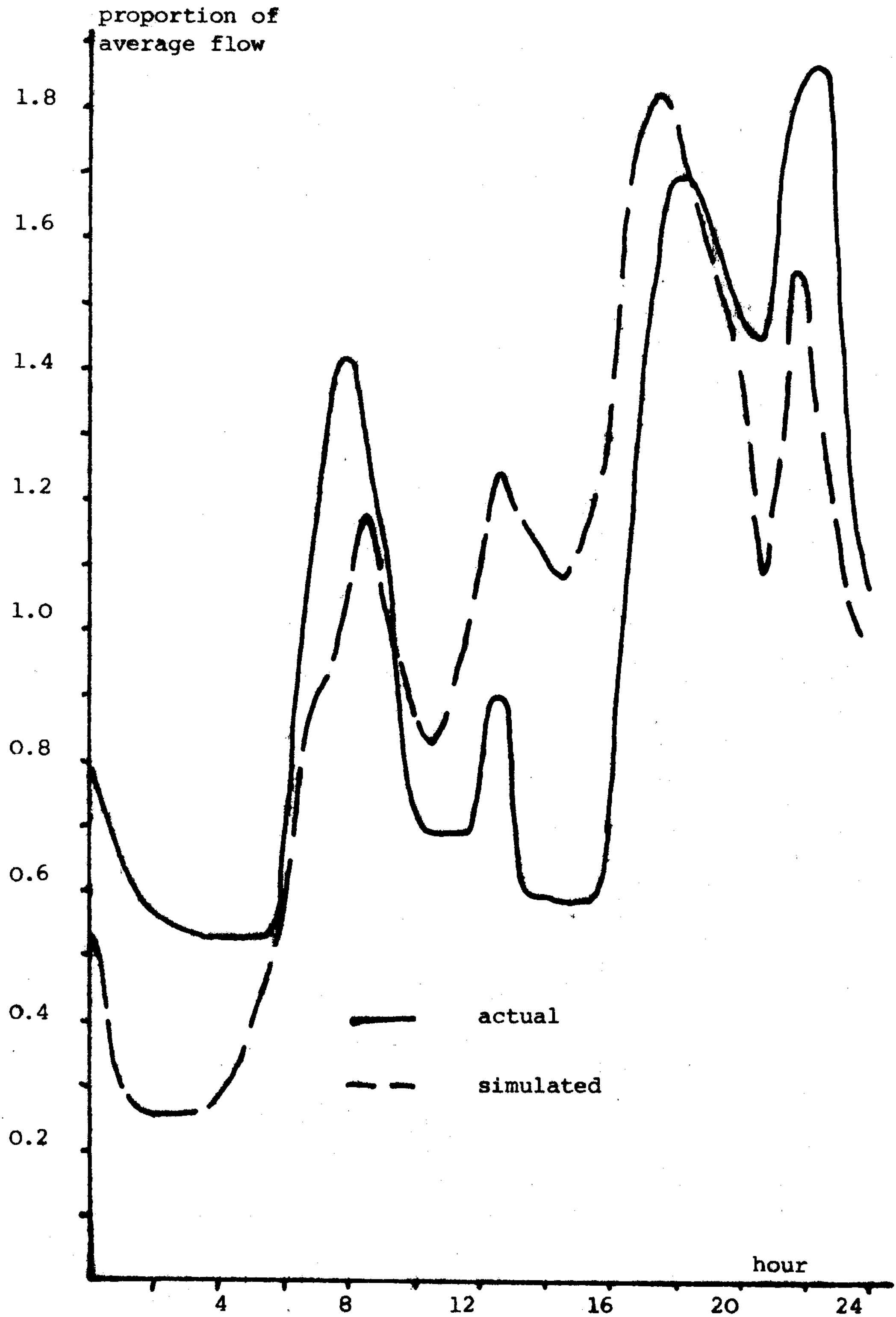


Figure 3.3 Summer's day industrial electricity load curves

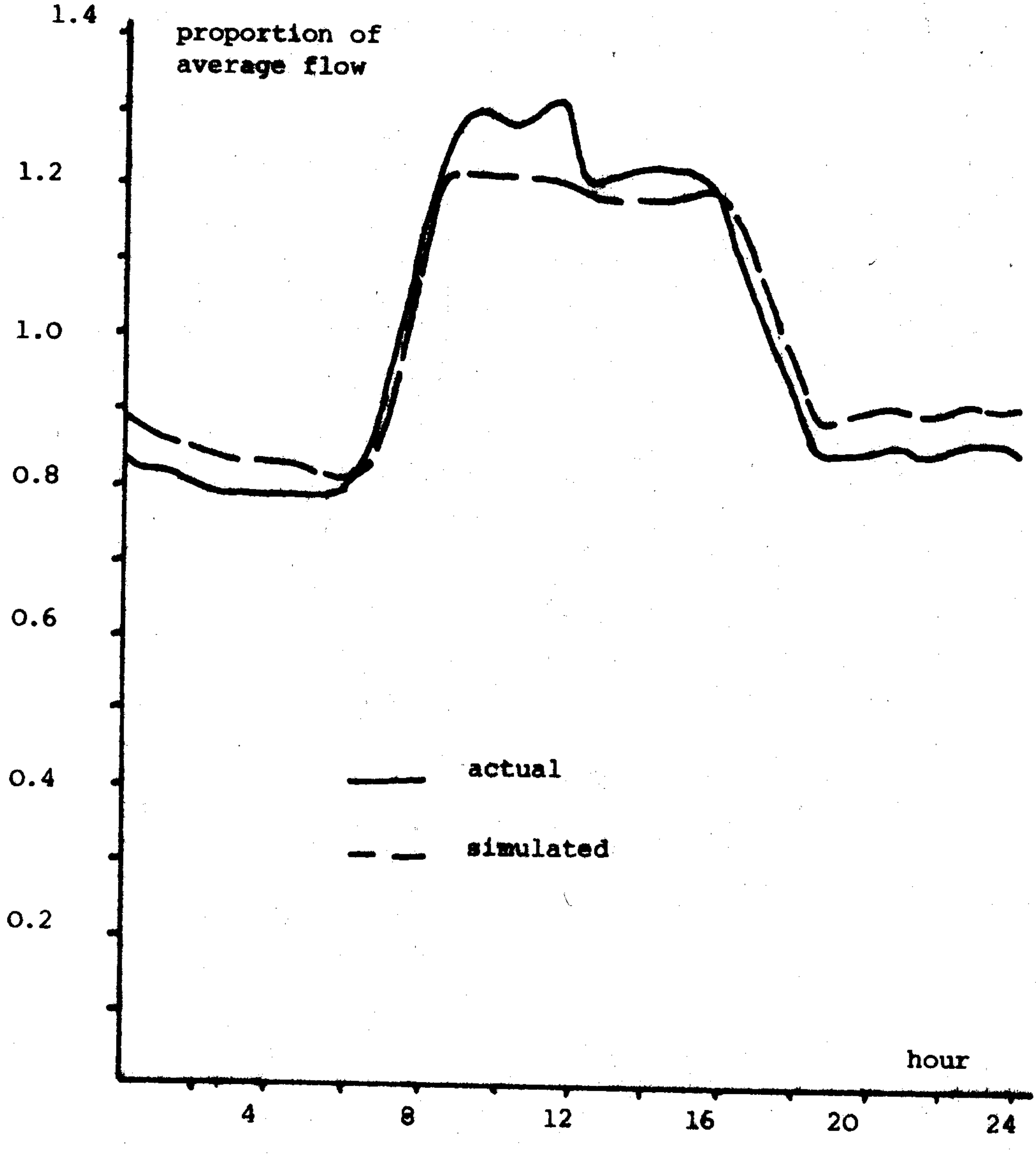


Figure 3.4 Summer's day commercial electricity load curves

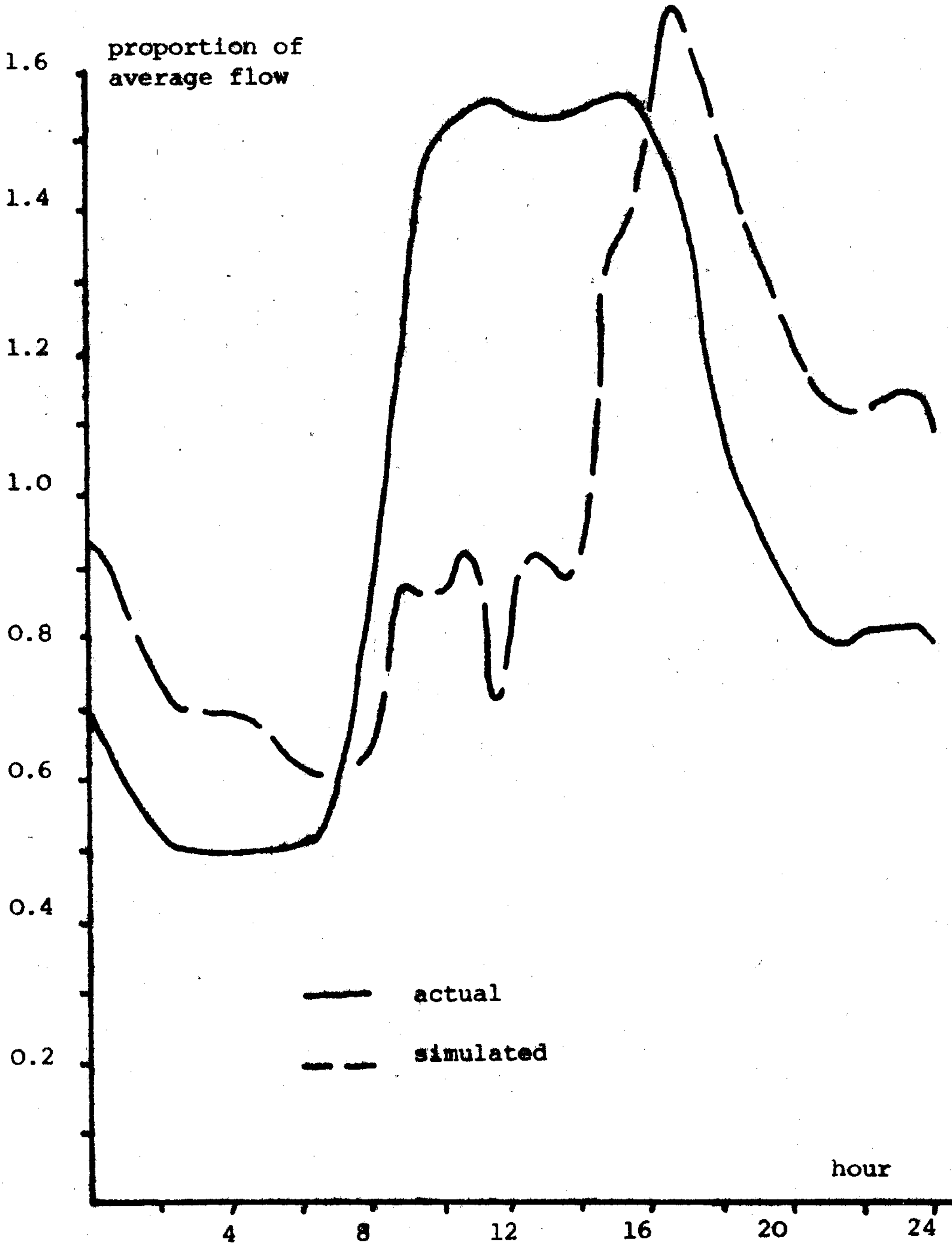
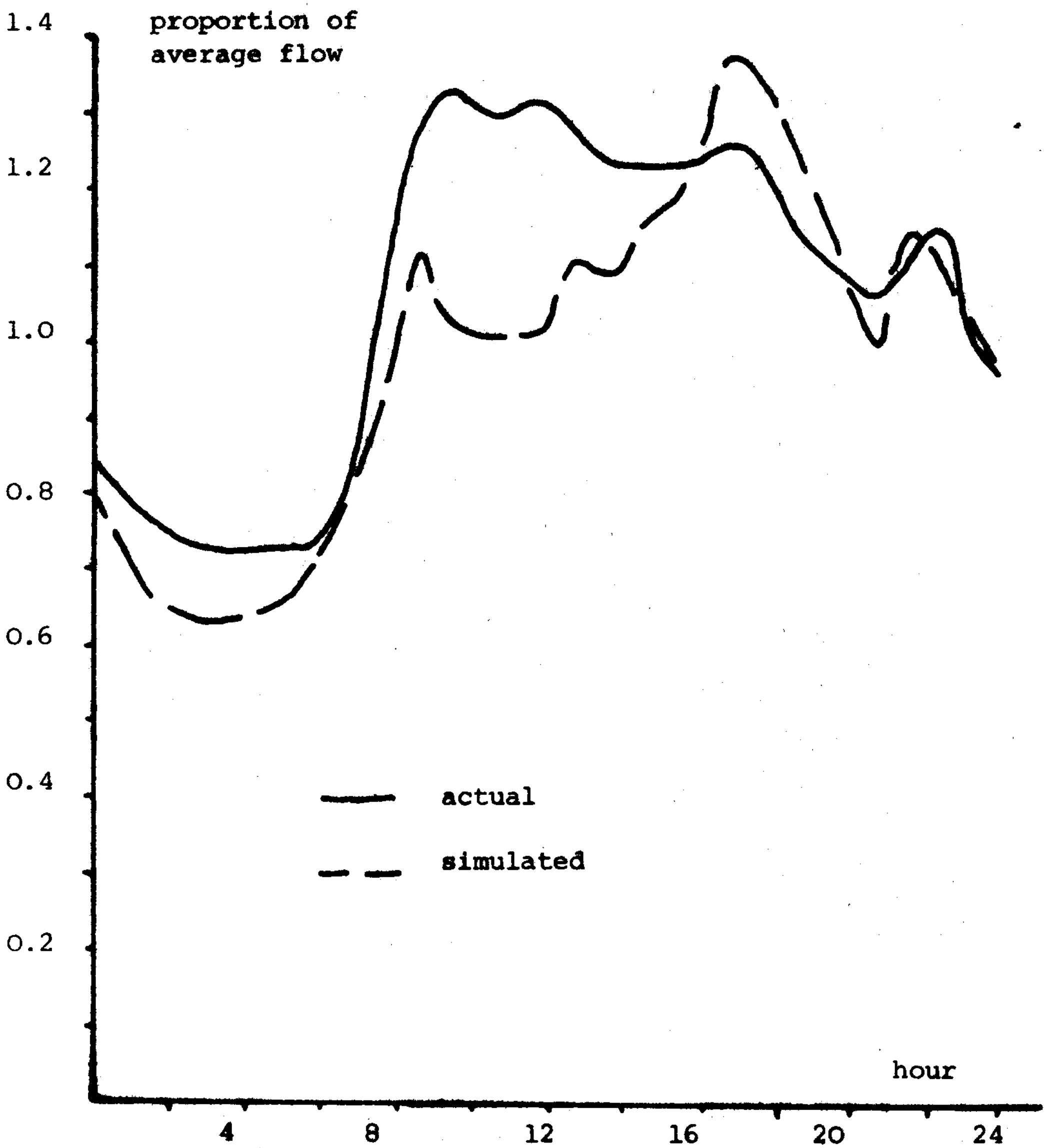


Figure 3.5 Summer's day total electricity load curves



3.6.2.2 Winter's day

This section repeats the series of graphs above, but for a winter's day. The average ambient temperature is 0 C.

Figure 3.6 Winter's day domestic electricity load curves

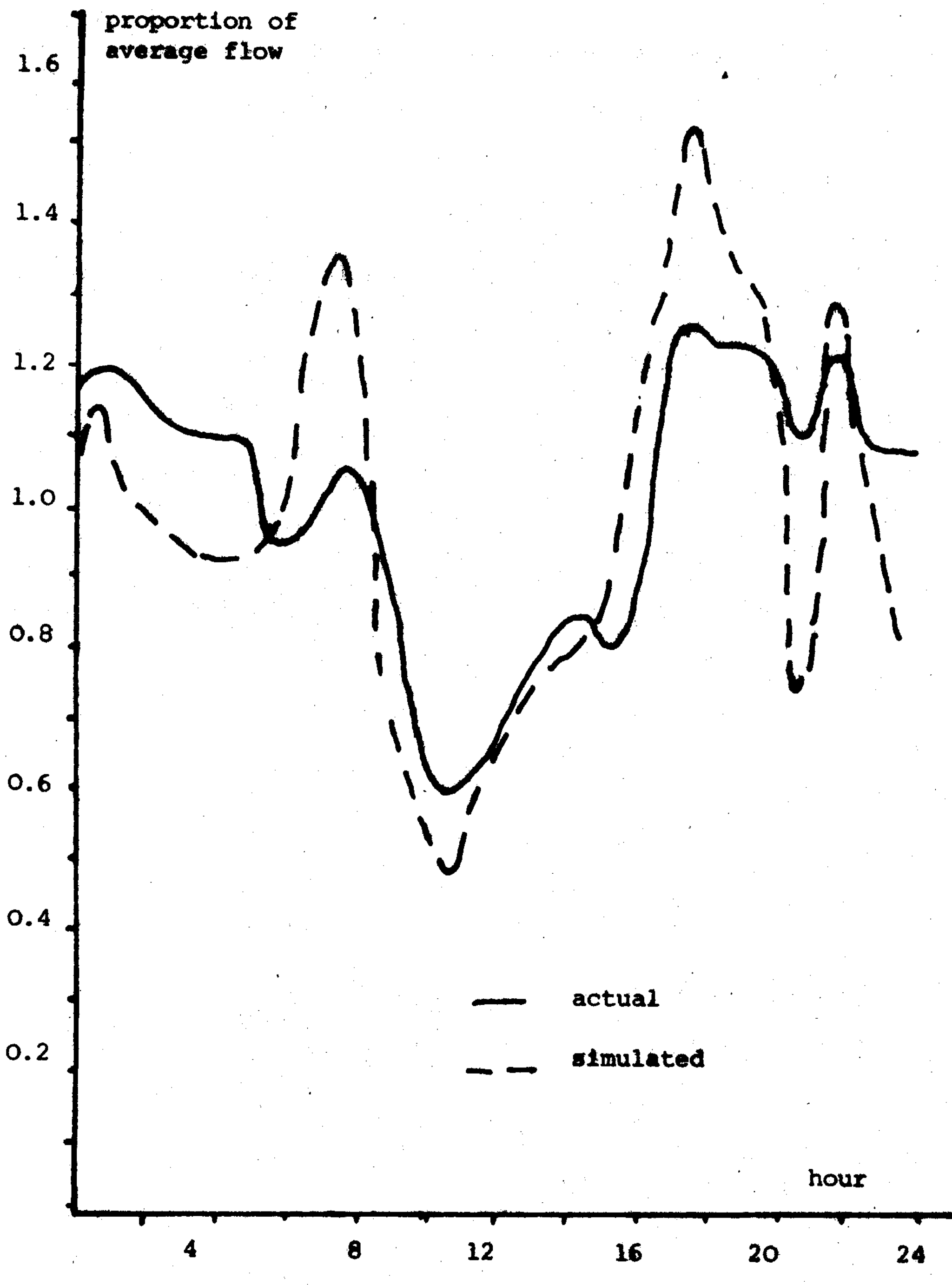


Figure 3.7 Winter's day industrial electricity load curves

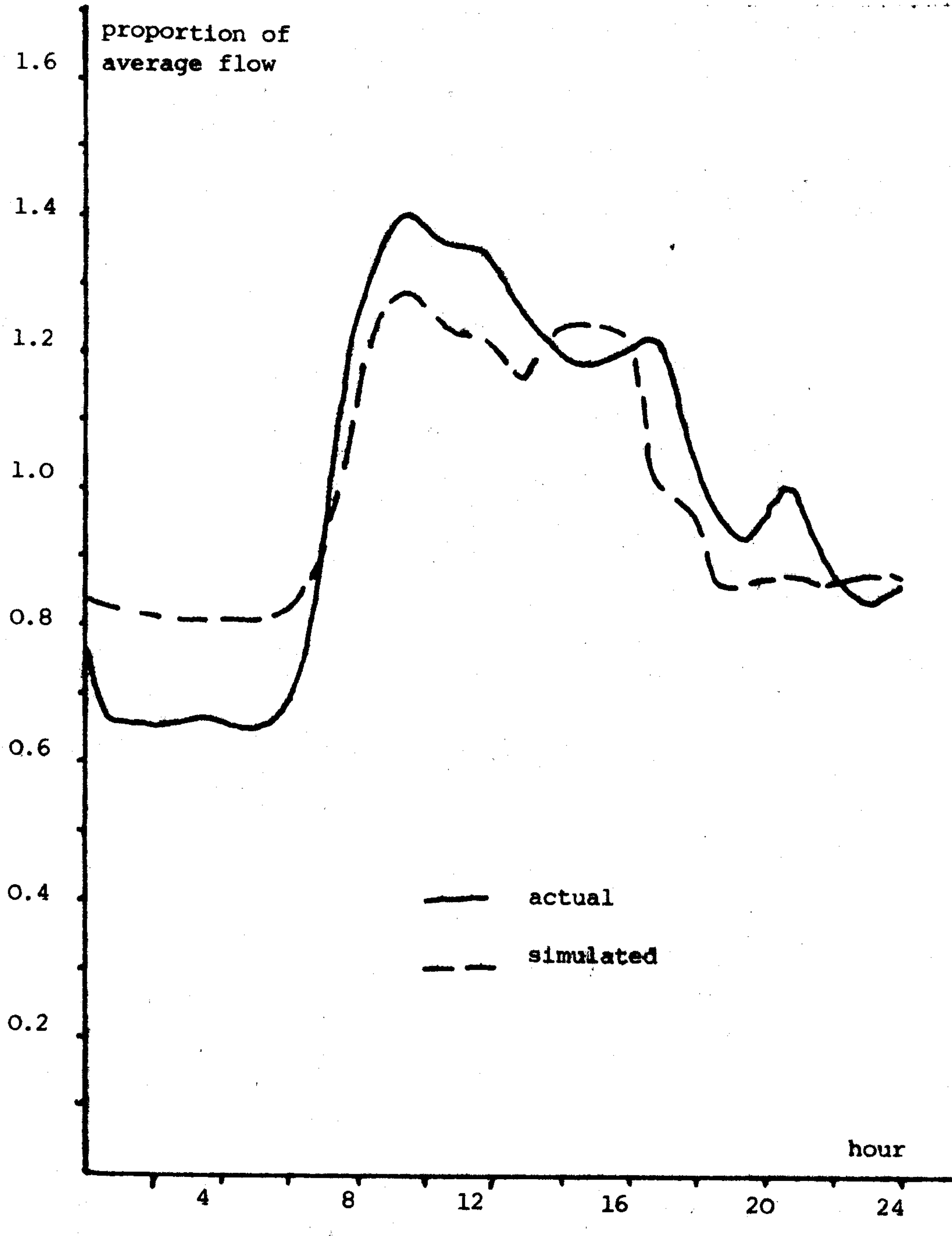


Figure 3.8 Winter's day commercial electricity load curves

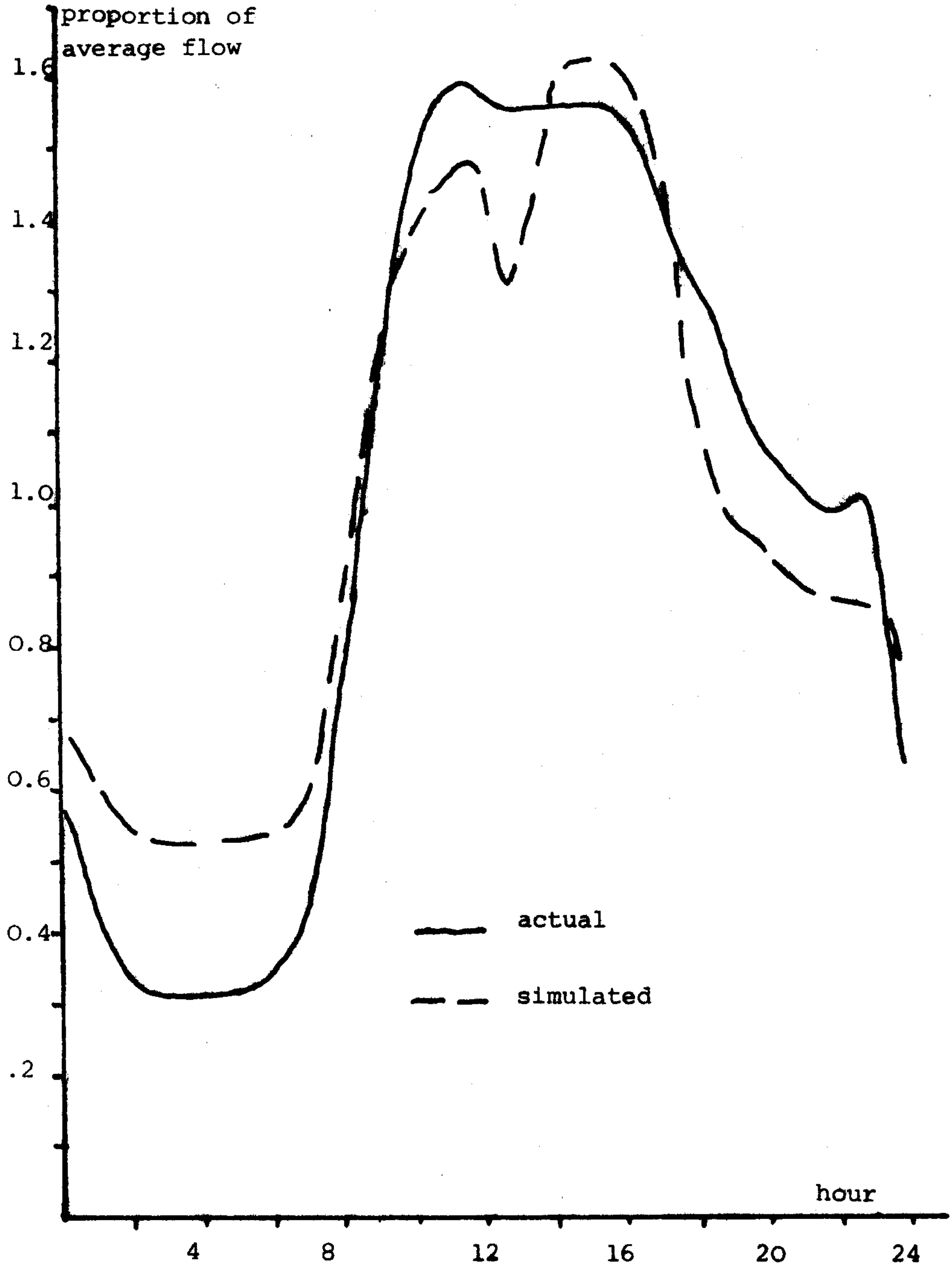
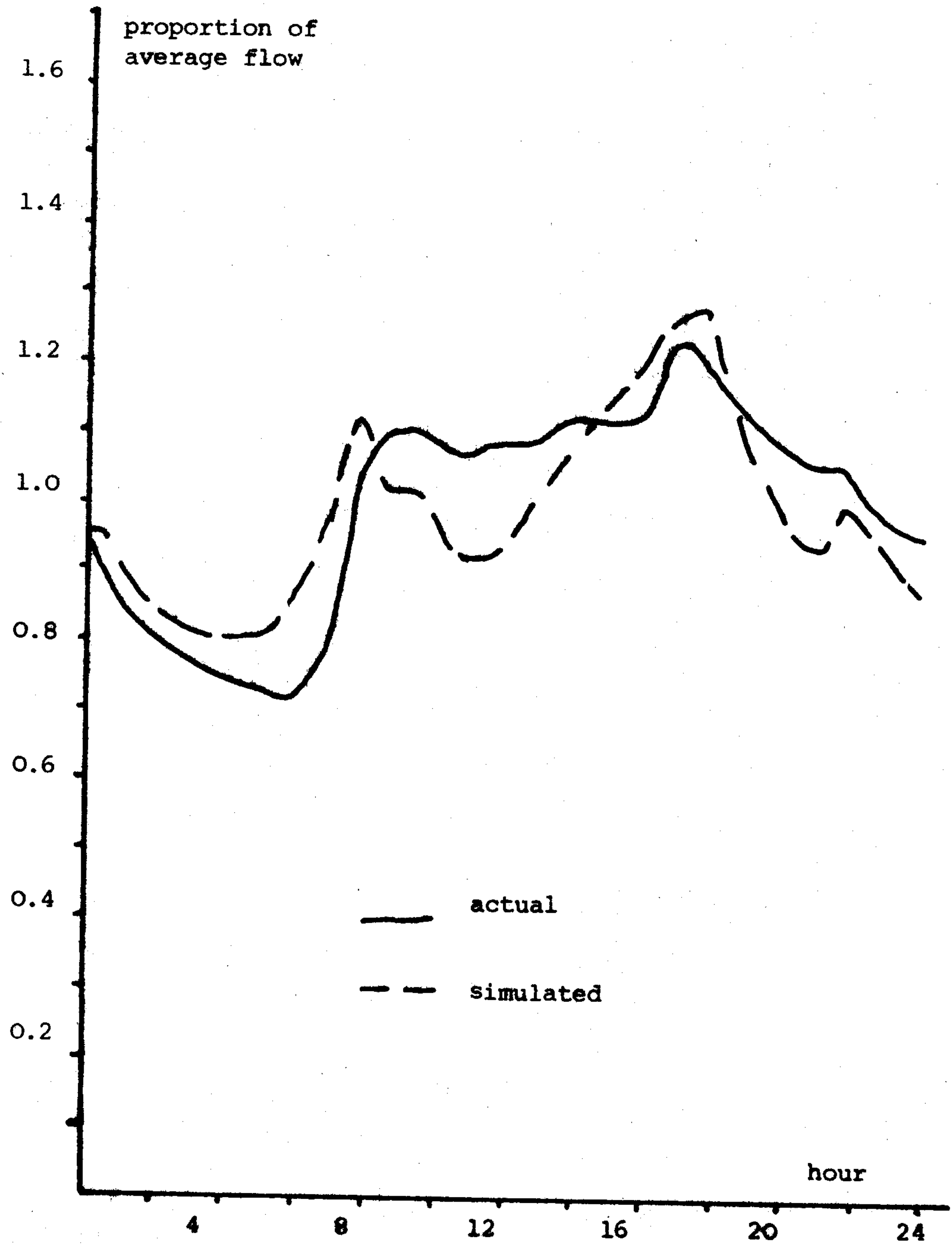


Figure 3.9 Winter's day total electricity load curves



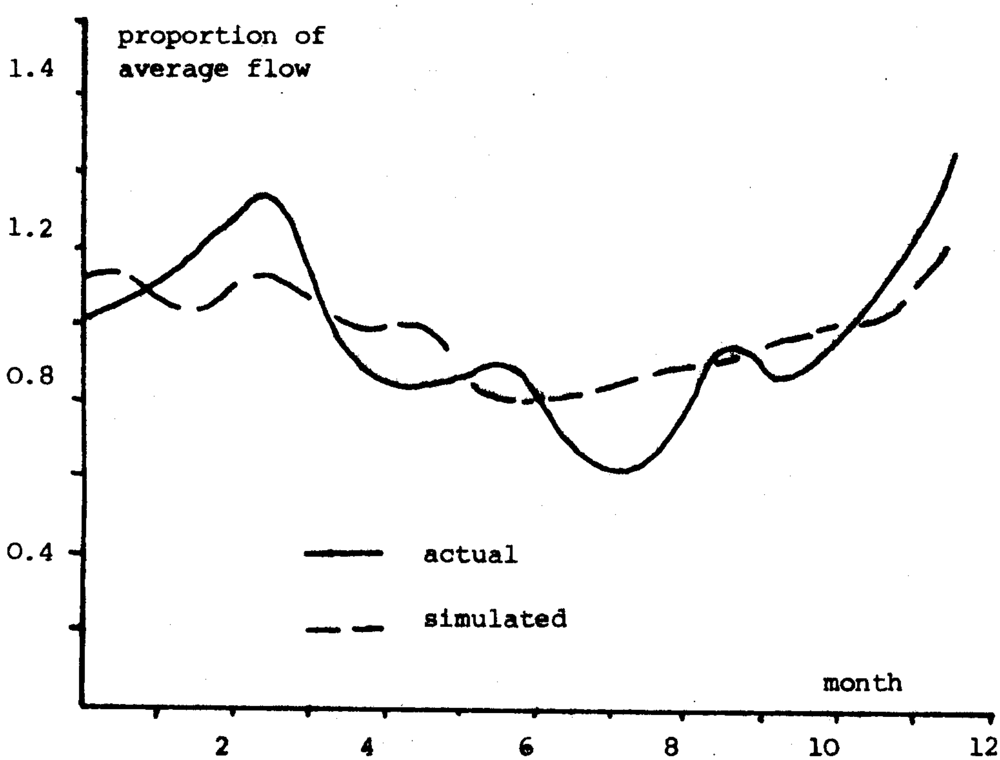
3.6.2.3 Twelve months

The monthly and quarterly electricity flows were obtained from Energy Trends. The annual totals compare well (see table above), the data from Energy Trends has therefore been used as a comparison for the variation of energy flow. The figures have therefore been normalised to an average of 1.0. These normalised figures are shown below.

1.057 1.192 1.343 0.922 0.842 0.912
0.691 0.656 0.962 0.892 1.042 1.473

The graph below compares actual and calculated flows through 1976.

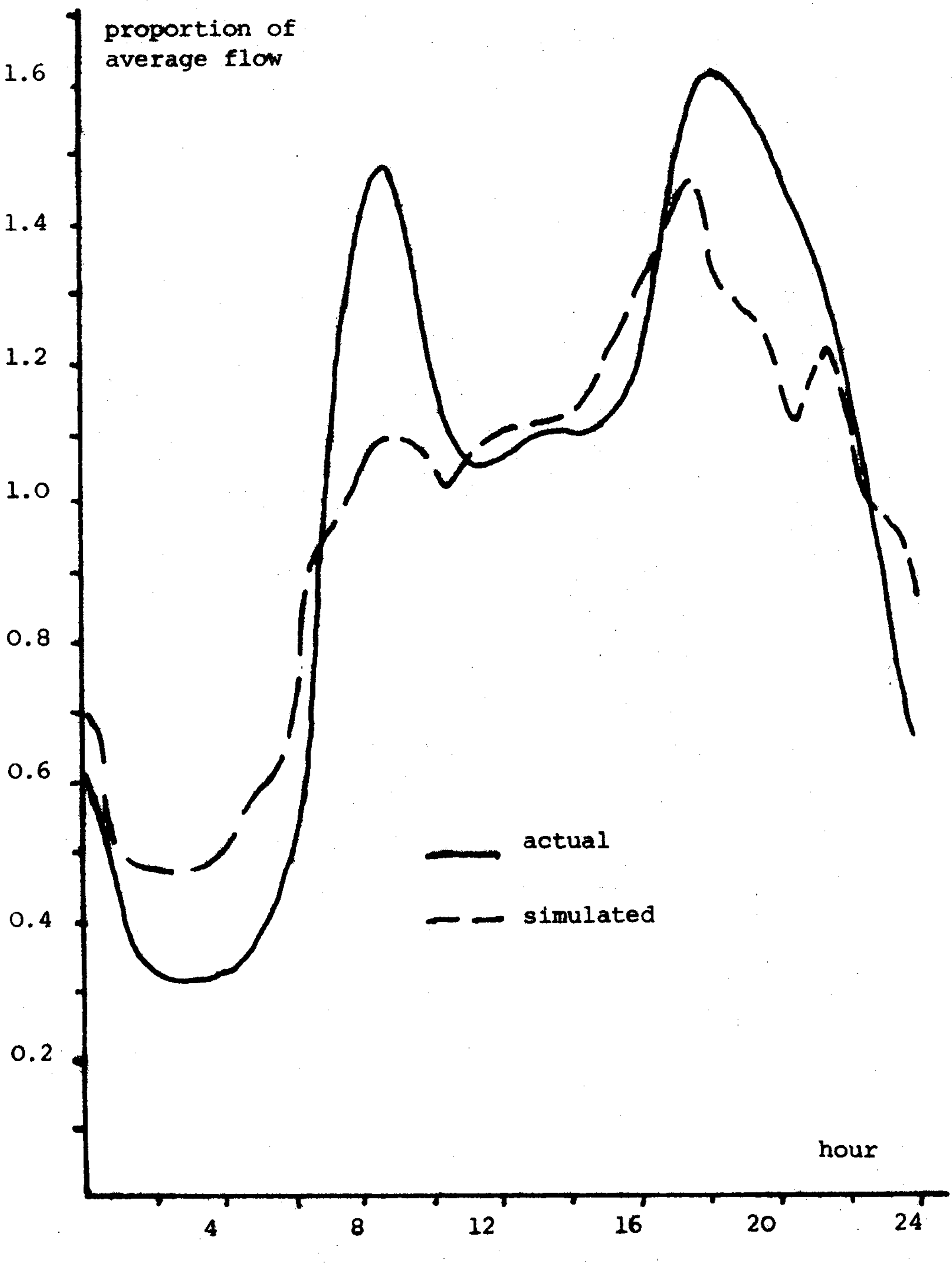
Figure 3.10 Monthly electricity flows



3.6.3 Gas

The actual winter's day diurnal load curve below is taken from ERG027 (1979), and is compared with that from the simulation.

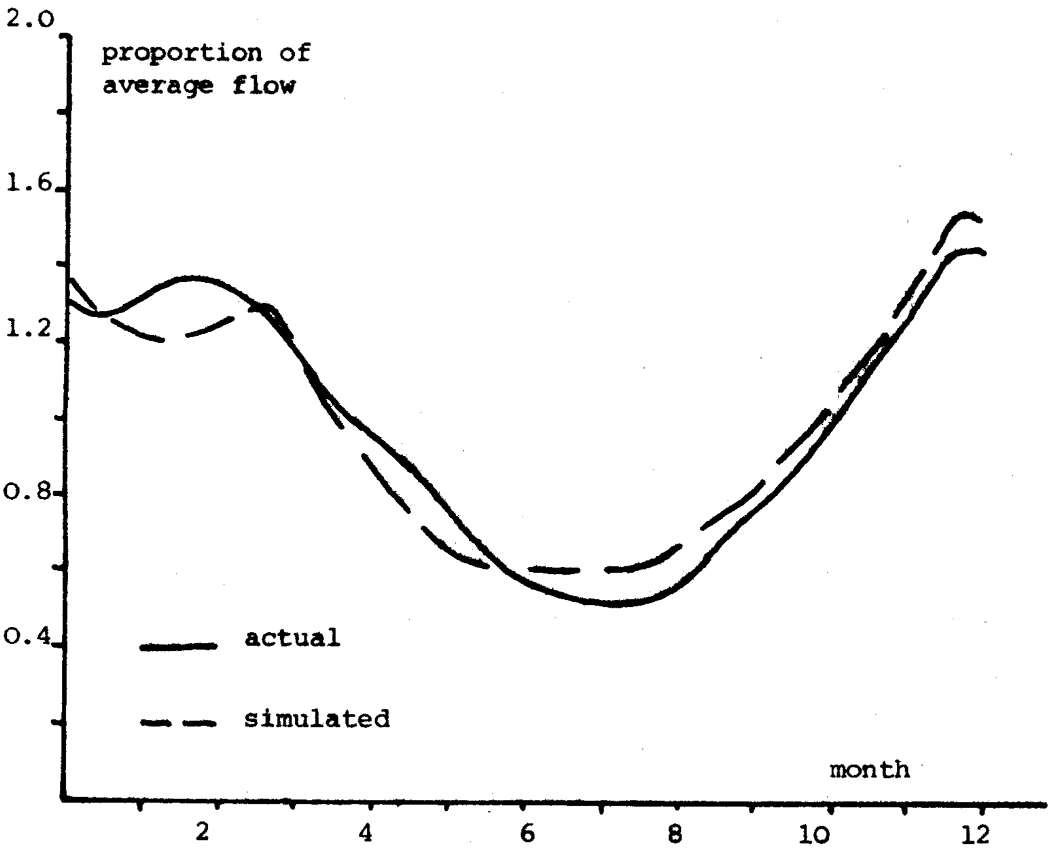
Figure 3.11 Diurnal gas flows



3.6.3.1 Twelve months

The total actual flows of gas in 1976 are taken from Energy Trends and compared with the calculated flows in the graph below, after having been normalised like the electricity flows.

Figure 3.12 Monthly gas flows



The normalised numbers from Energy Trends are given below.

1.271 1.393 1.325 1.064 0.898 0.623
0.548 0.529 0.682 0.900 1.169 1.438

3.6.4 Liquids and solids

Due to the ease of storing liquid and solid fuels diurnal flow variations are not a problem, and consequently have not been surveyed. However the annual variation is of interest and has been estimated from Energy Trends and normalised as for gas and electricity. The graph below compares the seasonal variations, actual and simulated, for liquid and solid fuels.

Figure 3.13 Annual load curve for liquid fuels

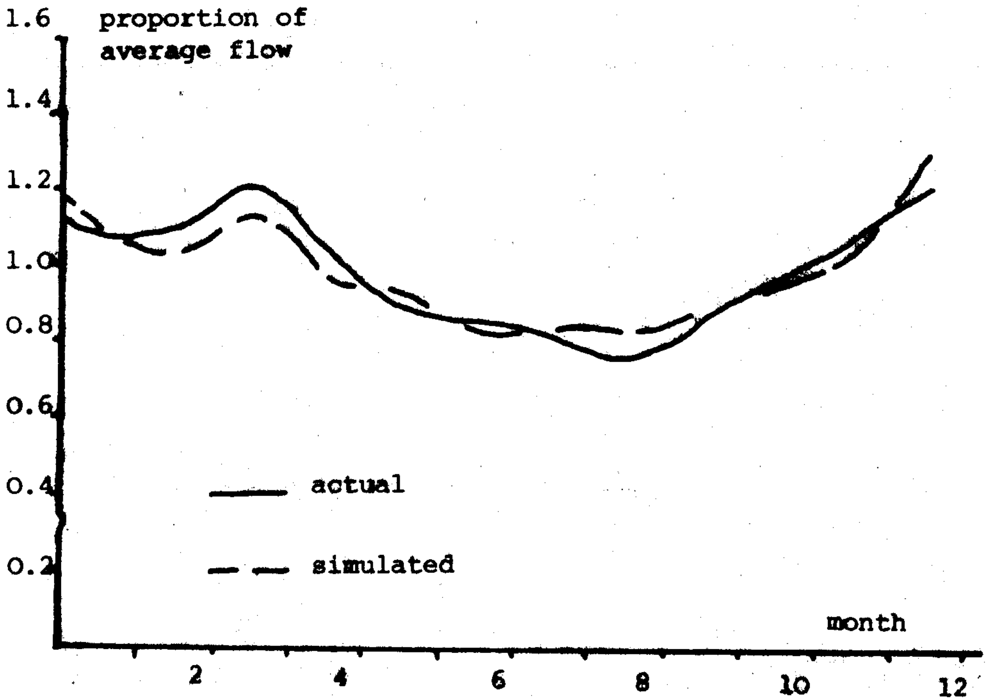
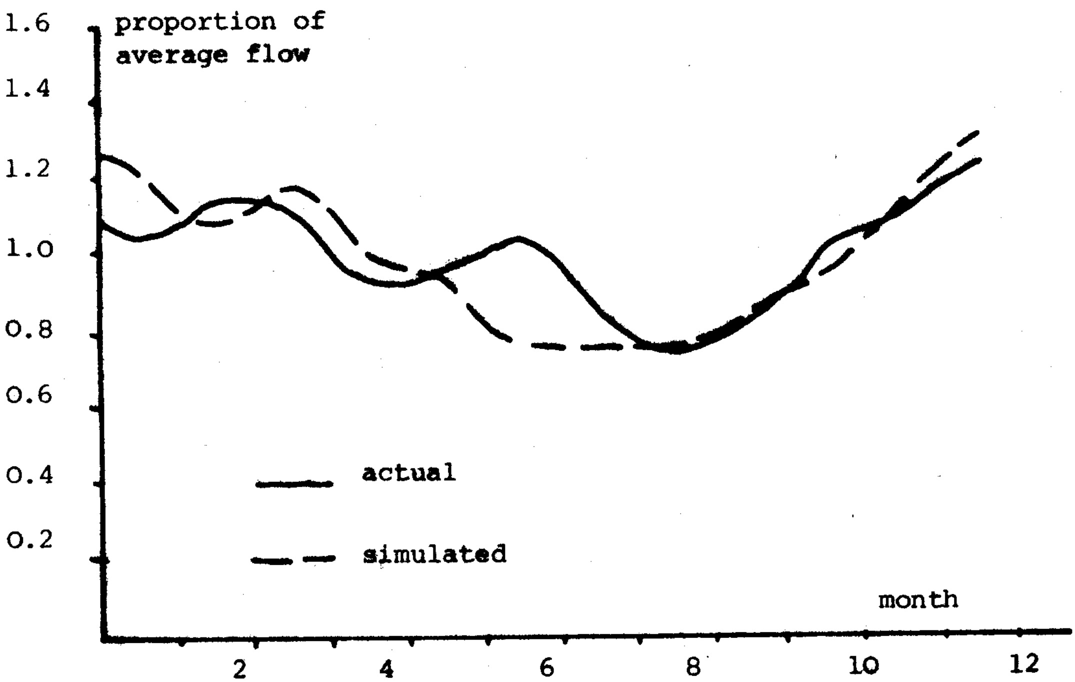


Figure 3.14 Annual load curve for solid fuels



The normalised numbers, from Energy Trends, are as follows:

For liquids

1.081 1.120 1.205 1.056 0.894 0.862

0.830 0.774 0.889 0.980 1.085 1.223

For solids

1.060 1.150 1.130 0.930 0.960 1.050

0.830 0.730 0.850 1.000 1.080 1.230

3.7 Discussion of comparison

3.7.1 Comparison of demands

The magnitudes of useful energy demands calculated with the model compare well with those calculated from demand survey data; this is to be expected when demands have been calculated from deliveries and an assumed efficiency. But it is a genuine check when considering space heating in the domestic sector since the demands are calculated from independent data (fabric loss etc.) The variation in space heat demand, as opposed to its magnitude, is also in good agreement with reality by inference from the fuel delivery curves.

3.7.2 Comparison of fuel flows

The table below summarises the comparisons between actual and simulated diurnal load curves.

Table 3.3 Diurnal load curve comparisons

CURVE	SHAPE	MAXIMUM ERROR	PERIOD (hrs)
Elec: domestic summer	fair	2:1 high	13 - 16
Elec: industrial summer	good	small	
ELec: commercial summer	bad	1:2 low	10 - 14
Elec: total summmer	fair	1:1.4 low	10 - 12
Elec: domestic winter	fair	1:1.3 high	6 -8
		1:1.3 low	21
Elec: industrial winter	good	1:1.3	
Elec: commercial winter	good	2:1 high	1 - 6
Elec: total winter	good	small	
Gas : total winter	good	1:1.5 low	7 - 9

"High" and "low" refer to a comparison between simulated and actual.

The discrepancies are due to either incorrect modelling and/or input data or to the curves used for comparison. Discrepancies due to the first reason are discussed generally through the text, and particularly in chapter 5. The curves deemed to be "actual" are from the Electricity Council; they are derived from survey analysis, they are not measured directly except in samples. It is probable that differences occur for all these reasons. To explain and rectify them would take enormous effort in modelling and in the surveying of actual load curves. However, a conspiracy of errors makes the total load curves agree well. For systems similar in demand to the 1976 system the errors should be small since they will not propagate upstream in the system from delivered to primary/income energy. Despite this the model must still be used with caution since it is only fitted to historical data of uncertain accuracy.

The variation in fuel deliveries through the year as calculated by the model compare well for gas and liquid and solid fuels, but not so well for electricity. Lighting and space heating account for about 10% and 15% of electricity demand respectively. Since the model uses monthly average ambient temperatures and solar radiation some increased peak electricity consumption in severe patches of weather over those calculated might be expected. (This problem would be resolved in two ways. First, hourly ambient air temperatures, weighted for the UK, could be used. Secondly, since the average monthly air temperature can be specified explicitly, long periods of cold (or hot) weather can be simulated. The requirements for peak capacity can thereby be estimated.) It is also likely that electricity is used as a supplement to the main source of heating during cold weather, since the model assumes only one form of space (or water) heating per house (with the exception of domestic solar systems using gas as an auxiliary fuel) it ignores this effect. Another source of error might lie in the assumed mains feed temperatures for hot water heating systems. Domestic water heating accounts for about 10% of electricity demand and the abnormally high summer temperatures of 1976 might have made the water feed temperatures unusually high.

All the annual magnitudes of fuel flows are within 10 % of the actual flows, most of them are considerably closer. The fuel consumptions of power stations are roughly in the 1976 ratio and the simultaneous maximum demand of 43.5 GW (for the UK) which DYPHEMO calculates is a "reasonable" figure since the SMD recorded by the CEGB was 42 GW in 1976.

3.8 Validation

The above exercise was intended to serve as a check on the accuracy of the model's simulation of a system that used to exist. This is perhaps the most important test which can be applied when trying to validate the model. If it is used assumed that the model can accurately simulate past systems it does not necessarily follow that it can be used to simulate different hypothetical systems. It is worthwhile discussing some of the problems encountered in validating DYPHEMO, and other energy models.

In the case of dynamic physical energy models such as DYPHEMO, wave and solar energy models, data is taken for the performance of the technology (wave machine or solar collector) and used in conjunction with meteorological parameters (wave heights, periods and solar intensities, geometry) in order to simulate the performance of the system over time. Data on the response of the technology to meteorological conditions may be theoretical or obtained from experimental or full-scale prototypes, or a combination of all three. Data on the meteorological parameters may be detailed (e.g. hourly solar intensity) or coarse (e.g. average wave data). What is certain is that the sytem modelled has not existed in the meteorological conditions assumed, otherwise there would be no point in modelling it. There is always the possibility therefore that the data used (technological and meteorological) is inaccurate and so also the results of the model. This possibility is <u>inevitable</u>. However, despite the existence of this doubt, all modelling is not thereby rendered futile. Modelling and experimentation are complementary activities: modelling depends on experimental data (to ensure it corresponds with reality at some point) and models can be used to investigate different systems more cheaply and quickly than building and testing each system, if the latter were possible. With these two methods fairly extensive and reliable information about various options can be generated. In effect, the above states that it is impossible to validate the model without building and testing the system in the assumed conditions, in which case there would be no point in modelling. It is for practical reasons that models are used.

From the point of view of validation, physical energy models have advantages as compared with energy/economic models. This is the fact that all physical systems operate within certain well defined constraints, such as the laws of thermodynamics. Furthermore, the physical basis of certain energy phenomena is well known, as for example wave and solar energy. In addition, the laws dictating these phenomena do not change with time. Thus for many processes within the energy system, it can at least be ensured that they are feasible and physical reasoning can sometimes quantify the process quite accurately without further experimentation. A further advantage in the validation of physical systems is that if part of the system is not well defined, experimental and theoretical studies can be used for clarification. If, for example, the hot water use pattern assumed produces load shapes very different from those measured, then surveys of use pattern can be instigated. Similarly, If it is suspected that the function assumed for the coefficient of performance of a heat pump is unrealistic, a prototype can be built and tested. There are often discrepancies between actual events and those predicted by energy/economic models which can not be easily investigated by experiment. For example it is difficult to quantify energy elasticities for different consumers in a direct way.

DYPHEMO is based (where possible) on measured data at a disaggregated level. The model starts by calculating disaggregated demands and the corresponding disaggregated fuel deliveries (via user converter efficiencies). These fuel deliveries are aggregated for each sector, and over all the sectors, and then compared with measured diurnal and seasonal flows. The quality of fit varies. However it is important to note that the simulated flows arise by a process of aggregation and that the "actual" sectoral flows used for comparison are themselves estimated, not measured. Thus given the uncertainty in some of the disaggregated data and in the actual flows, discrepancies are to be expected. The disbenefit of these discrepancies is balanced by the benefit of some understanding the disaggregated causes of the aggregated flows.

In contradistinction, it is possible to produce an energy or energy/economic model by fitting functions to historical aggregated data. For example the aggregated sectoral fuel flows could be fitted by minimising the square of the difference between the actual flows and some polynomial function. As long as sufficient parameters are employed and the polynomial is of the correct form the actual flows could be fitted to any desired accuracy. However, the resultant function does not necessarily confer any insight as to the causes of the aggregate flow to the modeller. For example, it is easy to fit fairly accurately a simple linear model of energy consumption and GDP to data for 1960 to 1973 (It is not quite linear, the energy/GDP coefficient gradually falls). But the model would be of little help in predicting the course of events after 1973. Thus good correlation with historical aggregated data may be achieved at the expense of understanding. It should be noted that the measure of correlation is in itself arbitrary except for the case of the perfect fit. The least squares method places great weight on statistical outliers, or extreme values. Indeed methods of fitting have been evolved which do not use the least squares method, as for example the fitting of resistant lines using summary points based on medians. [2]

This discussion of validation is summarised below:

(i) It is never possible to completely validate a model unless there is measured data covering the entire domain in which the model is to be used. Furthermore, if this data exists there is no point in developing a model.

(ii) It is always possible to fit a model arbitrarily closely to historical aggregated data. However a close fit does not necessarily confer understanding or validation.

(iii) Validation by arbitrary measures of fit can be useful, but does not guarantee the accuracy of the results of the model.

(iv) Discrepancies between the simulated and actual behaviour of physical systems can sometimes be explored experimentally. This is rarely the case with energy/economic models.

---

[2] An exposition of this method is to be found in a book by P.F. Vellman and D.C. Hoaglin (1981) called "Applications, Basics, and Computing of Exploratory Data Analysis", Duxbury Press, Boston, Massachusetts.

4. SOME APPLICATIONS

4.1 Introduction

If it is assumed that DYPHEMO has passed the tests in the chapter above and that it can also simulate the performance of novel changes to the energy system, one can experiment with hypothetical systems based on developments of the 1976 system. It is difficult to think of a watertight rule for deciding whether DYPHEMO can be assumed accurate for "non 1976" systems, it must be a matter of judgement based on a comparison of the model's results and historical data as well as an assessment of the model itself. It is notable that such a watertight rule has not been proposed for other types of energy model.

Before using DYPHEMO to model the performance of different energy sydstems a description of the procedure used to define and assess an energy system will be given.

4.2 DYPHEMO as an aid to energy policy

DYPHEMO was developed to facilitate the technical assessment of a range of possible energy systems. It is hoped that this technical assessment will aid the investigation of various energy policy options. Although it should inform policy makers of certain technical features of energy systems and help their economic evaluations, DYPHEMO will not itself generate decisions about policy. With these preliminary remarks having been made the text below gives some background to the use of such models, mentions some difficulties involved and suggests a procedure for assessing policy options with the role of DYPHEMO therein described.

It is notable that dynamic energy/economic models that project the course of the energy/economic system over periods of twenty or more years are no longer considered to produce forecasts; they produce scenarios, or their equivalent. This is because the past forecasts of models have generally been so innaccurate when compared with the future which actually came into being. This failure lead to the notion of scenarios which can perhaps be seen as hypothetical pictures of the future which help people assess the implications of various options. A scenario may also be thought of as a vehicle with which the possible consequences of assumed initial conditions and relationships can be ascertained. A range of scenarios is sometimes produced (e.g. high and low energy systems) perhaps with the hope that the future will then no longer hold surprises.

However, whether scenarios (or forecasts) are produced, there is no possible means of validating the models that produce tham unless the hypothetical system actually comes into existence. Neither the accuracy of a prediction nor the consistency of a scenario can be tested with certainty. Energy/economic models assume certain relationships to have existed in recent history, and more importantly, that they will be similar in the future. It is interesting to note how the confidence in the relationship between energy consumption and GDP in the UK has subsided since 1973. (This coincides with the departure from an apparent simple linear relationship after 1974, as is depicted graphically on page 37 of the 1981 edition of a Digest of United Kingdom Energy Statistics). The inability of many energy/economic models to accurately portray events of even the near future casts doubt on the assumption that present relationships are properly understood, let alone possible future ones. The use of scenarios in which future events are essentially postulated is indicative of the realisation of this failure. It is worth giving two examples of important relationships which are not properly understood.

First, many useful energy demands and/or end use efficiencies are innacurately known. Yet the consumer demand is for useful energy, not delivered fuel. In economic terms, the consumer derives utility from useful energy, where utility might be defined as that which makes a commodity desirable. Therefore, models which ignore this fundamental demand and the relationship between useful demand and delivered energy (via the efficiency of the user converter) are unlikely to produce realistic results. A recent conference on Energy Statistics (1981) demonstrated the need for data concerning demand. One paper entitled "Energy Statistics in the Nationalised Industries" by P. L. Ashdown and T. A. Boley demonstrated that whereas fuel deliveries to the domestic sector increased by only 7 % in the period 1968 to 1979, the useful heat supplied to the consumer increased by 24 %, more than three times as much. A second example of an unknown relationship is the effect of fuel price in stimulating the investment by consumers in conservation. This is a critical relationship since conservation reduces useful energy demand and consequently energy flows upstream in the energy system. Knowledge is so limited that it is even unclear what conservation has already taken place. This problem is expressed by the following quote from K. J. Wigley in his paper entitled "The Department of Energy Long-term Energy Model" presented at the Statistics Conference mentioned above. He says:

> "Provided that energy prices reasonably reflect their marginal opportunity costs then the standard investment appraisal rule should ensure a sensible allocation of national resources when applied to conservation measures. However, it is clear that a wide range of cost-effective energy conservation measures are not currently being undertaken, either because of extreme uncertainty during the current low level of economic activity and/or because of a lack of awareness of, or interest in, the gains in energy saving that are available. Further work is required to check that although the model contains the two main mechanisms of energy conservation, the numerical effects of those mechanisms adequately captures the realisation of the potential available for energy conservation."

The problems of uncertain knowledge about the present state of the energy/economic system, about future relationships within the UK (let alone relationships with and events in the rest of the world) and about the effects of deliberate policy make it difficult to evolve a neat, reliable and accurate procedure for looking at alternative future energy options. Indeed, there is a case for advancing policies which explicitly accept these uncertainties. Flexible policies which can accomodate uncertainties may be more robust; resting on the principle of minimising large risks rather than maximising potential benefits.

A procedure for assessing policy options, with the aid of DYPHEMO, is outlined below. The reader should refer to the domains of possibilities outlined in 1.2.3 for an understanding of the domain in which DYPHEMO is applied and an introduction to the criteria used in evaluation. The procedure is based on the idea of scenarios rather than predictions. A future state is postulated, and then assessed by progressively restrictive criteria. The reliability of the assessment using this procedure would probably diminish as the difference between the postulated state and the present state increases. The question of whether the scenario will actually come into being is ignored.

The procedure is done in two steps:

(i) Postulate a future energy/economic system.

A hypothetical system is defined in as much detail as is possible and relevant. Assumptions concerning technologies, economic costs and relationships and the use of resources such as labour, land and water should be specified.

(ii) The system is evaluated according to increasingly stringent criteria. Although each set of criteria progressively limits the options, it is increasingly difficult to produce uncontrovertial evaluations. It is possible to decide absolutely on physical feasibility, more difficult and contentious to to evaluate economic feasibility and hardly possible to offer more than an opinion on political feasibility.

Below is a description of how the author would set about postulating the energy technologies in a hypothetical system. However, there has been no attempt to describe how the economic or other features of such a system would appear. This is beyond the competence of the author.

4.2.1 Postulating a physical energy system

The following describes a sequence of steps that could lead to the construction of a hypothetical physical energy system, the dynamics of which can be simulated with DYPHEMO.

First, the exact nature of the assumed useful energy demands must be defined. Each extant sector of demand would be surveyed and then hypotheses about the future existence and composition of these sectors would be made. For example, activity levels in the iron and steel industry and insulation and temperature levels in the domestic sector would have to be assumed. Analysis of the social basis of energy use patterns (temporal) could provide information with which to estimate future possible patterns. Thus a scenario in which there is an increased number of old people staying at home, a shorter, flexitime working week, less commuter travel and increased leisure activity might be assumed. It would be possible to estimate the effects of such changes in social behaviour on energy use patterns and incorporate them into DYPHEMO.

Secondly, the range of conservation techniques suitable and available for the reduction of useful energy demand might be surveyed. Behavioural reduction in demand by means such as car sharing could be quantified and simulated. The efficacy, cost, applicability and stock turnover rates pertaining to insulated fridges or houses could be surveyed and evaluated before assuming levels of implementation. For example, it is unlikely that new passive solar houses could make a rapid impression on the energy used by the domestic sector because the turnover rate has historically been of the order of 60 to 70 years.

Thirdly, consideration would be paid to the allocation of user converters and the consequential allocation of fuel types before the final conversion from delivered fuel to useful energy demand. Questions of capital costs, efficiency and the use of scarce or abundant fuels would be addressed. A small proportion of oil fired domestic heaters might be assumed because it is likely that they would produce useful energy more expensively than other competing fuels. It is possible that the competitive use of oil in the transport sector will make the oil price relatively high compared to other fuels for domestic heating. Both oil and gas have relatively limited depletion lifespans (both in the UK and the world) and so the assumption that solid and electric fuelled user converters will eventually predominate may be reasonable for periods more than thirty years in the future. In the longer term passive and active solar systems might be assumed when fossil fuel costs will probably be higher and better design and mass production may have reduced the costs of solar systems.

Fourthly, the part of the system which delivers energy to the consumers must be constructed; this part is run by the energy industries. The magnitudes and load shapes of the solid, liquid, gaseous and electric fuels and CHP heat delivered to the consumer need to be estimated with DYPHEMO. Given these, the necessary capacities and mix of energy industry converters (and stores) could be estimated. Economic, and other criteria, can be used to generate this estimate. The possible primary inputs to the energy industry part of the system are coal, oil, gas and uranium (natural stores) and solar (biomass), wind, wave, hydro and tidal power (income sourcs). Although there is a large number of primary sources (9) and delivered fuels (5) the number of possible combinations can be limited somewhat. Thus it is unlikely that synthesised gas or liquid fuels could compete with natural gas or oil, although there would be a mixture of the two in a changeover period. The most difficult problem therefore would be the allocation of CHP heat and electricity. The former has four potential fuels (coal, oil, gas and nuclear heat), the latter eight (the fossil/fissile fuels and all the income sources except solar). In the case of electricity the problem is compounded by the fact that the future fuel costs of conventional thermal stations are not accurately known, nor are the capital costs of the ambient (or nuclear) stations. Therefore the costs per kWh are not precisely known and so arriving at an allocation of stations to electricity demand on the basis of economic criteria alone is a dubious process. Consideration might be paid to electricity producing technologies having short lead times since these reduce the risks of over or underinvestment in these comparatively expensive technologies. A CHP plant operated by the Midlands Electricity Board came into operation about two years after construction began.

This sort of reasoning is not of an exact nature, it merely advances arguments for regarding certain changes in the energy system as being feasible and as making a "sensible" energy policy. The system eventually postulated after such arguments would not necessarily be optimal in any technical sense, but it would hopefully be one worthy of consideration.

The data defining the hypothetical system is found, estimated and assumed and then used as an input to DYPHEMO when in a suitable form. In fact DYPHEMO would be used at each stage, working from demand to primary sources. This would ensure the technical feasibility of each part of the sytem and define some of the constraints that technologies downstream would have to meet (e.g. SMD). DYPHEMO also indicates whether the whole system is feasible technically. The simulation results (necessary capacities of plant, load factors, savings due to insulation etc.) can aid the design and assessment of the system according to economic and other criteria.

The physical energy system postulated and the results of the simulation of this system with DYPHEMO could be combined with assumptions about the energy/economic structure as a whole. It is possible that DYPHEMO itself could be extended to aid the analysis of non-energy resource use. DYPHEMO requires a comprehensive, reasonably detailed description of the energy system. Data on populations, power and storage capacities and sizes of ambient energy technologies are explicitly quantified. It would therefore be possible to extend the domain of DYPHEMO to include resources other than energy, and to assign these resource uses to the utilisation of particular technologies.

The capital costs and lifetimes for each technology could be assumed and in conjunction with assumptions about fuels a crude estimate of the total capital and running costs of the energy system could be made. It would be possible to derive figures for labour used directly in the major fuel industries. If expressed in terms of hours worked per capacity of the industry or per unit of energy produced (i.e. $hrs.GW^{-1}.a^{-1}$ or $hrs.GWh^{-1}.a^{-1}$) these data and the data used by DYPHEMO could produce estimates of the direct labour requirements of different energy systems. It is unlikely that such an approach would produce accurate results for systems very different from the present one.

DYPHEMO produces figures for the throughputs of the different energy technologies in the system. It is possible to find estimates of the amount of water consumed per unit of energy produced by a technology, and thus possible to calculate the water requirements of different energy systems. It would further be possible to estimate the pollution produced in a similar way.

The above describes possible extensions to DYPHEMO. In the meantime the system postulated would have to be assessed without these additions according to the criteria outlined below.

4.2.2 Physical criteria

Is the energy system postulated physically feasible? The use of physical resources assumed in the system must not exceed their availability and no physical law must be contravened. The required quantities of primary or income energy, land, labour, water, materials and so forth must be less than that physically available. Physically is used here in distinction to economically or technically.

DYPHEMO incorporates estimates of the availability of indigenous primary and income sources and can therefore help check the system for physical feasibility in energy terms.

4.2.3 Technological criteria

Is the system technologically feasible? The technologies assumed must transform primary and income energy in order to meet useful demand. DYPHEMO can show whether the technologies can fulfill this demand in terms of the magnitude, temperature and temporal pattern of useful energy supplied to consumers.

There are also the difficulties involved in guessing what future technologies might be available and the problems of fabricating and installing the technologies. If the technologies are well known there are factors such as lead times and manufacturing capacity which must be considered. If new technologies on a large scale are postulated, substantial changes in manufacturing plant and the associated infrastructure would be required. The feasibility of these second order technical requirements of the energy system can not be assessed with a model such as DYPHEMO.

4.2.4 Environmental criteria

Is the hypothetical system environmentally sound? All technologies have direct or indirect effects on the environment, but these effects are of a differing nature; namely chemical, radioactive, thermal or mechanical. In general there are great uncertainties of the effects of these pollutants on plants or animals (including human beings). Even if the effects were precisely known the acceptability of the effects can only be subjectively evalued. Despite the subjective nature of the evaluation, some energy technologies have been restricted because their waste products were generally agreed to be unacceptable.The introduction of smokeless fuel zones and the lowering of lead levels in petrol are examples of this. However, the assessment and comparison of technologies according to environmental criteria is typically a more intractable problem. For example, suppose three types of electric power generator were being compared: nuclear, coal fired and a Severn tidal scheme. How can the environmental impacts of radioactive waste, sulphur dioxide and silting or the reduction of the feeding grounds of wading birds be compared? There is the scientific problem of understanding the effects of such pollution on the environment and the philosophical problem of weighing incommensurate effects against each other. Despite these problems, it is still necessary that effort is directed at estimating pollutant outputs from energy technologies and the effect of these pollutants on the environment.

4.2.5 Economic and social criteria

Is the system economically and socially feasible? This is a crucial question, certain facets of which are sometimes be addressed using methods with which the author has no great familiarity. The following text should therefore be taken more as a commentary on the problems associated with economic and social criteria. Examples of evaluations performed by analysts using these criteria are discussed.

In some cases the economic evaluation of options can be practically useful to policy making. For example, to decide between two coal fired boilers with well known capital costs may be possible since the future ratio of capital costs may not substantially alter and because they both use the same fuel the evaluation will be less sensitive to uncertainty in the future price of the fuel. However, even the evaluation of two technologies which produce the same energy is sometimes problematic. For example, a report by Dixon and Lowe (1981) contains the estimated capital costs of the same technology, the pressurised water reactor. These estimated capital costs vary from 309 $£.kW^{-1}$ to 850 $£.kW^{-1}$. This 1:2.75 ratio pertains to a technology which already exists. Thus data on the capital costs may be uncertain, and so may the apropriate discount rate to use. The real rates of return required vary from perhaps 20 - 30 % in private industry, 5 % in public industry to 0 % for the private consumer (this latter being the real rate of return available from banks or building societies with inflation at the present level). Thus the investment decision may vary according to who takes it. This makes it difficult (if not impossible) to consistently apply the same investment criteria to the UK as a whole.

It is possible to use conventional methods to assess the microeconomics of ambient energy technologies. For example, Barrett and

Everett (1977) used discounted cash flow analysis to evaluate the cost effectivenes of different domestic heating systems. They compared the relative net present costs of single and grouped heating schemes using active solar systems, gas boilers and gas and electric heat pumps. A method of finding the economically optimal sizes of solar collection area and storage volume was employed. The effects of different rates of return and fuel price inflation as well as scale economies (due to grouping the houses) were investigated.

To extend economic evaluation beyond such "local" microeconomic issues to the entire energy/economic system is much more difficult. The basic complexity of the system of the UK and its connection with the rest of the world via trading in energy and other commodities makes an exact and comprehensive analysis beyond present capabilities. As was mentioned above, the basic relationship between energy and GDP has apparently changed substantially. This is an example of how an apparently simple relationship at the aggregated level masks the underlying causes to the extent that the change in the relationship in 1974 came as a surpise. Attempts have been made to study the role of energy in the economy at a level of disaggregation using energy intenstities and input/output matrices. However, one study by M. Common and P. McPherson illustrates the problems encountered when trying to analyse the historically changing role of energy in the economy by using input/output matrices based on data from 1968 and 1974. It seems that such data are often outdated, unreliable and inconsistent due to changing methods of classification and aggregation. The energy intensities of particular industries are generally inferred from financial data, not directly from process analysis.

This view is supported by the following quotes from the aforementioned paper.

page 1

> "However, Wright is not explicit on how how, and with what data, he converts the values of fuel requirements to physical fuel requirements, or on how he moves from fuel requirements to primary energy requirement. With the majority of Wright's kWh energy intensities coming out greater than those in Table 12 [of Common's report] it must be the case that he overstates the

total primary enrgy input. What cannot be ascertained is the source of the differential, across commodities, impact of the average proportional difference: it is unlikely that the source is Wright's computational method."

"However, this comparison is misleading since the units in which the commodity outputs are measured, £, change between 1968 and 1974. Typically, a £'s worth of commodity at the 1974 price is less in quantity terms than a £'s worth of commodity output at the 1968 price. Further, the extent of the price increase per physical unit of the commodity varies across commodities, so that a direct comparison of Tables 9 and 12 [of Common's report] does not even support an examination of the differential impact of technological change in total primary energy requirements."

page 15

"This paper has reported primary energy intensity results computed on a consistent basis for 1968 and 1974. It has used those results to describe some aspects of technological change, as revealed in input-output tables, from 1968 to 1974. Clearly the range of possible descriptive exercises has not been exhausted here."

This last quote illustrates the state of the art: it is implicitly described as a "possible descriptive exercise", not as a reliable, accurate quantified analysis.

In a further paper entitled "Scenario Analysis and UK Energy Policy" (June 1981), M. Common developes an algorithm for analysing scenarios for economic consistency and feasibility. In particular he examines the scenarios developed by the IIED (1979) and by ETSU in Energy Paper 39 (volumes I and II). Some of the difficulties Common encounters are illustrated by the following quotes from his paper

page 10. "Given the way the ETSU and IIED scenarios are generated and reported, it is difficult for an economist to properly appreciate them, either in terms of what they actually say or in terms of their comparative plausibility."

page 28. "(iii) Neither the ETSU nor the IIED (high energy) snapshot of the UK economy in the year 2000 appears to be internally consistent, at least on the basis of published reports."

"In considering future energy requirements, it is necessary to consider the production and use of non-energy commodities as well as the production and use of energy commodities."

His conclusions are uncertain for two reasons. First, the scenarios are inadequately detailed in their assumptions. Secondly, the uncertainty in the data and the fact that he uses static analysis means that the methods of analysis themselves may be innacurate. Furthermore, it appears that Common's analysis does not extend to useful energy demand. It stops at delivered energy.

It is apparent that there are areas of great difficulty in both the micro and macroeconomic analysis of UK energy scenarios.

It is important to realise that energy options could have important social consequences. For example, it is as yet unclear what the implications for employment of different scenarios might be. The amounts of labour required, the skills needed and the geographical locations of these needs are unclear. Since the labour used directly in the energy system (e.g. in coal mining) is not always much larger than that used in the supporting manufacturing and managing infrastrucutre it is likely that input/output modelling would again be required. This sort of modelling is affected by the same problems as energy input/output modelling, except they are even more severe.

Finally, scenarios should be assessed according to certain non-quantifiable criteria relating to social accepatability. The purely social effects of energy technologies are manifold; factors such as thermal comfort, mobility, aesthetics and the freedom of consumer choice should be considered. Again, it is difficult to evolve an objective method for this kind of evaluation.

4.2.6 Political feasibility

Is the scenario politically feasible? To be politically feasible the scenario must be tolerable to all the groups in society who influence, generate and implement policy. Consumers, Government and the interests of labour and capital in private and public fuel industries are perhaps the main agents in the UK. The likelihood that future Governments will attempt to implement the policy which will bring a particular scenario into existence must be considered. The UK can act in such a way as to realise a particular future, or not. It is certain that the Government, which is a representative of energy consumers, can directly affect energy futures.

The sequence of criteria suggested above has not yet been comprehensively and consistently applied to any scenarios. To do so is certainly beyong the scope of this report, since it appears that scenarios which were developed with the aid of far greater resources of manpower (those of the IIED and ETSU) are possibly economically inconsistent. Most scenarios seem to be consistent from the physical and technical point of view. For example, the annual energy demand balances annual energy supply in all the scenarios. Futhermore, the framework used to evaluate such technical consistency is generally agreed upon by policy analysts. However, evaluations according to subsequent criteria are frequently inadequate in coverage or accuracy and give rise to contentious debate. In many cases there is disagreement as to the evaluative framework and data that should be employed. Arguments about the economics of single technologies exist, let alone the macroeconomics of entire energy systems.

The problems mentioned in the discussion above may be eased by further theorising and data collection. But ultimately there will always be the problem of which comprehensive framework to use to evaluate different options. Policy decisions will have to cope with uncertainties in the data and relationships assumed in scenarios and with mutually incommensurate factors. For example power station A produces electricity for E_A p.kWh^{-1}, P_A tonnes of polluting sulphur dioxide and requires L_A hrs.kWh^{-1} of labour in the Midlands region. Station B produces electricity for E_B p.kWh^{-1}, reduces birds feeding territory by P_B km^2 and requires L_B hrs.kWh^{-1} of labour in the Severn estuary region. Is there an objective framework for deciding between these options?

Cost benefit analysis attempts to provide such a framework. But the weighting given to each factor is ultimately subjectively determined.

It is for this reason that policy formulation and implementation is necessarily a political process. Only in the arena of reasonable political concensus can the problems of uncertainty and incommensurability be resolved and a publicly acceptable policy be generated. One of the principal agents in this arena, the Government, can act both as a mediator between the major energy factions and directly as an exponent of national energy policy. In this latter role Government can affect the future by its research, development and implementation investment, by regulating the activities of fuel supply industries and by legislatory limits on demand and technologies (e.g. building insulation and appliance efficiency standards respectively).

4.3 Applications of DYPHEMO

The energy system changes hypothesised below are some of those which seem to be technically feasible and yet at the same time relatively benign to the environment. It is also possible that they are as feasible economically as other proposed systems. The general feature shared by the systems simulated with DYPHEMO is that they are "low energy" systems. This means that in general the aggregate energy flows at the point of demand and the point of primary energy extraction are reduced by comparison with 1976. However, there are potentially disturbing consequences to the "low energy" systems investigated in the applications below. For example, the implementation of conservation would create employment in a conservation industry producing insulation, efficient appliances and so on for the domestic and foreign markets. On the other hand certain of the energy supply industries would necessarily suffer some contraction, unless useful energy demand increased correspondingly. To the author's knowledge, these effects have not been fully investigated for either orthodox or alternative scenarios as exemplified by Energy Paper 39 and the IIED study (1979). The environmental, economic,social or political implications of energy systems are not the explicit area of study of this report. However, the motivation for this research is not one of pure scientific curiosity, if such be possible. The systems investigated below are "low energy" systems.

Even if the range of applications be confined to low energy systems, there are many technically feasible UK systems that might be simulated. Furthermore, if several changes are made simultaneously, the effect of each individual change may be difficult to estimate. In general, changes are synergistic; that is to say the total effect E of changes C_i and their respective effects E_i is not a simple linear sum: i.e.

$$E \neq \sum (E_i(C_i))$$

Thus the combined implementation of active solar heating and insulation would cause a different saving in coal consumption than the sum of the two applied separately.

To illustrate the range of applications of DYPHEMO, four types of change will be made; each subsequent change will be independent of the previous ones, with the exception of the last application. They are

(i) Changes in demand

(ii) Conservation

(iii) New appliance distributions, improved efficiency.

(iv) New technologies and (i)-(iii) above.

Sample output will be given for each simulation based on these changes. They are modifications and additions to the UK energy system which might be feasible within the next thirty years. Some changes, such as in consumer behaviour, could happen very rapidly and have little effect in any non-social way (i.e. economically or technically). Other changes, such as the implementation of wave power, could have large effects economically or socially. Energy technologies themselves require energy for their fabrication. This "capital" energy requirement is discussed briefly where necessary, but the effects of this requirement will need further work, maybe in the field of energy input/output modelling. There are many other effects of implementing technologies which are presently little understood, such as the implications for employment locally or nationally. Basic types of tasks for which useful energy is required are assumed to remain unchanged.

Detailed justification for the system changes posited here is beyond the scope of this work. However, in general the values assumed for improvements in efficiency and so on are loosely based on data given in other works, particularly the IIED study.

The sections below give a brief description of the system assumed. The detailed output of the performance of these systems is in the companion volume. Each system is based on changes from the 1976 system, details of which are again given in the companion volume.

4.4 Changes in demand

This section investigates the effects of certain changes in the demands for useful energy. These changes arise from different use levels brought about by changes in behaviour such as sharing cars or increasing thermostat settings. These changes do not require any technological change. The changes are described in more detail in the companion volume.

The major effects of this change in the performance of the behaviourally reduced demand system as compared to the 1976 system are :

(i) Total demand is reduced by 6%; space heating by 6%.

(ii) Primary fossil and fissile energy consumption is reduced by 5.4%.

(iii) The simultaneous maximum demand (SMD) on the electricity system is 41 GW instead of 43 GW.

4.5 Conservation

Conservation is here defined as the reduction of useful energy demands by technological change. Thus draughtstripping and decreasing the drag coefficient of cars are conservation techniques. Most conservation changes could be made with little increases in energy demand for fabrication, provided the conservation were introduced at a sensible rate. Most conservation technologies save more energy than is needed for their manufacture within a few years; their long lifetimes mean that their net "energy benefit" is large. It is therefore unlikely that such technologies will cause transition problems in the energy system but they could have large implications for employment, the economy and so on. The companion volume contains more details.

Major features of the performance of the system incorporating technical conservation (compared to 1976) are:

(i) Total demand is reduced by 21%; space heating by 49%.

(ii) Total primary fossil and fissile energy consumption is reduced by 16.4%.

(iii) SMD is reduced from 43 GW to 32 GW.

4.6 New appliances and distributions

This section deals with improved effiencies in appliances and redistributions of appliance populations which might achieve better fuel/demand matching. An example of this might be the increasing of domestic gas boiler efficiency from its present average value of about 0.55 to 0.70. Efficient solid fuel heaters might substitute for electric heaters (where possible) thus reducing primary energy use and reducing the seasonal swing in electricity demand.

Most appliances have lifetimes in the range ten to twenty years. In general the fabrication of more efficient appliances does not require substantially more energy or materials. One can therefore envisage the total replacement of contemporary appliances with more efficient ones as being possible within thirty years. Such a replacement would have little effect in any way, except that Government legislation (or British standards) and some design and retooling industrially would be needed, on the assumption that these appliances were to be manufactued in the UK, and not imported.

A comparison of this increased efficiency system with 1976 shows these effects:

(i) No substantial change in total or space heating demand.

(ii) A decrease in fossil and fissile energy use of 31 %.

(iii) The SMD is reduced from 43 GW to 29 GW.

(iv) The gross efficiency (demand/primary) is increased from 0.34 to 0.50.

4.7 New converters and all other changes

The low overall efficiency of the present energy system, and its reliance on finite natural energy stores, has stimulated research into technologies which convert energy more efficiently and devices which collect energy from income sources. Examples are combined heat and power and solar collectors. The comparatively low level of funding for these technologies made it difficult to estimate what might be achieved with them. As understanding increases ways have been found to utilise income sources (e.g. solar energy) more cheaply (e.g. passive solar houses). The relative decrease in the real cost of fossil fuels in recent historyy has meant little interest even in the ambient energy successes in the UK (such as Wallasey school or hydroelectric power).

The energy costs of fabricating some energy technologies is fairly well known; the work of Harrison, Jenkins and Mortimer (1978) on the energy analysis of wave machines being a good example. However there are some technologies which need a similar analysis. It is likely that the rapid construction and implementation of any large new energy technology would have a considerable effect on energy demand as well as society generally. However, the UK's economic and social system is already capable of building things like power stations. It is possible therefore, that if the UK were to build wave machines instead of nuclear or coal fired power stations, the UK would have much of the necessary infrastructure to do it and the UK's fabrication energy demands would not alter dramatically from present levels.

The market penetrations of these technologies is assumed to be large because it is of interest to know what possible effect they might have. Futhermore, most technologies have relatively short lifetimes (with notable exceptions such as buildings and hydroelectric stations). Penetration therefore arises both from replacement of obsolete machines by improved devices and from the "retrofitting" and refurbishing of technologies that still have some useful life.

In addition to the introduction of new technologies, many of the assumptions about reduced demand (because of behaviour and conservation) and improved efficiency are retained.

The new technologies introduced may be summarised as follows:

(i) In the domestic sector the following technologies are introduced: active solar hot water and space heating systems, gas and electric heat pumps, combined heat and power heating and electric vehicles.

(ii) Combined heat and power is used increasingly in the industrial sector and is introduced to the commercial sector on a large scale.

(iii) Aerogenerators, wave machines, tidal machines and an increased freshwater hydroelectric component are introduced to the electricity supply system.

The effects of these innovations on system performance are as follows:

(i) Total demand is reduced by 24%,; space heat by 44%.

(ii) Total fossil and fissile fuel consumption is reduced by 61%.

(iii) SMD is 22 GW instead of 43 GW.

4.8 Discussion

The sequence of changes briefly examined above is not accidental. To fill a sieve it is best to first stop as many holes as possible, since then there is more time to find water, and not so much of it to find. And when looking for water supplies it is best to use a range of replenishable sources in case one becomes depleted or unusable. Thus the sequence of DYPHEMO applications first examines reduction in demand and then looks at increased efficiency and alternative supplies. It is important to start with demand since this is the foundation of the whole "energy problem" and any reduction in demand reduces the problems "upstream" in the energy system. This is a good energy strategy in that primary supply needs are reduced; it <u>may</u> also be a good strategy in environmental, economic and sociopolitical terms. All the measures reduce chemical and thermal pollution, and the sequence is one of increasing cost and uncertainty, from proven conservation techniques to uncertain supply options.

The table below summarises the effects of the changes posited.

Table 4.1 Comparison of system performances

All energy in TWh.

	1976	Demand	Cons	Effic	All
Total demand	917	858	722	918	698
		-6%	-21%	+0%	-24%
Space demand	235	222	121	236	132
		-6%	-49%	+0%	-44%
Foss/fissile	2671	2527	2233	1844	1033
		-5%	-16%	-31%	-61%
SMD (GW)	43	41	32	29	22

The behavioural reduction in useful energy demand can be implemented rapidly for little or no financial or resource cost. Demand reduction by technical conservation does require resources, although it is sometimes argued that saving a Joule costs less than producing one. For example, one issue of Energy Manager (Dec 1981, Vol 4, No 10, p28) discusses the conclusions of two reports on the economics of energy conservation in domestic dwellings. The general finding of these reports by the Economics Advisory Group (EAG, 1981) and the Electricity Consumer's Council and the National Consumer's Council (ECC/NCC, 1981) is that in general investment in domestic energy conservation is less risky and offers better returns on investment. The table below shows some figues taken from the EAG report.

Table 4.2 Conservation costs

MEASURE	REAL RATE RETURN	RETURN ON INVESTMENT kWh/a/£
Draught strip	11 - 31 %	8 - 31
Loft insul	15 - 39 %	16 - 41
Cavity insul	8 - 16 %	6 - 30
Nuclear generation		3.5 - 5.5
(including trans)		1.5 - 2.5

This shows that the real rate of return on investment is high as compared to the normal rates available to private consumers, being of the order of 10 to 40 % rather than 0 to 5%. The comparison of conservation costs as compared to those of generating and transmitting electricity by nuclear power shows that conservation can be cheaper than supply. Care must be taken, however, that the fuel saved is matched to the fuel supplied in these comparisons. Reduction of demand technically and behaviourally alleviates all problems upstream in the energy system.

Primary energy demand is reduced with the consequence that existing supplies will last longer; this in turn implies more time to look for alternatives (and less of them to find). Furthermore, reduced demand literally insulates the UK against some unforeseen changes such as the climate becoming colder and diminishes problems which might arise with certain supplies. Thus potential problems such as a severe nuclear accident, suplhur dioxide or carbon dioxide pollution from coal or political/economic action can be alleviated by decreased demand.

Increasing efficiency has most of the same effects as reduced demand. Since the lifetime of most energy converters is short, this measure could be introduced fairly rapidly without major resource costs or changes to the infrastructure of the UK economy.

The last system to be simulated explores a highly diversified set of supplies; income sources are utilised as well as fossil and fissile fuels. In so far as income sources are used, pollution is decreased and the long term energy supply is assured. Finite primary supply sources will have to be employed for the medium future but since they are finite it is best to preserve them for uses it is difficult to substitute another fuel for.

In addition to these energy aspects one should consider the broader implications of technical changes to the energy system. These implications are of an economic and a political nature.

If it is true that it is cheaper to save than supply energy (in general) then the attention given to demand reduction would have beneficial effects on the economics of energy in the UK. This effect would be direct, in that consumers would achieve the same standards at less cost, and indirect in that money would be available for investment elsewhere. Furthermore, the potential of earning foreign currency by the sale of indigenous fuels is enhanced with conservation. It is possible that the simpler techniques of efficiency or conservation will be adopted first in the world. This is because they offer a greater independence politically and are more appropriate for developing (and developed?) countries. An exclusive development of one or two supply technologies could put the UK at more risk and might also mean the UK would be treading a different course from much of the rest of the world. It is likely that very large export markets for efficient appliances and the like will develop. For example, domestic gas boilers efficient at low load were only recently manufactured in the UK, until now they were imported from France. It seems that condensing gas boilers, which approach maximum efficiency, have been developed in Holland, these will also be imported. To date no thorough work has been done on such economic implications of high or low energy systems, although it is a frequent criticism of the latter.

There are also political implications of energy systems; domestic and international. Firstly, low energy systems based on indigenous finite or renewable fuels are more secure from political events (e.g. war in the middle east) and from supply cartels (whether for oil or some other fuel). Secondly, the types of change explored with DYPHEMO attempt to reduce the use of fossil and fissile fuels. The utilisation of fossil fuels causes complex long term changes in the atmosphere and hydrosphere; the full implications of which will not be understood for many years. It is interesting to note therefore the implications that certain technologies, and their waste products, have in limiting the the options of future policy.

5. CONCLUSIONS

5.1 Success of research

The overall aims of this research programme were given in section 1:4. These aims were to develop and test the model and illustrate its use with some applications. These aims have been realised and the research has produced interesting results. This chapter summarises the main limitations encountered and ideas for extensions to this research.

5.2 Limitations of DYPHEMO

5.2.1 Introduction

In general the accuracy of the model is limited in two ways: firstly by the lack of certain information such as demand data, and secondly by the necessarily restricted detail of the model itself. Further surveys and experimentation should make up for the lack of measured data. However the restricted detail of the model is due mainly to the aim of producing a realistic model of manageable proportions. The limitations are briefly summarised below, but in general the reader should refer to the relevant part of the text for particular points; for example the availability of wave data.

5.2.2 Inconsistent statistics

A major problem with this research has been the fact that statistical and other data sources are incompatible due to different definitions, details and assumptions or because they refer to different time periods. Dissimilar units are often used; this is acceptable provided the necessary conversion factors are given. It is hoped that this report is an advance towards a complete, consistent description of the energy system in a common set of units (S.I.).

5.2.3 Lack of technical data

Certain parts of the energy system lack good, detailed documentation. This particularly applies to the industrial and commercial sectors; especially with reference to the energy converters they use and the variety and exact nature of their demands. These sectors are obviously highly variegated in the tasks energy is used to perform. Furthermore the complexity of the present system will possibly be increased by the implementation of innovatory technologies, for some of which there is sparse experimental data. Existing technologies are often mass produed and hence the typical efficencies and other technical details assumed are hopefully not greatly in error. Supply technologies are centralised and particular types of equipment do not vary dramatically in their performance. Furthermore, the UK has a populace which presently shows predictable mass "energy behaviour" by dint of centralised mass communication and economic systems; therefore the average energy use patterns assumed should be fairly representative. It is possible that this assumption will be inappropriate some time in the future when social patterns may be very different.

5.2.4 Inherent bias of model

In general data on technologies and demands are collected and published by organistions and institutions having fairly orthodox aims and viewpoints. In particular, data is plentiful and accessible for energy supply but not for energy demand. Since the construction of the model has relied on this type of data it has inevitably developed an "orthodox" bias. This may not be objectionable; but it is worth noting as a problem which any such exercise will meet. Groups with very unconventional views do not get comparable funding and hence can not develop their own databases. This problem can be partly solved by using the model on a regional or metropolitan scale. But the acquisition of data on the performance some novel technologies or the reappraisal of old ones would need substantial funding. For example, local energy needs and small scale technologies are not assessed and developed to any degree because research and development monies are mostly controlled by bodies interested in large, centralised technologies. This does not mean their results are wrong, it means that certain parts of the energy system are neglected; particularly conservation and high efficiency user converters.

5.2.5 Lack of meteorological data

The climate varies both temporally and geographically. These variations affect the climate dependent demands and income sources. There are several areas of deficiency in these data; especially concerning wave data. Even if good data are available there is the problem of the geographical extension of the energy system, which is discussed below.

5.2.6 Geographical variations

In reality the UK energy system is spread over regions in which the climatic and social determinants of energy use differ. The model assumes the system to exist on the head of a pin as it were. None of the variables and parameters defining the system or the climate relate to geographical location. The values of certain meteorological variables are derived from data pertaining to specific geographical sites or regions, tidal and wave data being good examples. In particular the long term weighted average UK ambient temperature used in Energy Trends has been assumed. Whether this is adequate for the temperature sensitivity of the UK energy demand is something to be discussed. It would obviously be more accurate to combine several models accounting for any regional differences, but much more time consuming. It is likely that due to the non linearities in the response of the energy system (particularly space heating demand) to the climate that different results would arise if regionalised models were used. Some regional energy groups have initiated research into regional energy demand and supply (eg. the SW energy group,Exeter University; the Energy Centre ,Newcastle University).

5.2.7 Divided energy system

Due to the advanced state of centralisation of the UK energy system, energy supplies are distributed to meet highly diversified demands. This aspect is very important since the performance and control of the energy system would be very different if it were decomposed into several subsystems. Merit orders, peak loads and load factors are the kind of things which might change dramatically. Despite overall centralisation, there are difficulties as exemplified by the electricity system which is largely controlled by four operators (namely the Central Electricity Generating Board (CEGB), the South of Scotland Electricty Board (SSEB), the North of Scotland Hydro Electricity Board (NSHEB) and the Northern Ireland Electricity Services (NIES)). The SSEB and NSHEB operate the Scottish public electricity supply jointly. The other operators control systems which are not connected by high capacity transmission lines, and are therefore largely isolated. Such problems are dealt with in more detail in the appropriate part of the text, but in general the effect of England and Wales having a much larger combined population and energy demand than Scotland and Northern Ireland makes the assumption that the system is centralised largely justifiable. These comments apply to the gas (and other) supply systems too.

If the technical features of decentralised energy systems in the UK were to be examined a number of regional studies would be required because of the local needs of people , the regional resources and climate and the varying local social, economic and industrial structures.

5.2.8 Distribution and diversity of demand

The demands for useful energy are diverse in nature and numerous. To make this diversity susceptible to manipulation in the model many simplifying assumptions are required. For example, houses vary widely in terms of construction, size, use, heating system and so on. But the model assumes that an "average" construction and use pattern exists and further it assumes that each type of heater warms the same type of house. In fact the housing stock is varied in all these matters and there are correlations between the type of house and heating system; a large detached house is more likely to use gas central heating than a small intermediate flat. Such assumptions will probably cause errors which can only be discovered by comparison with measured energy flows. If they appear large refinements in the model will be made. Again, the problem of producing an accurate, yet manageable model must be noted.

5.2.9 Fuel substitution

The fuel industries sell their products under tariffs which partially reflect the marginal cost of production. Marginal cost is the addition to total cost attributable to the addition of one unit of output. Thus, to produce an extra unit of fuel at a certain level of production will cause increased costs due to increases in capital plant, labour, fuel purchased (by the industry) and so on. For this reason the marginal costs of producing gas, oil, coal and electricity are lower in the summer than the winter because the capacity requirements for production and distribution per unit sold are less. Thus in certain cases one can purchase a particular fuel more cheaply at times when other demand is low (e.g. off peak electricity). It also costs the fuel industries a certain amount to deliver fuels with a high reliability or security of supply. If a consumer allows the industry to interrupt the supply at short notice the cost is often less. Consumers will try to take advantage of these varying costs by using technologies which can be driven by more than one fuel type.

The changes in fuel use entailed by dual firing and interruptible supplies are fairly important (about 20 % of gas supply is interruptible, mostly to industry,Energy Manager,Vol 12,No 9,Nov,1979). To model these substitutions and interruptions as they occur at different times of year and day is beyond the scope of this work.

5.2.10 Non energy uses

Fossilised hydrocarbons are used in large quantities for non energy uses, although this demand is "only" about 7% of the use of fossil fuels for energy production. Obviously energy needs will compete with feedstock needs for these fossil (or other) hydrocarbons and feedstocks are therefore included. No attempt has been made to investigate feedstock needs in detail and it is therefore assumed that only coal, oil and gas are suitable, as has been the case historically. In principle it is possible to use biomass products as a source of hydrocarbons.

5.2.11 Imports and Exports

The model assumes that all the energy flows occur within the UK, with the exception of the importation of ores suitable for producing nuclear fuels. It is also assumed that no primary or secondary fuel is exported or imported.

5.2.12 Time periods

The model is presently intended for simulating system behaviour for periods of up to one year. Simulation for longer time periods would represent practical computing problems, but more importantly the energy implications of technical change would require attention. Problems such as the energy required at all stages in the fabrication of passive solar houses or nuclear power stations would probably require a physical input output model for their solution.

5.3 Further applications

The applications in this report cover the wide range of investigations possible with DYPHEMO in its present state of development.

There is an infinity of hypothetical systems one could examine with the model, so it is pointless to attempt a list. DYPHEMO has already been used for a first look at the integration of "mini CHP" schemes into the domestic part of the energy system. The effects of integrating wave and tidal machines into the electricity system and of introducing solar technologies into the domestic sector will be the subjects of forthcoming papers.

5.4 Further developments

The possibilities for developing DYPHEMO are as variegated as the imagination, but three main types of development come into my mind: development of the model technically, the inclusion of non-energy quantities and the application to energy policy making.

5.4.1 Refinements and extensions of the physical model

There are many technologies and details presently ignored in the physical modelling so far.

Some possible refinements and extensions are

(i) using real ambient energy source and climatic data from magnetic tapes.

(ii) increased analysis of the results such as calculating minimum storage requirements for a particular fuel.

(iii) detailing the housing stock (instead of having one house type).

(iv) including ambient energy sources in the industrial and commercial sectors.

(v) including other sources such as geothermal.

These are mentioned because futher development of DYPHEMO might include these changes.

There is also the possibility of integrating DYPHEMO with other physical models. DYPHEMO has been integrated with a model of dispersed aerogenerators developed by R. Lowe of the OUERG. This integration produces realistic results but no careful analysis of the results has yet taken place.

Finally, it might be of interest and use to chart the temperatures (as well as magnitudes) of the demands and supplies in more detail. Possibilites such as cascading, the use of "waste" heat from conversions and of atmospheric heat via heat pumps could thus be more readily assessed.

5.4.2 Increased domain of DYPHEMO

To date only physical energy processes have been modelled. It would be interesting to develop separate submodels, or modules, which would deal with non-physical or non-energy quantities. These possible extensions are mentioned in the text relating to the applications of DYPHEMO.

For example

(i) Labour requirements in the energy system (LABEMO ?).

(ii) Money requirements (MONEMO ?).

(iii) Water (or other resource) needs of the energy system (WATEMO ?).

(iv) Pollution resulting from the energy system (POLEMO ?).

It is of course easier to name a model than develop it. However it is possible that some simple accounting models of these aspects could be a very useful adjunct to DYPHEMO.

5.4.3 Using the model(s) for policy analysis

The ultimate aim of DYPHEMO (and other suggested models) is to facilitate the analysis of energy policy alternatives. There are many ways in which these models might be used to such an end

(i) Use the models to test energy scenarios for technological consistency. Assumptions concerning technologies and energy flows are input to DYPHEMO and the resultant simulation should indicate the technical feasibility of the system.

(ii) Use of them to construct scenarios. DYPHEMO is used to aid the "design" of an energy system. The other models suggested above would provide some information on other aspects.

(iii) Use the models in an energy policy "game". The participants in the game would represent the main factions in energy policy; consumers, Government, management, and labour and capital in the fuel industries. The game would serve as a forum in which these parties would negotiate and lobby for different policies. This process of negotiation would illustrate the many criteria which would have to be considered and the practical difficulties in generating a policy which would be acceptable to all parties.

APPENDIX 1. SOME THERMODYNAMICS

A1.1 Introduction

Phenomenonological thermodynamics is a physical theory of the behaviour of macroscopic systems in thermal equilibrium. It uses thermodynamic coordinates to define thermodynamic states. These take the form of intensive parameters (density, temperature etc.) and extensive parameters (mass, volume etc.). Of interest here is energy (E (J)) and temperature (T (K)) in an energy demand/supply system.

It is difficult to even give a general definition of energy, as Poincare (quoted from Hoffman, 1977) noted :

> " .... In every particular case we clearly see what energy is, and we can give it at least a provisory definition; but it is impossible to find a general definition of it. If we wish to enunciate the principle in all its generality and apply it to the universe, we see it vanish, so to speak, and nothing is left but this - there is something which remains constant....."

The laws of thermodynamics will be summarised and the main limits imposed by these laws on energy conversions in an energy system will be briefly described. The reader should refer to a comprehensive textbook on this subject for a proper detailed account of the physical theory (e.g. Hoffman, (1977); Abbott, Van Ness (1972)).

A1.2 The four laws

Law 0

> Two systems, each in thermal equilibrium with a third, are thereby in thermal equilibrium with each other. Equilibrium defines these systems as having the same

temperature (T (K)).

Law 1

If an isolated system is changed from state A to state B, then the amount of work (dW (J)) required is independent of the conversion path followed.

If the change is non-adiabatic, an amount of heat (dQ (J)) is transferred.

$$dQ = dU + dW$$

Law 2

The entropy (S (JK^{-1})) of any isolated system remains constant through reversible changes, and must increase through irreversible changes.

Law 3

There is a minimum temperature, called absolute zero (0 deg. K), which can not occur in any physical system.

A1.3 Conversions

The most important parameter in conversions is probably efficiency. There are two commonly used efficiencies; first law efficiency (η_1), and second law efficiency (η_2).

First law efficiency, η_1, is the most frequently used; it is a practical measure of the useful energy (Q_u) output from a device, divided by the defined energy input (Q_i).

$$\eta_1 = Q_u/Q_i$$

For example, a solar collector has an η_1 value of 0.33 if it delivers 1 MJ of useful heat from 3 MJ of incident solar energy. An electric heat pump delivers 3 MJ of useful energy whilst using 1 MJ of electrical energy and 2 MJ of atmospheric heat. If the atmospheric heat is included the η_1 is 1.0, if excluded η_1 is 3.0.

This η_1 efficiency is generally used because a measure of how much useful heat output can be obtained from a certain fuel input is desired. Unless a heat pump is used the η_1 efficiency is in the range 0.0 to 1.0. If all input and outputs are accounted for, $Q_u = Q_i$ and $\eta_1 = 1.0$.

In addition to this practical measure, it is desirable to know the best that can be done; what is the theoretical maximum efficiency? Given a certain quantity of chemical or heat energy as fuel input to the converter, and given a practically infinite reservoir of heat at ambient temperature, how much heat at a certain temperature can be produced? To answer this question requires thermodynamic analysis and some measure of the second law efficiency, η_2.

In the UK energy system the main interests are mechanical, chemical, nuclear and heat energy. It is desirable to know the theoretical constraints imposed on conversions from one form of energy to another. The matrix below maps out the possible conversions and the theoretical maximum efficiencies of those conversions.

FROM \TO	1	2	3	4	5	6	7	8
1 Elec	1	1	1	1	$\frac{T}{T-T_a}$	1	$\frac{T}{T-T_a}$	1
2 Kin:wind	0.59	1	0.59	0.59	$\frac{0.59T}{T-T_a}$	0.59	$\frac{0.59T}{T-T_a}$	1
:other	1	1	1	1	$\frac{T}{T-T_a}$	1	$\frac{T}{T-T_a}$	1
3 Gravity	1	1	1	1	$\frac{T}{T-T_a}$	1	$\frac{T}{T-T_a}$	1
4 Chemical	1	1	1	1	$\frac{T}{T-T_a}$	1	$\frac{T}{T-T_a}$	1
5 Black	$\frac{T-T_a}{T}$	$\frac{T-T_a}{T}$	$\frac{T-T_a}{T}$	$\frac{T-T_a}{T}$	1	$\frac{T-T_a}{T}$	1	$\frac{T-T_a}{T}$
6 E.M.	1	1	1	1	$\frac{T}{T-T_a}$	1	$\frac{T}{T-T_a}$	1
7 Heat	$\frac{T-T_a}{T}$	$\frac{T-T_a}{T}$	$\frac{T-T_a}{T}$	$\frac{T-T_a}{T}$	1	$\frac{T-T_a}{T}$	1	$\frac{T-T_a}{T}$
8 Nuclear	1	1	1	1	$\frac{T}{T-T_a}$	1	$\frac{T}{T-T_a}$	1

NOTES

Ki refers to kinetic energy.

Black refers to black body radiation.

E.M. refers to electromagnetic energy.

The efficiency of 1.0 quoted for a 77 converter (heat to heat) only applies if the input and output heats are at the same temperature. In general, if the converter transforms heat from a temperature T_i to a temperature T_o via a heat pump the maximum overall efficiency is:

$((T_i - T_a)/ T_a)\ (T_o/(T_o - T_a))$

The two bracketed expressions refer to the " motor " and heat pump efficiencies respectively.

In the above matrix, T (K) refers to the temperature of the heat output by the process and T_a (K) is the ambient temperature. Richard McBride is thanked for some of the advice and reasoning which led to this matrix.

It is not possible to detail the thermodynamics of all these conversions.

Conversions which do not involve heat cause increases in entropy that arises through disordering processes, such as friction or the emission of radiation. In many cases it is possible to reduce such losses to a very small proportion of energy throughput, as for example, the case of an electric motor (a 11 converter). The most important conversion in the UK is from chemical energy to heat energy. The heat energy is used to satisfy demands for the heating of buildings and water and materials in various processes. In general, this conversion of chemical to heat energy is done directly without interposing a heat pump. Therefore, in practice, the efficiency is theoretically limited to 1.0. Other considerations such as the cost of heat exchangers and the desire to avoid exhaust gas condensates further limit the efficiency to be less than about 0.8.

Perhaps the next most important conversions involve the extraction of work from heat with a heat engine and the pumping of heat from a low to a high temperature with work. It is possible to outline the thermodynamics of these conversions. In particular type 71 and 17 converters will be discussed. (Note: row numbers from the matrix are given first, thus a 71 converter transforms heat into electricity.) In the UK there are two common conversions involving heat and work; one is the production of mechanical work by allowing heat to flow from a high to a low temperature via a heat engine; the other is the use of work to pump heat from a low to a high temperature. The theoretical, best performance that may be obtained from these processes is estimated by the use of the Carnot cycle.

Let T_1 and T_2 be the high and low temperatures (deg. K) of the reservoirs between which the heat flows, and let dW be the amount of work input or output to the system and dQ be the amount of heat (J) that flows between the reservoirs.

A heat engine is a device for extracting work by allowing heat to flow from a high to a low temperature reservoir. The efficiency is as follows

Efficiency = work out/ heat in

$$= dW/dQ$$

Carnot cycle theory enables the efficiency to be expressed as

$$= (T_1 - T_2)/T_1$$

$$= 1 - T_2/T_1$$

This is the maximum efficiency theoretically attainable. The actual efficiency is usually about 50 % of the theoretical in practical machines. The equation shows that the higher the temperature the heat from the fuel is used (T_1) and the lower the temperature the heat is rejected to the atmosphere (T_2) the greater the efficiency will be.

A heat pump is a device into which we put work in order to take heat from a low temperature source at T_2 (such as the atmosphere) and output it a useful higher temperature T_1. The efficiency is as follows

Efficiency = heat delivered at T_1 / work put in

$$= dQ/dW$$

Carnot cycle theory tells us the efficiency is

$$= T_1/(T_1 - T_2)$$

Again, the practical limitations presently restrict the actual efficiency to about 40 or 50 % of the theoretical.

This brief survey of the thermodynamics relevant to energy modelling has shown some of the main contraints to the performance of energy technologies, particularly those which involve heat at some stage.

APPENDIX 2. USEFUL ENERGY DEMANDS

The general definition of useful demand is given in the main text. One must refer to the specific task and technology involved to estimate useful energy demands. Most of the demands fit reasonably well into three sectors: domestic, industrial and commercial. However, there seems to be a case for separating energy demands for transport and iron and steel. This latter is dealt with separately after commercial demands. A short discussion of the transport demands below will describe the rationale of their subsequent divisions and allocations to each of the main sectors of demand, namely domestic, industrial and commercial. Feedstock requirements are dealt with after iron and steel; although not an energy demand per se, it will be necessary to include them since they may compete for fossil resources.

Each section details the demand and will at least give a value for the annual useful energy demand (Q_u).

Transport demand

Transport demand will be divided into three parts: each part will be characterised by a different use pattern, type of use and motor. The useful energy demands for each part of the transport sectors are derived from the respective delivered energies and assumed motor efficiencies. This approach enables changes to be made in fuel requirements due to both improved efficiency and alterations of the useful demand by modifications of the construction and operation of the car, aircraft or ship. (e.g. by weight or drag reduction, or improved load factors). In this report the only electric vehicle considered is the car for domestic use.

The table below summarises the types of vehicle, the annual delivered energies and the sector to which they are assigned. The division of transport types is made by consideration of the dominant engine type (e.g. diesel or petrol motors).

Table A2.1 Transport fuel deliveries

SECTOR	VEHICLE	DELIV(PJ)
Domestic	Cars, taxis	656
Industrial	Buses	43
	M/cycles	7
	Rail	40
	Lorries	223
	Vans	118
	TOTAL	431
Commercial	Aircraft	186
	Ships	210
	TOTAL	396

(All figures from IIED (1979), p 134, 171)

Given this disaggregation and sectoral split of transport types and delivered demands; one can proceed to estimate the useful energy demands and their corresponding use patterns in the appropriate appendix.

A2.1 Domestic demands

Domestic demands are those demands for energy which arise from peoples' use of appliances in the home and their use of cars and taxis for transport. Food energy is ignored. It should be noted that the food input to the mouths of the UK populace is not small; it is of the order of 7300 MWth. [1]

The table below summarises the useful demands, efficiencies and fuel deliveries for the domestic sector in 1976 (from IIED, 1979).

---

[1] On page 26 of the Manual of Nutrition (1976, Ministry of Agriculture, Fisheries and Food, HMSO) typical energy requirements for different people are given. A male sedentary worker requires about 11.3 MJ/day, which is equivalent to an average 130 W. If this is approximately the UK average, the total UK populace would require $130(56.35)10^6$ = 7320 MW.

Table A2.2 Summary of domestic energy flows

Energy in PJ

	USEFUL	EFF	DELIV
Misc. elec(e)	104.0	1.00	104.0
Light (e)	2.34	0.13	18.0
Cooking (g)	7.7	0.11	70.6
(e)	6.5	0.20	32.6
Hot water (g)	69.6	0.55	126.5
(l)	1.7	0.30	5.6
(s)	53.9	0.40	110.0
(e)	53.9	0.69	78.2
Space heat(g)	215.8	0.52	415.0
(l)	90.2	0.60	150.3
(s)	135.0	0.39	342.9
(e)	78.9	0.91	86.2
Transport (l)	78.7	0.12	656.0
TOTALS			
Gas			612.0
Liq (ex tran)			146.0
Solid			453.0
Elec			319.0

Since the domestic use pattern is used for the determination of many demands it will be described directly below.

Domestic house use pattern ($U_h(t)$)

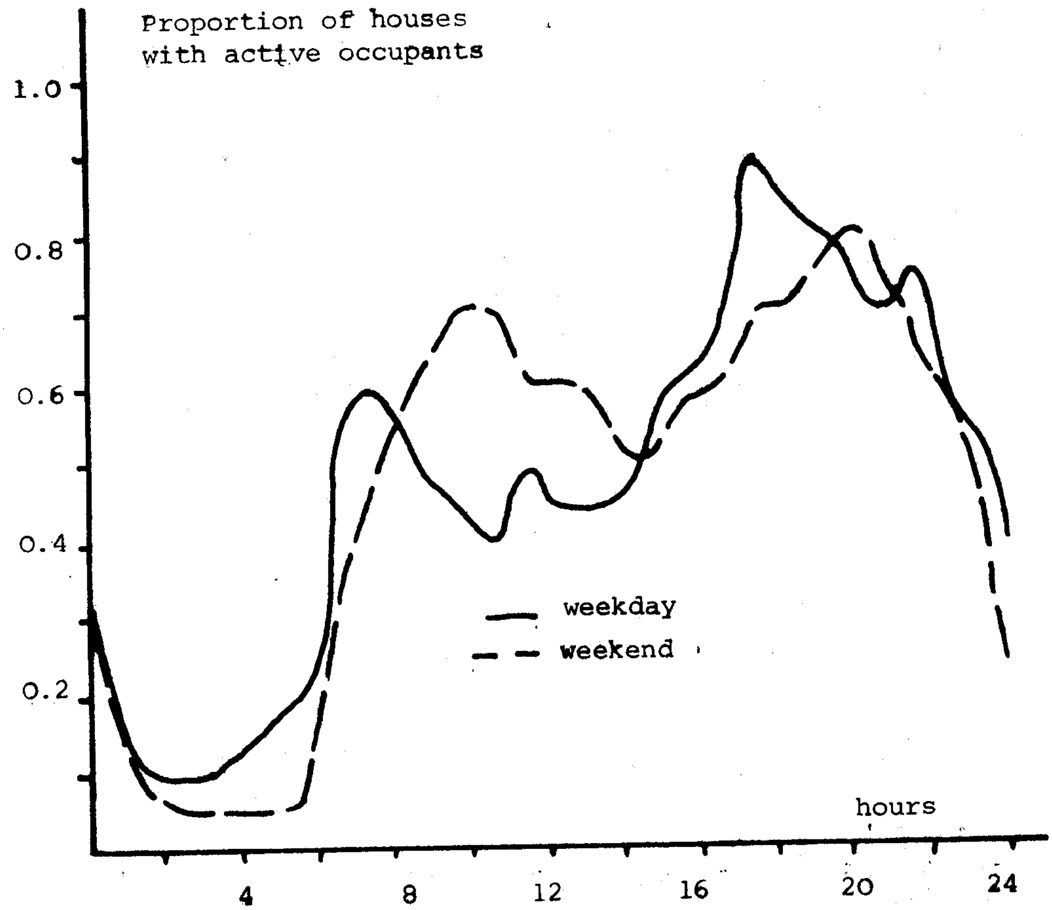
In order to estimate the temporal variation of energy use in the domestic sector various use patterns are required. The use patterns for cooking, hot water and transport are given in the sections below. The use pattern described here pertains to the need for space heating, lighting and energy from miscellaneous electric appliances such as kettles and televisions. This use pattern, called the domestic house use pattern ($U_h(t)$), is defined as the proportion of houses occupied by active tenants. This proportion is thus high in the evenings, lower during the day when some houses are left unoccupied because the inhabitants work, and lowest early in the morning when most are asleep.

Information on this domestic house use pattern is scarce. Surveys in this area have been limited for reasons of privacy, complexity and perhaps because there has been no reason to find out.

The use pattern is divided into weekday and weekend use patterns. The levels of occupancy are derived from a small group of people at the Open University and their parents and other indications of use patterns given by Desson (1976) and Monogue (1977). This data is of doubtful accuracy but it may be indirectly checked by comparison with load curves encountered in surveyed and measured houses. Further interesting information concerning peoples' use of their homes may be found in work by Field and Hedges (1977).

The graph below shows the assumed occupancy patterns.

Figure A2.1 Domestic house use pattern



Weekday

0.40 0.10 0.10 0.10 0.15 0.40 0.50 0.60 0.50 0.45 0.40 0.50
0.45 0.45 0.50 0.60 0.70 0.90 0.80 0.80 0.70 0.75 0.50 0.50

Average= 0.50

Weekend

0.25 0.10 0.05 0.05 0.05 0.05 0.30 0.50 0.60 0.70 0.70 0.60
0.60 0.55 0.50 0.60 0.60 0.70 0.70 0.80 0.80 0.70 0.60 0.30

Average= 0.5

The average occupancy is assumed to be 0.5.

A2.1.1 Transport

The useful power demand for the domestic car population may be estimated from the annual fuel use of the cars, the efficiency of the car traction and survey data detailing the use patterns. Thus the useful energy demand is:-

$$D(t) = P_m U_t(t) / 4.2 \qquad (W)$$

where $P_m = N_c P_{pm}$

N_c is the car population

P_{pm} is the average useful power per car.

The IIED (1979) estimate the population of cars to be 14.0 million. Given an efficiency of 0.12 and the total fuel consumption of 656 PJ/a the annual useful energy demand per car may be calculated (656(0.12)/14.0= 5.6 GJ). The average useful power per car is then easily calculated to be 178.3 W

Domestic transport use pattern ($U_t(t)$)

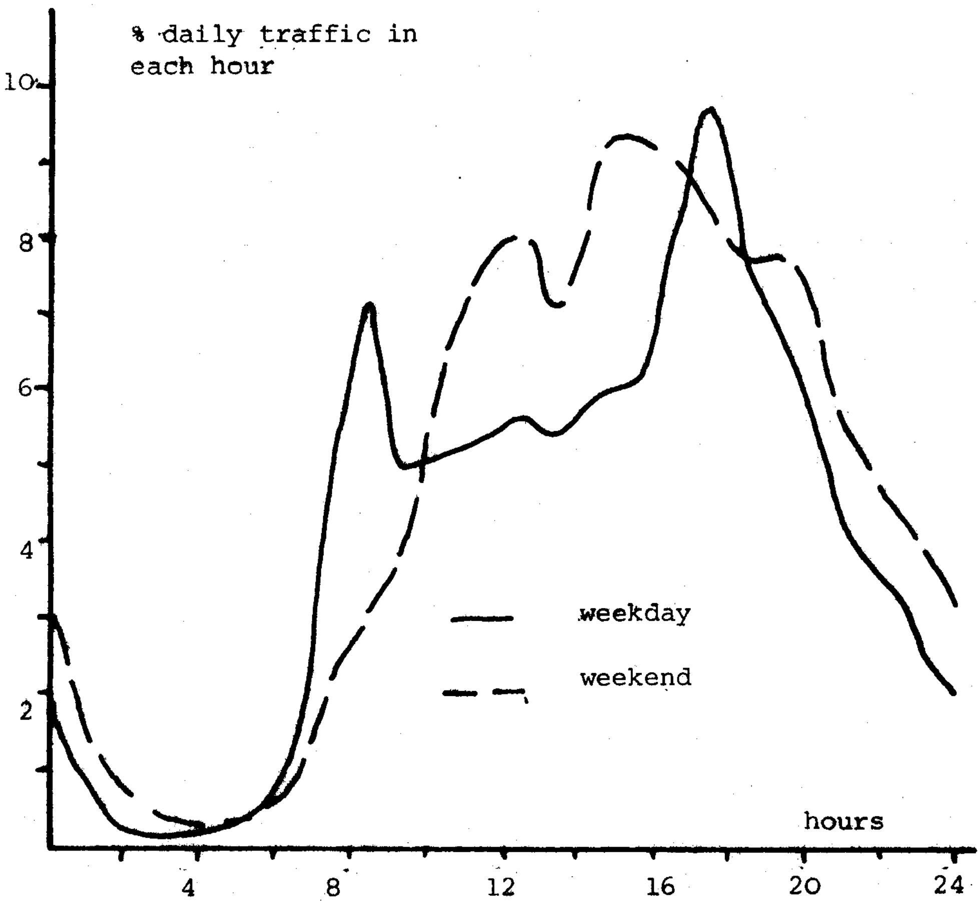
$U_t(t)$, the domestic transport use pattern is derived from the hourly and seasonal measured traffic flows reported by Dunn and Hutchings (1969). This use pattern may be decomposed into two patterns; one relating to the variation of flow during the week ($U_{tw}(t)$) and the other relating to seasonal variations ($U_{ts}(t)$).

The values comprising the use pattern $U_{tw}(t)$ are the percentages of the daily travel in kilometres for cars and taxis. The daily volume of traffic at weekends is about 5% higher than weekdays in February and 25% higher in August; an average of 15 % throughout the year has been assumed. It is of course possible to model the actual weekday/weekend variations more accurately. However this is deemed beyond the present level of detail. The hourly variations in car and taxi flows for weekdays and weekend are given by Dunn and Hutchings for various types of road. These data have been used to derive $U_{tw}(t)$.

Daily domestic transport pattern ($U_{tw}(t)$)

The graph below shows the diurnal domestic transport patterns. The numbers are the percentages of the total daily traffic.

Figure A2.2 Daily domestic transport patterns



The numbers are as follows.

Weekday

0.90 0.30 0.10 0.10 0.20 0.30 1.00 4.50 6.80 4.80 5.00 5.20
5.50 5.20 5.70 5.80 7.30 8.20 7.30 6.40 4.70 3.70 3.10 2.10

Weekend

2.30 1.00 0.60 0.30 0.30 0.40 0.90 2.20 3.00 4.10 6.30 7.50
8.00 7.10 9.10 9.40 9.00 8.30 7.70 7.80 6.60 5.10 4.30 3.60

Hourly average over whole week = 4.2

The seasonal variation, $U_{ts}(t)$, is defined by the fixed low point of traffic flow (in February) and the high point (in August) for car and taxi use. Data for this seasonal variation is given by the Transport and Road Research Laboratory. The variation is from a daily average of 280000 vehicle kilometres in February to 415000 in August (in 1968). This variation of about ± 20% from the average is assumed to occur sinusoidally through the year. The seasonal use pattern is thus

$$U_{ts}(t) = 1.0 + 0.2\sin(2\pi(m-5)/12)$$

where m is the number of the month (January being 1)

$U_{tw}(t)$ and $U_{ts}(t)$ may be combined to give $U_t(t)$; thus

$$U_t(t) = U_{tw}(t)\, U_{ts}(t)$$

The table below summarises domestic transport demand.

Table A2.3 Domestic transport demand

TRANSPORT	
	Liquid
Delivered(PJ/a)	656
Efficiency	0.12
Useful energy	78.7
Q_u/Y (MW)	2496

The total domestic useful transport demand is 78.7 PJ (=21861 GWh).

A2.1.2 Miscellaneous electric

The total annual demand for electricity for miscellaneous purposes domestically may be calculated from knowledge of the populations of the appliances and their average consumption. Due to the range of tasks performed by these appliances it is not appropriate to assume an average efficiency, although improvements in the efficiency of most appliances is feasible.

The total demand will be divided into a baseload component, consisting of fridges and freezers, and a varying component consisting of the other miscellaneous appliances.

The base load, E_{mb}, may be calculated as follows:-

$$E_{mb} = (n_1 E_1 + n_2 E_2)/Y \qquad \text{(W)}$$

where

n_1 is the number of freezers

E_1 is the electricity use of freezers

n_2 is the number of fridges

E_2 is the electricity use of fridges

Y is the number of seconds in a year

In 1976 there were about 2.535 million freezers and 16.38 million fridges with average annual electricity consumptions of 3.6 GJ and 1.17 GJ for each unit respectively (IIED, 1979). This implies a calculated value for E_{mb} of 897 MW.

The varying load is assumed to vary as the occupancy pattern of the house. The varying load, E_{mv}, is thus :-

$$E_{mv}(t) = P_m U_h(t) \qquad (W)$$

where $P_m = (n_3E_3+n_4E_4+.....)/ (\overline{U}_h(t)\ Y)$

The n's and E's refer to the populations and annual electrical energy consumptions of appliances such as T.V.'s, kettles, washing machines, irons and so on. The annual consumptions of these appliances and their respective average annual consumptions gives a total national annual electricity consumption of 75.7 PJ. (It is interesting to note that this implies an average electricity demand of 2.4 GW for these appliances). Since $\overline{U}_h(t)$ is 0.5, P_m has the value 4.8 GW.

Thus the total miscellaneous load at time t is:-

$$E_m(t) = E_{mb} + E_{mv}(t) \qquad (W)$$
$$= 897 + U_h(t)\ 4800\ (MW)$$

The table below summarises these demands.

Table A2.4 Miscellaneous domestic electricity demands

MISC. ELEC.	
Fridges, freezers	28.3 PJ/a
Q_u/Y (MW)	897
Other appliances	75.7 PJ/a
Q_u/Y (MW)	2400
Total	104 PJ/a
Total Q_u/Y	3297

The total miscellaneous electricity demand is 104.0 PJ (= 28888 GWh).

A2.1.3 Light

The demand for artificial visible light depends on the nature of the task involved (e.g. work, rest, sleep) and the traditional level of lighting as well as the building fenestration/orientation and the level of natural lighting at the task.

The demand for useful light is calculated thus:-

$$D_l(t) = D_l \, d(I) \, U_h(t) \, P \qquad \text{(MW)}$$

where

D_l is the maximum demand when $d(I)=1$

$d(I)$ is the darkness factor as a function of the

total global insolation, I (in Wm^{-2}). : $d(I)=1-I/900$

$U_h(t)$ is the house use pattern

P is the population of dwellings

D_l may be calculated by knowing the annual electricity use (E_l) and the efficiency of the lumieres (η_l). The average household uses about 0.925 GJ of electricity each year for lighting (or about 30 W on average).

$$D_l = El \, \eta_l / \int d(I) \, U_h(t) \, dt \qquad \text{(W)}$$

$$= 0.925(10^9) \, (0.13) / \, (0.36 \, Y) \qquad \text{(W)}$$

$$= 10.0 \qquad \text{(W)}$$

where Y is the number of seconds in a year.

This is the maximum; the average is 3.6 W.

The table below summarises domestic light demand.

Table A2.5 Domestic light demand

LIGHT	Elec
Delivered(PJ/a)	18.04
Efficiency	0.13
Useful (PJ/a)	2.34
Q_u/Y (MW)	74.3
Population (mill)	19.5

The efficiency of domestic lights is discussed in the relevant appendix on domestic converters. The total domestic useful light demand is 2.34 PJ (= 650 GWh).

A2.1.4 Cooking

The useful energy demand for cooking is very difficult to define. The actual energy used in heating food from room temperature to 100 or 200 deg. C and in causing low energy chemical changes is very small. Of course many cooking methods of the British kitchen (such as toasting or roasting) inevitably require more energy than simple heating up of the food.

Estimates of the efficiency of cookers are given in various sources, but the exact meaning and relevance of these values is obscure. If an electric cooker consumes 3.7 GJ per annum and has an efficiency of 0.2 (IIED, 1979) it will produce 0.74 GJ of useful energy. This in turn implies an average useful power (P_m) of 23.5 W; this is the average useful demand per household (cooker). If the population of households is P (millions) and the cooking demand pattern is $U_c(t)$ the total useful heat demand for cooking $D_c(t)$ is

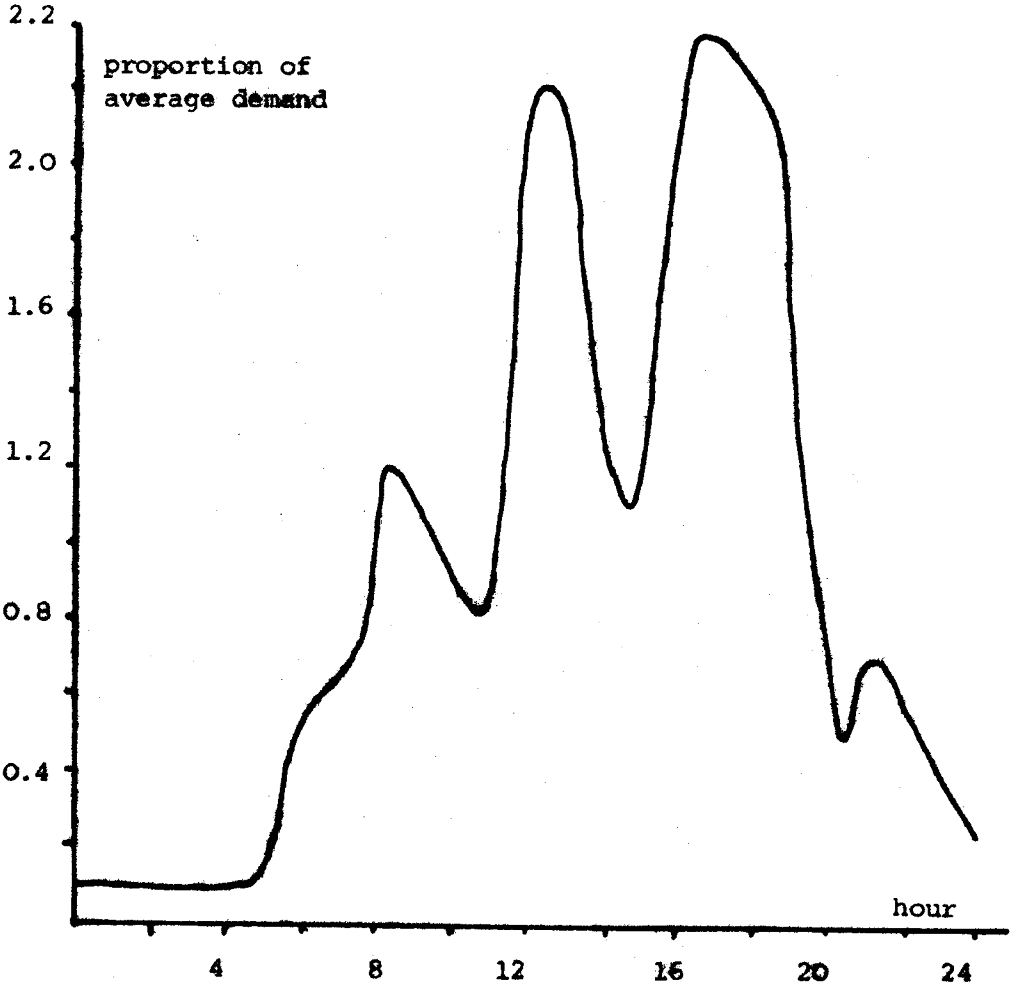
$$D_c(t) = P_m \; P \; U_c(t) \qquad \text{(MW)}$$

$$D_c(t) = 23.5 \; 19.5 \; U_c(t) \qquad \text{(MW)}$$

Domestic cooking pattern ($U_c(t)$)

The graph below shows the diurnal cooker use pattern.

Figure A2.3 Domestic cooking pattern



The numbers are

Weekdays and Weekends

0.10	0.10	0.10	0.10	0.20	0.40	0.70	0.90	1.20	1.00	0.80	1.70
2.20	1.70	1.20	1.80	2.40	2.30	2.10	1.10	0.50	0.70	0.50	0.30

Average = 1.0

This use pattern is derived from Addison and Wong (1976). It is likely that weekend and weekday patterns will be different, but it is difficult to find information on such variations.

The table summarises domestic cooking demand.

Table A2.6 Domestic cooking demand

COOKING			
	Gas	Elec	Total
Deliv. (PJ/a)	70.6	32.6	103.0
Efficiency	0.11	0.20	
Useful (PJ/a)	7.8	6.5	14.3
Q_u/Y (MW)	246.2	206.7	453.4
Pop. (M)	10.7	8.8	19.5

The total useful cooking demand is 14.3 PJ (= 3972 GWh)

A2.1.5 Hot water

The useful energy for hot water is defined as the heat required to raise the demand volume of water from the mains temperature (T_m) to the delivery temperature (T_d) at the tap. Note that the mains temperature varies seasonally. Given the daily demand volume for hot water (V_d) , the hot water use pattern ($U_w(t)$) and the population of consumers (P), the total demand for useful energy at time t ($D_w(t)$) is given by :

$$D_w(t) = K\ V_d\ /24\ (T_d - T_m)\ U_w(t)\ P \qquad (J)$$

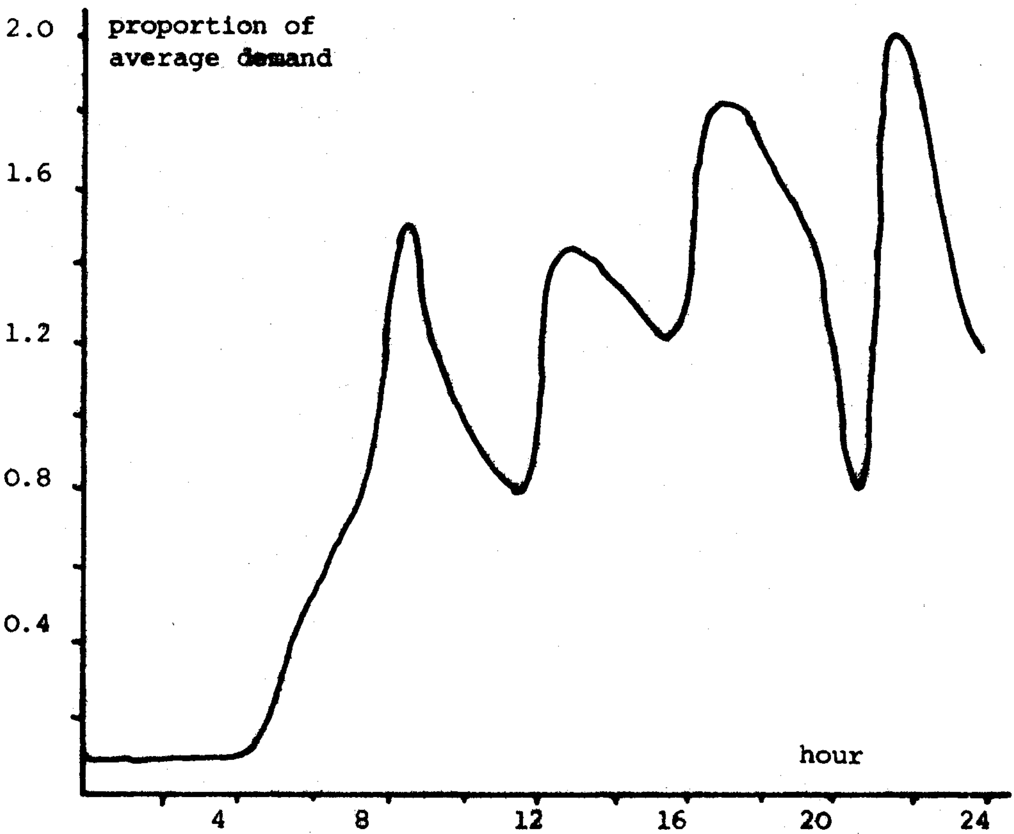
where K is the specific heat of water (4180 $Jkg^{-1}C^{-1}$)

Values for these variables are given below.

Domestic hot water use pattern ($U_w(t)$)

The graph below shows the diurnal hot water use pattern.

Figure A2.4 Domestic hot water use pattern



The numbers are

Weekdays and Weekends

0.10	0.10	0.10	0.10	0.15	0.40	0.60	0.80	1.50	1.10	0.90	0.80
1.40	1.40	1.30	1.20	1.80	1.80	1.60	1.40	0.80	2.00	1.60	1.20

This pattern is derived from Addison and Wong (1976).

The monthly mains water temperatures (T_m) are assumed to be as follows (after Courtney, 1977). Values in degrees Centigrade.

J	F	M	A	M	J	J	A	S	O	N	D
7.0	6.0	7.0	9.0	10.0	11.0	13.0	15.0	13.0	11.0	10.0	9.0

Daily hot water demand per house (V_d) = 126 litres.
Demand temperature (T_d) = 55 C

The table below summarises domestic hot water heating demand.

Table A2.7 Domestic hot water heating demand

Energy in PJ

	Gas	Liq	Sol	Elec	Tot
% Use	40.8	1.0	26.6	31.6	100
Pop	7.96	0.19	5.19	6.18	19.5
Use	69.6	1.7	45.3	53.9	170.5
Eff	0.55	0.3	0.49	0.69	
Deliv	126.5	5.6	110.0	78.2	320.0

The total domestic hot water demand is 170.3 PJ (= 47300 GWh).

A2.1.6 Space heating

The detailed calculation of the useful space heat energy of houses is not possible in this model. Indeed, the accuracy of house models is always poor because of the unpredictable ways in which occupants will use houses. The model will therefore use a simple steady state thermal representation of an average house with an average type of occupancy. This is fraught with inaccuracies, but more detailed research into the theoretical and experimental inadequacies is required. The major effect neglected in such a simple model is undoubtedly the omission of any considerations concerning the thermal mass of the house. In general this acts as a thermal flywheel for all the heat flows in the house and the net effect is to decouple the heat inputs and losses in time. Of particular importance is the role this thermal mass assumes when the house is being warmed up from cold. Since the walls and furniture have to be heated up a large output is required from the space heater, this output being determined by the past thermal history of the thermal mass and its physical characteristics. It is worth noting that computer models attempting to detail the flows of energy in " real houses" can be of a comparable size to the entire energy model developed for this report. In a zero thermal mass house the heat flows are more simply determined.

In addition to the problems of physical modelling are those relating to usage of houses. Field and Hedges (1977) provide some information on how many rooms are heated for how long in various types of house. In general people try to heat the room they are about to use; hence the whole house is not heated to the same temperature; hence the model is bound to be inaccurate. Furthermore, the efficacy of most heaters is such that the daily average house temperature falls as the external temperature falls (Romig, Leach, 1977).

These difficulties are overcome by calibrating this simple model with the measured results.

The instantaneous demand for useful energy of a house may be calculated thus:

$$ds(t) = ((\sum UA+V)(T_i-T_a(t))-F\ G(t)) \qquad (W)$$

where ds(t) is the useful demand for space heat

$\sum UA$ is the total fabric loss coefficient (WC^{-1})

V is the total ventilation loss coefficient (WC^{-1})

T_i is the average internal house temperature (deg. C)

$T_a(t)$ is the ambient air temperature (deg. C)

F is the incidental gain fudge factor [2]

$G(t)$ is the total incidental gain (W)

If it is assumed that all the population of houses (P) are the same and that the proportion of houses occupied is given by the use or occupancy pattern $U_h(t)$, the total demand $D_s(t)$ is given by:

$$D_s(t) = P\, U_h(t)\, ds(t) \qquad \text{(MW)}$$

The values for the variables in these equations are given below.

Leach and Romig (1977) give a disaggregated survey of the thermal properties of the UK housing stock. From this study an average fabric heat loss coefficient (UA) of 250 WC^{-1} can be estimated (15.2 million houses with 306 WC^{-1} and 4.3 million flats with 51 WC^{-1}). The average ventilation loss can be similarly calculated to be 97 WC^{-1} (15.2 million at 103 WC^{-1}, 4.3 million at 77 WC^{-1}). These values will be assumed but note the crudeness of modelling implied by lumping all the different house types together into one average figure. It may eventually be worthwhile accounting for the variation of the ventilation loss coefficient with climate since strong, cold winds could significantly contribute to peak loads. This effect would be proportionately more important in highly insulated houses. The fabric and ventilation loss coefficients can be combined to give the total or specific loss coefficient for the house (347 WC^{-1} in this case). It will be assumed to stay constant although of course drawing curtains or opening doors will influence the loss.

The average house comfort temperature (T_i) is the average house air temperature when the house is occupied. The average temperature over a day usually falls into the 14 C to 16 C range (IIED, 1979); but T_i, which refers to occupied periods only will of course be higher. Initially a value of 16.0 C will be assumed; although this might be altered in the light of

---

[2] The incidental gain fudge factor is the proportion of the useful energy demands for non space heating that is useful for space heating.

future available data.

The ambient air temperature ($T_a(t)$) at any time is either calculated or input from measured data .

The incidental gains (G(t)) are simply the sum of the domestic useful energy demands for non space heating purposes, with the obvious exception of transport demand. These are detailed in the text above. The usefulness of waste heat from these other uses for space heating obviously depends on the timing and location within the house of the incidental gain. For example, waste heat from cooking is often associated with hot, humid smelly air in the kitchen and is therefore not a great help for warming the lounge. A more accurate account of the effect of these gains is beyond the scope of this report despite the fact that they are very important in "low energy" houses. Incidental solar gains are not presently included although even for a standard randomly oriented house with typical glazing areas the the solar contribution is sometimes substantial.

The table below summarises the useful space heat demands in the domestic sector.

Table A2.8 Domestic space heat demands

Energy in PJ

	Gas	Liq	Sol	Elec
Use	215.8	90.2	135.0	78.4
Eff	0.52	0.60	0.39	0.91
Del	415.0	150.3	342.9	86.2

The total domestic net (of incidental gains) useful space heating demand is 509.4 PJ (=141500 GWh). This is an average of 26.1 GJ per dwelling.

A2.2 Industrial demands

A2.2.1 Introduction

The disaggregation of annual energy deliveried to the industrial sector (excluding iron and steel and non energy uses) for different uses has been tabulated by the IIED study (p 190); it represents an analysis and reporting of surveys conducted under the surveillance of ETSU, Harwell. Agriculture is included as a small industrial energy consumer. These figures for annual energy deliveries (Q_d) can be used in conjunction with notional average "efficiencies" (η) to calculate the useful energy demands (Q_u) for the different tasks in industry. Thus

$$Q_u = \eta \, Q_d \tag{J}$$

The diverse nature of individual energy use and the paucity of detail with respect to Q_d, and especially η, means that the Q_u calculated is of dubious accuracy. However values for η different and less than unity have been assumed so that any better future data may be used by the model. In the meantime the results the model will give for the delivered energy requirements will tally with those from the survey since the efficiencies used will be the same as those used to calculate Q_u. Most of these efficiencies are derived from the IIED (1979). There are problems in calculating the temperature of the useful energy demands supplied from converters. One main problem is that of cascading. Energy used for one purpose initially (e.g. lighting) may also be useful at a lower temperature (for space heating). Furthermore the utilisation of the output energy is often at a lower temperature than the converter was designed for. For example, a boiler which can produce heat at 300 C may have much of its output used at 90 C.

Given the calculated Q_u and an industrial use pattern ($U_i(t)$) the useful energy demand in any hour may be calculated,

$$D(t) = U_i(t)\, Q_u / Y \qquad \text{(MW)}$$

where Y is one year in gigaseconds and the average use factor

$(= (1/Y) \int (U_i(t)\, dt\ )$ is one.

The values of η and Q_d are given below in the appropriate section.

The table below summarises industrial energy demands, efficiencies and deliveries. All the values for the delivered energy are taken from table A.1, page 190 of IIED, 1979; except for transport and agriculture.

Table A2.9 Summary of industrial demands

All energy in PJ.

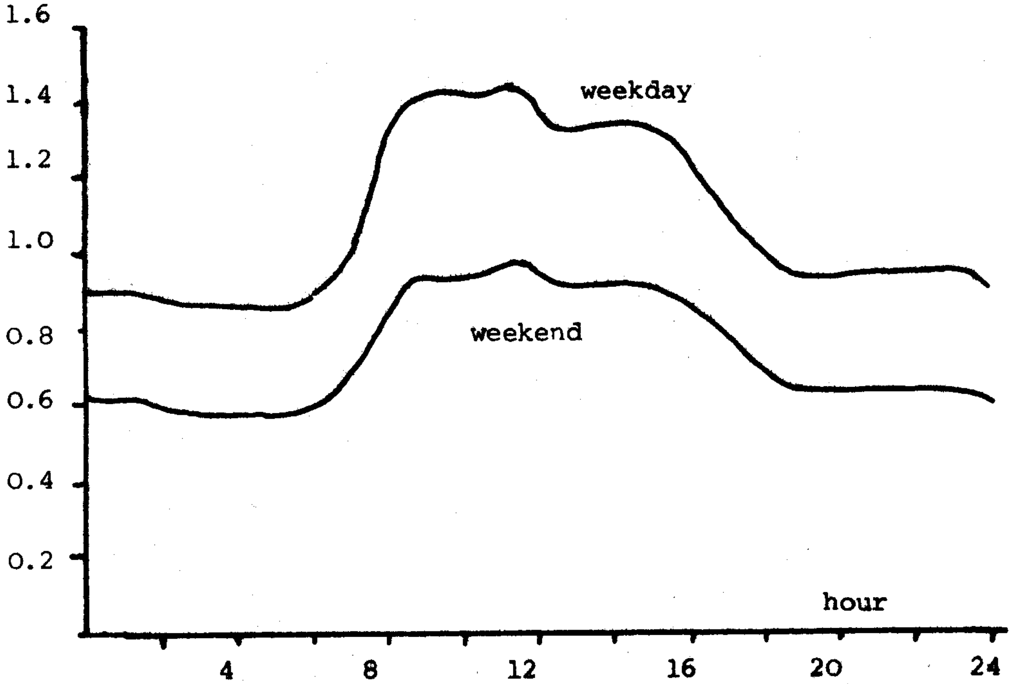
	Useful	Eff	Deliv
Kinetic(l)	16.6	0.17	97.6
(e)	72.1	0.35	205.0
Light (e)	12.0	0.4	29.9
HT heat(g)	96.8	0.6	161.4
(l)	92.5	0.6	154.2
(s)	61.6	0.6	102.6
(e)	55.6	1.0	55.6
(h)	72.6	1.0	72.6
LT heat(g)	69.5	0.6	115.9
(l)	119.2	0.6	200.6
(s)	29.4	0.6	49.0
(e)	4.5	1.0	4.5
(h)	95.4	1.0	95.4
H water(g)	195.0	0.6	32.5
(l)	55.9	0.6	93.1
(s)	11.1	0.6	18.5
(e)	3.5	1.0	3.5
(h)	20.5	1.0	20.5
Space (g)	19.5	0.6	32.5
(l)	55.9	0.6	93.1
(s)	11.1	0.6	18.5
(e)	3.5	1.0	3.5
(h)	20.5	1.0	20.5
Trans (l)	73.3	0.17	431.0

TOTALS	Non CHP	CHP	TOTAL
Gas	352.0	111.0	453.0
Liquid (ex tran)	637.0	203.0	842.0
Solid	189.0	62.0	251.0
Elec	260.9	42.0	302.9
Heat	0.0	209.0	209.0

All industrial demands follow the use pattern $U_i(t)$ except for transport. Industrial space heating and lighting are of course influenced by the climate as well as the use pattern. The function $U_i(t)$ assumed below is derived from the summer's day electricity load curves estimated by the Electricity Council for the industrial sector (kindly supplied by Dr. J. Rhys, April, 1980). Presumably the electricity load curve is a good indicator of the general energy activity level in industry, or at least as good as any other.

The figure below shows the diurnal industrial energy use pattern.

Figure A2.5 Industrial use pattern



The weekday average is assumed to be 10 % higher than the average and the weekend average 25 % lower than the week's average.

Midweek day

0.90	0.90	0.90	0.90	0.90	0.90	0.90	1.10	1.40	1.40	1.40	1.50
1.30	1.40	1.40	1.30	1.20	1.10	0.90	0.90	0.90	0.90	0.90	0.90

Average = 1.1

Weekend day

0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.80	0.90	1.00	1.00	1.00
0.90	0.90	0.90	0.90	0.80	0.70	0.60	0.60	0.60	0.60	0.60	0.60

Average = 0.75

A2.2.2 Transport

A general introduction to transport is given in the relevant appendix. The industrial sector of transport includes buses, motorcycles, trains, lorries and vans. The latter two types comprise about 75% of the total fuel demand in industrial transport and therefore will mostly determine the use pattern and efficiency.

The demand for useful energy in the industrial transport sector at any time ($D_t(t)$) is determined by the annual useful demand (Q_{ua}), the use pattern ($U_t(t)$), and Y, the number of seconds in a year, thus:

$$Q_u(t) = Q_{ua} \, Uit(t)/Y \qquad (W)$$

The efficiency of the motors used in this sector will be characteristic of that encountered in diesel engines and transmissions, namely 0.17.

The annual useful demand for this sector is simply the annual fuel delivered (431 PJ) times the efficiency (0.17); hence the annual useful demand is 73.3 PJ.

The temporal variation of industrial transport demand is small on a seasonal basis, but large diurnally and hebdomadally; much as shown by the analysis of Dunn and Hutchings (1969). Since vehicles powered by other than liquid or solid fuels are not considered this short term variation may be neglected, but note that the extensive use of electric rail transport would necessitate a detailed consideration of use pattern. Until a transport fuel that is difficult to store is used the use pattern ($U_t(t)$) is assumed to be constant 1.0.

Thus the useful energy demand above is evaluated simply:

$$D_t(t) = 2324 \qquad (MW)$$

for all t

The table below summarises industrial tranport demand.

Table A2.10 Industrial transport demand

TRANSPORT	
	OIL
Delivered(PJ/a)	431
Efficiency	0.17
Useful(PJ/a)	73.3
Q_u/y (MW)	2324

The total industrial useful tranport demand (mainly via diesels) is 73.3 PJ (= 20353 GWh).

A2.2.3 Kinetic

This sector of industrial demand includes all requirements in industry for mechanical power. The figures below give the deliveries of fuel to electric and oil motors providing mechanical power, both stationary motors and off road vehicles. Agricultural tractors (36 PJ oil) and general electricity use (13 PJ) are included as kinetic demand. This sector of demand follows the general industrial use pattern $U_i(t)$. The fuels delivered are oil and electricity, the table below summarises kinetic demands.

Table A2.11 Industrial kinetic demand

KINETIC		
	OIL	ELEC
Delivered (PJ)	97.6	205.9
Efficiency	0.17	0.35
Useful (PJ)	16.6	72.1
Q_u/Y (MW)	526	2285

The total industrial useful kinetic demand is 89.0 PJ (= 24700 GWh).

A2.2.4 Light

Industrial useful light demand will be calculated in much the same way as for the domestic sector. Lighting and other uses accounted for about 29.9 PJ of delivered industrial energy (IIED 1979). It is assumed that all of this 29.9 PJ is for lighting. Assuming an efficiency of 0.4 (fluorescent light) one can estimate that 12.0 PJ of useful light is demanded. One can estimate that if the number of industrial workers is P (10.5 million) and the average value of ($U_i(t)$ d(I)) is 0.3 that the average maximum power is 70 W. The demand for industrial light $D_l(t)$ in any hour is then given by:

$$D_l(t) = P_m \; P \; d(I) \; U_i(t) \qquad \text{(MW)}$$

$$D_l(t) = 70 \; 10.5 \; d(I) \; U_i(t) \qquad \text{(MW)}$$

The table below summarises industrial light demand.

Table A2.12 Industrial light demand

LIGHT	
	ELEC
Deliv. (PJ)	29.9
Efficiency	0.4
Useful (PJ)	12.0
Q_u/Y (MW)	381

The total industrial useful light demand is 12.0 PJ (=3333 GWh).

A2.2.5 High temperature process heat

These figures for delivered energy are for all direct fired processes and those operating via steam and producing heat at a temperature greater than 120 C. This sector of demand follows the use pattern $U_i(t)$.

The table below summarises industrial high temperature heat demand.

Table A2.13 Industrial high temperature heat demand

HIGH T HEAT	SOLID	LIQUID	GAS	ELEC.	HEAT
Delivered (PJ)	102.6	154.6	161.4	55.6	72.6
Efficiency	0.6	0.6	0.6	1.0	1.0
Useful (PJ)	61.6	92.8	96.8	55.6	72.6
Q_u/Y(MW)	1952	2941	3071	1763	2302

The total industrial high temperature useful heat demand is 379.3 PJ, (= 105374 GWh). Heat is provided from CHP plant at 55 % efficiency; 16 % of the heat coming from coal, 54 % from oil and 30 % from gas. This gives Q_u/Y values of 368, 1243 and 691 MW respectively.

A2.2.6 Low temperature process heat

The figures for delivered energy are for process energy delivered via steam at a temperature less than 120 C. This demand includes liquid fuels (22 PJ) used for heating in agriculture.

The table below summarises industrial low temperature heat.

Table A2.14 Industrial low temperature heat demand

LOW T HEAT	SOLID	LIQUID	GAS	ELEC.	HEAT
Delivered (PJ)	49.0	200.6	115.9	4.5	95.4
Efficiency	0.6	0.6	0.6	1.0	1.0
Useful(PJ)	29.4	120.4	69.5	4.5	95.4
Q_u/Y (MW)	932	3817	2205	143	3025

The Q_u/Y values are 484, 1634 and 907 MW for coal, oil and gas CHP respectively. The total industrial low temperature useful heat demand is 319.0 PJ, (= 88669 GWh).

A2.2.7 Space and hot water heat

Space and water heating account for roughly 15% of industrial energy use (i.e. of energy delivered). However this percentage ranges from 2% in the iron and steel industry (where it will be omitted) to 36% in the engineering and other metal trades. Unfortunately, the delivered energy consumption for space and hot water heating are aggregated. Since the temporal variation of space heat demand has important system effects, space and water heating should be modelled independently. It will be assumed that each component (space and water heating) constitutes 50 % of the delivered energy. There is no justification for this assumption.

Space heating will be calculated by the same method used for the domestic sector. The demand for space heat ($D_s(t)$ is a function of the incidental gains ($G_i(t)$), the fudge factor (F), the internal (T_i) and external (T_a) temperatures, the average fabric loss and ventilation loss coeffcients (UA and V respectively), the number of people (P) , and the industrial use pattern $U_i(t)$, thus

$$D_s(t) = P\,U_i(t)\,[\,(UA+V)\,(T_i-T_a(t)) - F\,G_i(t)] \qquad (MW)$$

$G_i(t)$ is the sum of the useful energy demands in industry for process and lighting purposes. The actual waste heat evolved by these processes will of course be larger than the useful energy demand since the converters are not 100 % efficient. This, coupled with the heterogeneity of industrial space heating makes an assessment of the contribution of these free heat gains to space heating difficult. G(t) is therefore multiplied by an effectiveness or fudge factor F. This will be adjusted until the calculated net space heat demand accords with measured data. The problem with this fudging is that if the useful space heat demand calculated disagrees with "reality", one can not know which of the six determinants of the demand are incorrect. This problem is common to all space heat demands and only independent surveying of the determinants will solve it.

$U_i(t)$ is the industrial use pattern.

The temperature that the average industrial premises is kept at, T_i, is initially assumed to be 16.5 C. This will in fact vary widely.

In 1976 there were about 10.5 million people working in the industrial sector.

The total fabric and ventilation losses per worker, UA and V, are set to 65.0 WC^{-1} and 75.0 WC^{-1} respectively. These are guesses, the author can find no reference to average values for industrial premises.

Values for delivered energy for space or water heating are given below. They are each one half of the total for these uses (p 190, IIED, 1979).

The table below summarises industrial space or water heating.

Table A2.15 Industrial space or water heating demand

SPACE OR H/W	SOLID	LIQUID	GAS	ELEC.	HEAT
Delivered (PJ)	18.5	93.1	32.5	3.5	20.5
Efficiency	0.6	0.6	0.6	1.0	1.0
Useful(PJ)	11.1	55.9	19.5	3.5	20.5
Q_u/Y(MW)	352	1771	618	97	650
% Space	10	50.5	17.6	3.2	18.5
Pop(mill)	1.05	5.31	1.85	0.33	1.95

Q_u/Y values for CHP heat are 104, 351 and 195 MW for coal, oil and gas respectively. The total industrial useful space or hot water demand is 110 PJ (= 30560 GWh).

A2.3 Commercial demands

A2.3.1 Introduction

Commercial demands are treated in exactly the same way as industrial demands, apart from space and water heating which is proportionately larger for this sector (about 75 % as opposed to 15 %). In addition space and water heating energy deliveries are separately measured. The tables below may be understood better if the introduction to industrial demands is read.

The data for this sector is taken from the pages 123 to 132 of the IIED study (1979). These data refer to the fuel use of the commercial and institutional sector in 1975. The innaccuracy caused by using a different year should not be too large since the system changes slowly and 1975 did not have obvious peculiarities such as a three day working week.

The table below summarises the demands, efficiencies and deliveries in the commercial sector.

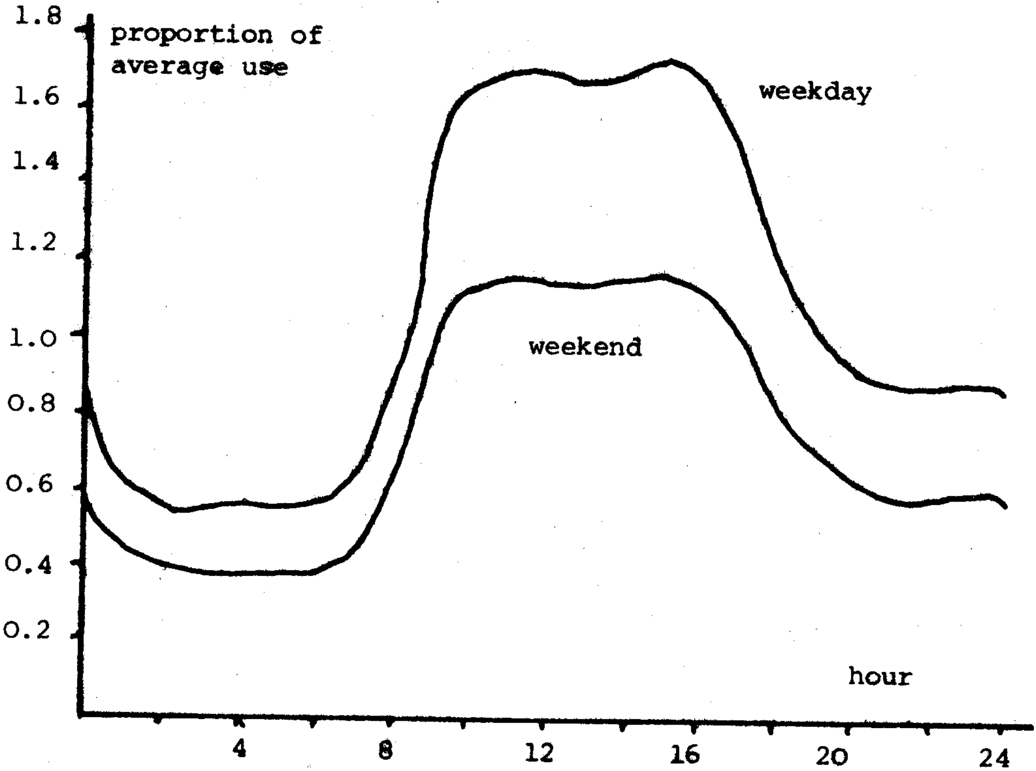
Table A2.16 Summary of commercial energy flows

		Useful	Eff	Deliv
Misc elec	(e)	33.0	1.0	33.0
Light	(e)	28.0	0.4	70.0
Cooking	(g)	8.8	0.2	44.0
	(l)	0.4	0.2	2.0
	(s)	0.4	0.2	2.0
	(e)	3.4	0.4	8.5
H water	(g)	18.0	0.6	30.0
	(l)	41.0	0.6	68.3
	(s)	8.8	0.6	14.7
	(e)	8.0	1.0	8.0
Space	(g)	41.2	0.6	68.7
	(l)	133.2	0.6	222.0
	(s)	34.2	0.6	57.0
	(e)	26.8	1.0	26.8
Trans	(l)	79.2	0.2	396.0
TOTALS				
Gas				146.0
Liquid				292.0
Solid				74.0
Elec				146.0

The commercial use or activity pattern ($U_c(t)$) is given below; it is derived from the summer day electricity load curves as is the industrial use pattern. Like this latter pattern, use levels are 10 % higher than average in weekdays and 25 % lower at weekends than the average.

The figure below shows the commercial diurnal use pattern.

Figure A2.6 Commercial use patterns



The numbers are

Midweek day

0.70	0.60	0.50	0.50	0.50	0.50	0.60	0.70	1.20	1.60	1.70	1.70
1.70	1.70	1.70	1.70	1.60	1.30	1.10	1.00	0.90	0.90	0.90	0.90

Average = 1.1

Weekend day

0.50	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.80	1.10	1.10	1.20
1.10	1.10	1.20	1.20	1.10	0.90	0.80	0.70	0.60	0.60	0.60	0.60

Average = 0.75

Average = 1.0

A2.3.2 Transport

The basic division of transport types is discussed in the appendix introducing domestic demands. The commercial sector of transport comprises aircraft and ships. The use pattern $U_{ct}(t))$ is assumed to be a constant 1.0, as for the industrial sector. The annual useful energy demand for this sector is derived from the assumed motor efficiency (η) and the annual fuel delivered (Q_d). The efficiency of aircraft and ships is assumed to be 0.2 on average.

$$Q_u = Q_d \, \eta \quad \text{(PJ)}$$
$$= 396 \; 0.2 \quad \text{(PJ)}$$
$$= 79.2 \quad \text{(PJ)}$$

The useful demand at any time ($D_t(t)$) is

$$D_t(t) = Q_u \,/Y \quad \text{(MW)}$$
$$= 2511 \quad \text{(MW)}$$

where Y is the number of gigaseconds in a year.

The table below summarises commercial transport demand.

Table A2.17 Commercial transport demand

TRANSPORT	
	OIL
Delivered (PJ)	396.0
Efficiency	0.2
Useful (PJ)	79.2
Q_u/Y (MW)	2511

The total commercial useful transport demand is 79.2 PJ (= 22017 GWh).

A2.3.3 Miscellaneous electric

The electricity delivered for miscellaneous purposes is found by assuming that it constitutes 33 PJ of the total 103 PJ used for miscellaneous and lighting (as on p 123, IIED, 1979). The table below summarises commercial miscellaneous electricity demand.

Table A2.18 Commercial miscellaneous electricity demand

MISC ELECTRIC	
Delivered (PJ)	33.0
Efficiency	1.0
Useful (PJ)	33.0
Q_u/Y (MW)	1046.0

The total commercial miscellaneous electricity demand is 33.0 PJ (= 9167 GWh).

A2.3.4 Light

Lighting is assumed to be 70.0 PJ of the 103 PJ delivered for lighting and other purposes (these include 1.9 PJ for the armed forces and 7.6 PJ for public lighting). This analysis is presented on page 123 (IIED, 1979). Commercial lumieres are assumed to be fluorescent tubes.

The demand for useful light in the commercial sector is calculated in the same way as for the domestic sector , except that the light demand per worker is estimated. The total useful light demand in the commercial sector $D_l(t)$ is

$$D_l(t) = D_l\ d(I)\ U_c(t)\ P \qquad \text{(MW)}$$

$U_c(t)$ and P (the number of people working in this sector) are given data. D_1 and d(I) are estimated as in the appendix on domestic lighting. The equation for $D_1(t)$ with values for D_1 and P is

$$D_1(t) = 80.0 \, d(I) \, U_c(t) \, 27.0 \qquad (MW)$$

The table below summarises commercial light demand.

Table A2.19 Commercial light demand

LIGHT	
	ELEC
Delivered (PJ)	70.0
Efficiency	0.4
Useful energy(PJ)	28.0
Q_u/Y (MW)	887

The total commercial useful light demand is 28.0 PJ (= 7778 GWh).

A2.3.5 Cooking (process)

The delivered energies are calculated from from figure 5.1, p 124 of the IIED study; these are summarised in the table below.

Table A2.20 Commercial cooking demand

COOKING				
	SOLID	LIQUID	GAS	ELEC.
Delivered (PJ)	2.0	2.0	44.0	8.5
Efficiency	0.2	0.2	0.2	0.4
Useful(PJ)	0.4	0.4	8.8	3.4
QU/Y	12.7	12.7	279.0	108.0

The total commercial useful process heat demand is 13.0 PJ (= 3611 GWh).

A2.3.6 Water heat

The table below summarises the deliveries, efficencies, useful energy demand and power for water heating in the commercial sector.

Table A2.21 Commercial hot water demand

HOT WATER	SOLID	LIQUID	GAS	ELEC.
Delivered	14.7	68.3	30.0	8.0
Efficiency	0.6	0.6	0.6	1.0
Useful(PJ)	8.8	41.0	18.0	8.0
Q_u/Y(MW)	280	1300	571	254

The total commercial useful water heat demand is 75.8 PJ (= 21065 GWh).

A2.3.7 Space heat

The commercial space heat demand is calculated in the same way as the industrial space heat requirement, except of course that the values of the parameters for the use pattern ($U_c(t)$), fabric and ventilation losses per person (UA and V), number of people (P) and the incidental heat gains in the commercial sector ($G_c(t)$) and the incidental fudge factor (F) are different. The free heat gains $G_c(t)$ are assumed to be the sum of the useful energy demands for the other uses, namely light, miscellaneous electric and process heat.

Initially UA and V are assumed to be 15.0.0 WC^{-1} and 35.0 WC^{-1} respectively, T_i is assumed to be 17.0 and the fudge factor F is 0.4. In 1976 there were about 27 million people using commercial and institutional buildings.

The commercial space heat demand $D_s(t)$ is calculated by the equation below.

$$D_s(t) = P\ U_c(t)\ (S\ (T_i - T_a) - F\ G_c(t)) \qquad \text{(MW)}$$

$$= 27.0\ U_c(t)\ 100.0\ (17.0 - T_a) - 1.0\ G_c(t)) \qquad \text{(MW)}$$

The table below summarises the data for space heat provision in the commercial sector.

Table A2.22 Commercial space heat demand

SPACE	SOLID	LIQUID	GAS	ELEC.
Delivered	57.0	222.0	68.7	26.8
Efficiency	0.6	0.6	0.6	1.0
Useful(PJ)	34.2	133.2	41.2	26.8
% Space	15	57	18	10
Pop(mill)	4.05	15.39	4.86	2.27

The total commercial space heat demand is 235.4 PJ (=65388 GWh).

A2.4 Iron and steel demands

The demands for delivered fuel in this industry are taken from page 51 of the IIED study. The efficiencies assumed in the estimation of the useful energy demands are estimated from data given by R. E. Critoph (1976). In his thesis he estimates the energy savings for each of the fuel types; these savings can thus be thought as applying to maximum technically realisable efficiencies. These efficiencies would only be attained if the major aim of the industry were to be fuel economy. The demands for useful energy are the delivered energies multiplied by the corresponding efficiency.

The use pattern in the Iron and Steel industry arises from technical and economic causes. Many of the furnaces for producing iron and steel must be operated continuously for technical reasons and their very large capital cost means that they are operated almost continuously by shift workers. For these reasons the use pattern in this industry tends to be fairly constant, although maintenance, holiday periods, low demand and industrial action obviously affect the use level. The use pattern for this industry will thus be assumed to be 1.0 all the time.

The table below summarises iron and steel energy use.

Table A2.23 Iron and steel energy demands

IRON & STEEL				
	SOLID	LIQUID	GAS	ELEC.
Delivered	429.0	135.0	49.0	47.0
Efficiency	0.43	0.54	0.78	0.30
Useful(PJ)	184.5	72.9	38.2	14.1
Q_u/Y(MW)	5850	2312	1211	47

There is no disaggregation of these deliveries according to use in the model. The total iron and steel useful demand is 309.7 PJ (= 86028 GWh).

A2.5 Non energy uses

Fossilised hydrocarbons are used in large quantities for non energy uses, although this demand is "only" about 7% of the use of fossil fuels for energy production. Obviously energy needs will compete with feedstock needs for these fossil (or other) hydrocarbons and feedstocks are therefore included. However no attempt has been made to investigate feedstock needs in detail and it is therefore assumed that only coal, oil and gas are suitable, as has been the case historically. In principle it is possible to use other biomass products as a source of hydrocarbons. The IIED study was the basis for the assumed non-energy use assumed in the table below. It is not easy to assume an efficiency other than unity. This is because there is not a single well defined commodity (such as heat) that is required for feedstocks. The range of chemical products derived from petroleum, coal and natural gas is large. It is perhaps possible that an efficiency might be useful defined in certain, well defined processes, but generally it is not possible.

The table below summarises feedstock energy flows.

Table A2.24 Feedstock energy demands

FUEL	GAS	LIQUID	SOLID
Delivered(PJ)	97	469	5
Power (MW)	3076	14871	159

The total feedstock demand is 571.0 PJ (= 158609 GWh).

APPENDIX 3. CLIMATE AND INCOME SOURCES

A3.1 Ambient temperature

The ambient air temperature is used to calculate heat losses and the peformance of devices such as solar water heaters and air source heat pumps. Energy Trends (HMSO) uses a UK temperature which is a composite of temperatures in various parts of the country, each with a different weighting. It is simplest to use these monthly averages and vary them diurnally as described below. An approximation for the annual variation is also given. In the future some hourly measured data might be used.

[The function below is for completeness only since the average monthly temperatures are explicitly input at present. The average daily temperature in any month (m) is given by:

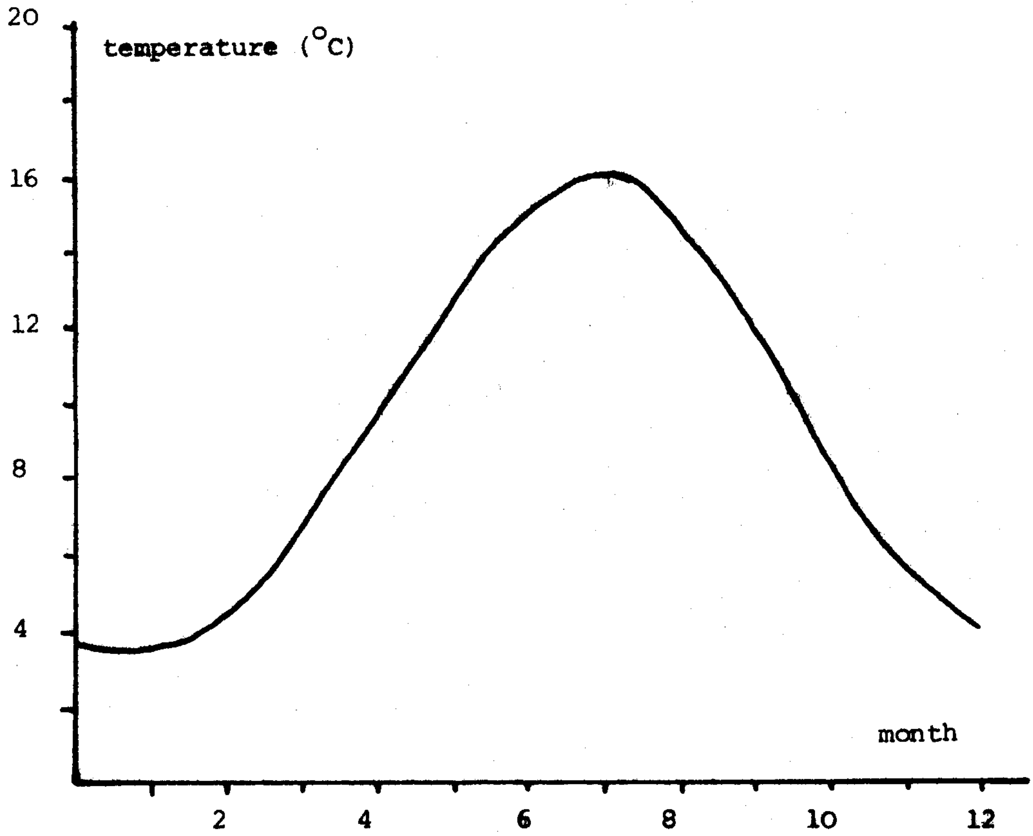
$$T_a(m) = 9.75 + 6.15 \cos(2 \pi m/12 + \pi) \text{ (C)]}$$

The average weighted monthly temperatures from Energy Trends (HMSO) are given below.

3.6 3.9 5.7 8.5 11.3 14.4 15.9 15.7 13.7 10.8 6.8 4.7 (C)

The graph below depicts this temperature variation.

Figure A3.1 Average monthly ambient temperatures



The average monthly temperature is modified through each day such that the temperature in any hour (h) is

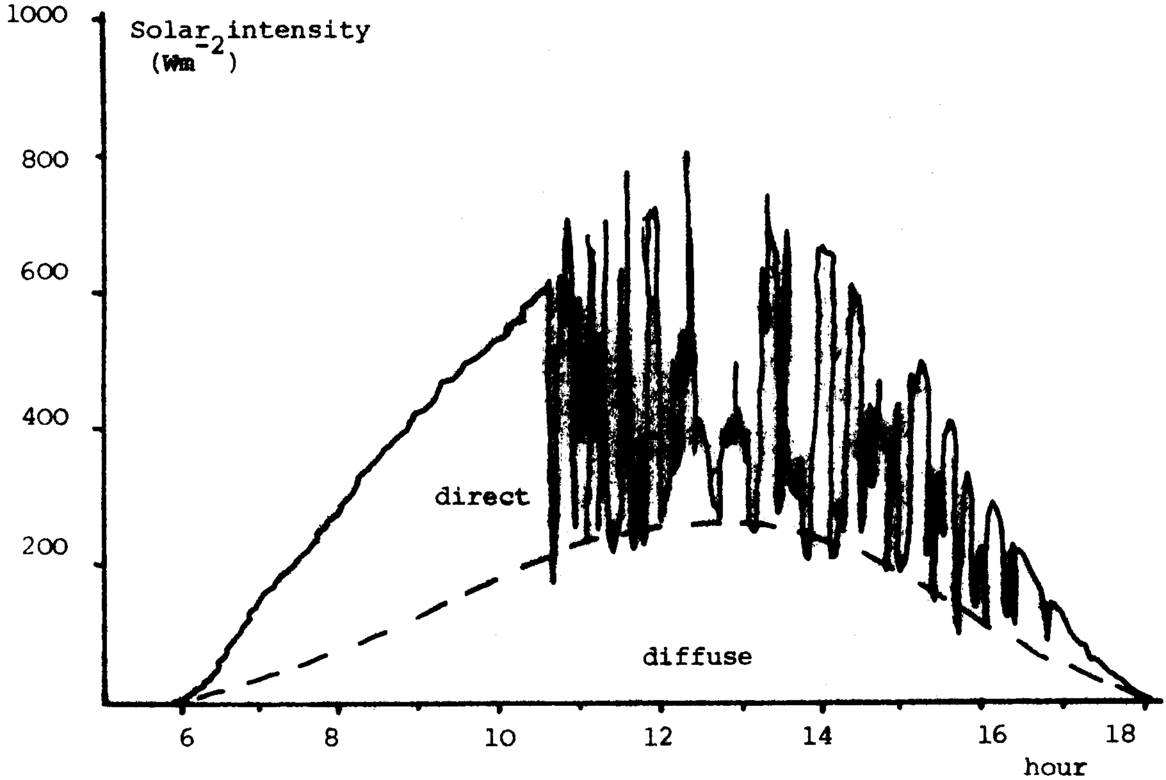
$$T_a(h) = T_a(m) \, [1.0 + 0.5 \cos(\pi + 2\pi(h-2)/24)] \qquad \text{(C)}$$

Obviously the temperature will vary beyond these values in exceptional weather. Since such times tend to determine the maximum loads encountered it may be necessary to amend the equations above to incorporate larger variations.

A3.2 Solar energy

The most comprehensive recordings of solar energy (or terrestial solar energy) available in the UK are the hourly average intensities of diffuse and direct radiation as measured at various meteorological stations. The Meteorological Office has these data recorded on magnetic tapes. Diffuse radiation is measured on a horizontal surface and direct radiation is measured in a plane perpendicular to the direct solar beam. These averages over an hour conceal considerable variations in the instantaneous radiation which normally occur within an hour. A typical continuous recording of the radiation intensity as measured at Garston (at the BRE) is given below from which it may be seen that variations of plus or minus 50% from the mean intensity with a frequency of 10 per hour are possible. The shape of the curve may be crudely analysed as consisting of a bell shaped function, representing the diffuse radiation intensity through the day, with a rapidly varying function representing direct radiation added to it.

Figure A3.2 A day's solar radiation



The variations in the direct radiation intensity are caused by clouds intermittently obscuring the sun.

In addition there is an absence of continuous measurements of the changing spectrum and directional distribution of radiation. Some attempts have been made to provide a model of the radiation spectrum which use input parameters such as the humidity, air mass and turbidity; although such models require corroboration through long term meteorological measurement and are generally rather complex (see Thaekaekera, 1965). It is an over simplification to describe radiation as comprising diffuse radiation of equal intensity from all directions above the horizontal (i.e. isotropic) and direct radiation which is emitted purely from the solar disc, as viewed at the earth's surface. In reality, the distribution of diffuse radiation is non-uniform over the sky hemisphere and some author's use 'augmented' radiation to describe the direct radiation which includes the radiation incident from the proximity of the solar disc (see

Loudon). These aspects of radiation modelling require further discussion if collectors are used which have a low thermal mass, or are directionally very sensitive, or have thermal properties which vary with the radiation spectrum. Fortunately most collectors likely to be used in the UK are not sensitive in these ways.

It is important to realise the variations of radiation which occur over time periods of either 10 seconds or ten years. Drastic changes in the intensity, composition, diurnal duration and spectrum of radiation can occur owing to latitude, altitude and local meteorological conditions (including pollution). For example, the annual total radiation incident on a horizontal surface at Kew has averaged 30% less than that incident on the surrounding countryside owing to London's polluted air (Oke T. R.), although this discrepancy is now diminishing because of the effect of the Clean Air Act. However many urban environments at present suffer greater pollution which may reduce the annual total to less than 70% of that normally expected. Atmospheric pollution tends to preferentially absorb short wave radiation owing to photochemical reactions and increases the proportion of diffuse radiation because of Rayleigh scattering by airborne dust; both factors may affect the performance of solar collectors adversely.

Finally, the annual total radiation may vary by ± 10% from the mean so that some typical reference year should be chosen. The averge insolation over a number of years is used in this report.

This preamble has described some of the difficulties involved in dealing with solar radiation, and underline some of the simplifying assumptions used below.

A3.2.1 Availability of solar radiation

As mentioned above, there are records of the hourly direct and diffuse radiation for several sites in the UK. It is straightforward to use this data; it is simply read from the tape for each hour of simulated time. Long term solar data can be used to derive functions which generate the average solar radiation likely to occur at different times of the year and day.

The following functions are derived from analysis by Barrie Jones of the OUERG. The average daily insolation at Kew is

$$S_d(m) = 2720.0 + 1940\cos(\pi+2\pi m/12) \qquad (Whm^{-2}day^{-1})$$

where m is the number of the month.

If sunrise for the month is at R(m) hrs. the average radiation in any hour (h) is

$$S_h(h) = (S_d(m)/L(m))\ [1.0+\sin((h-r)/L(m))2\pi+1.57) \qquad (Wm^{-2})$$

where the daylength $L(m) = 2(12-R(m))$ hrs.

and $R(m) < H < 12+L(m)/2$

Since the performance of solar heaters is not linearly dependent on the insolation variations from this mean are important. A "wobbling" function will therefore be employed; its task is simply to vary the radiation by ± 30 % in alternate hours. Thus the actual radiation in any hour is

$$I(h) = S_h(h)\ [1 + 0.3\ (-1)^{(h-r)}] \qquad (Wm^{-2})$$

It will assumed that half of I(h) is direct and half is diffuse, i.e

$$I_{dif} = I_{dir} = I(h)/2 \qquad (Wm^{-2})$$

A3.2.2 Calculating the radiation incident on a surface

The objective is the calculation of the intensity of solar radiation falling on an arbitrarily oriented surface given the recorded direct and diffuse intensities.

If the surface is oriented with an angle of elevation W, an azimuthal angle X (measured clockwise from north), and angle of solar declination Y, at latitude 52 N, for that day.

The angle of incidence (measured from normal) V of the direct solar beam on the collector is given by (from Petherbridge).

$$V = \cos^{-1}[\sin(Y)\sin(Z)\cos(W)+\sin(Y)\cos(Z)\sin(W)\cos(X)$$
$$+\cos(Y)\cos(Z)\cos(W)\cos(0.26t)$$
$$-\cos(Y)\sin(Z)\cos(X)\cos(0.26t)$$
$$+\cos(Y)\sin(W)\sin(0.26t)]$$

where t is the time in hours from solar noon .

The solar declination Y for a particular day is given by:

$$Y = \sin^{-1}[0.398\sin(0.01721D+0.03447\sin(0.01721D)-1.4096]$$

where D is the number of the day in the year (January 1st is day 1).

Assuming that all the direct solar radiation comes from the sun's disc and that the diffuse radiation is isotropic, the radiation intensity falling on the surface is given by (from Petherbridge):-

$$I(W, X) = I_{dif}(1+\cos(W))/2+I_{dir}\cos(V)/\sin(H)+ 0.5\ r\ I_{dif}(1-\cos(W)) \qquad (Wm^{-2})$$

where I_{dif} is the diffuse on the horizontal (Wm^{-2})

I_{dir} is the direct beam radiation (Wm^{-2})

r is the ground reflectance

H, the solar elevation is given by

$$H = \sin^{-1}[\cos(Z)\cos(Y)\cos(0.26t)+\sin(Z)\sin(Y)]$$

(NB all angles expressed in radians)

A3.3 Wind energy

The model requires hourly values for the wind speed. These values may be derived from statistical data or from actual recorded hourly data. Wind speed is recorded at about 30 sites in the UK by the UK Meteorological Office; speeds are averaged over periods of one hour and are stored on magnetic tape. Wind speed is a function of the local meteorological conditions, the local geography (e.g. hills, trees) and the height above the ground. The wind speed can vary randomly over short intervals (i.e. gusting) and systematically over long periods; these latter variations can be analysed from historical records. Gusting can cause variation in the power output for a particular generator for short periods, but large, dispersed arrays of machines as considered here would smooth out this short term variation. However diurnal and seasonal variations are not so averaged. Wind speeds are on average higher in winter than in summer, a ratio of about 1:1.3 for typical windy sites. This is due to the changes in the large scale weather system in the UK locale. Diurnal variations are also systematic; the wind speed at 14:00 hrs. being on average about 25 % higher than at 24:00 hrs. This is due to solar heating.

These variations obviously influence the correlation between wind speed (and hence wind energy) and electricity demand. The seasonal variation in wind energy intensity roughly matches the seasonal variation in demand; but the diurnal variations are not so well matched. It should be noted that the energy in the wind varies according to the cube of the wind speed and hence the variations in the incident energy are 1:2.2 seasonally and 1:1.8 diurnally.

Initially statistical data will be used. The meteorological data used will be historical and for one site only. Eventually hourly recorded data will be used. Average historical data will smooth the aerogenerators' output as if they were geograpically dispersed; but how realistic this is is not yet known fully. Robert Lowe (and others such as Grylls (1978)) is examining this effect in his studies at the OUERG. His research so far indicates that wind power variations will be small over periods of less than 10 hours if the aerogenerators are dispersed geographically (Lowe, Alexander (1980)).

A3.3.1 Calculation of encountered wind speed

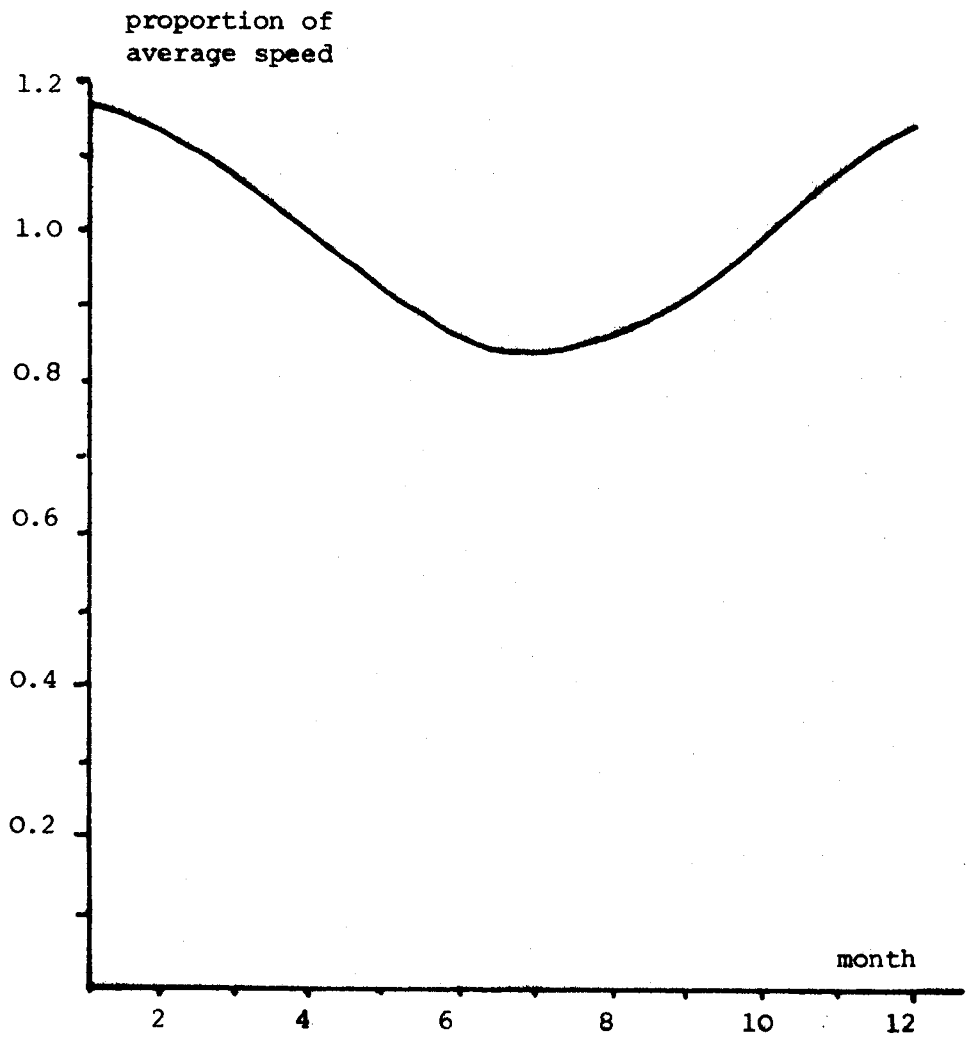
The annual variation in wind speed may be calculated knowing the annual distribution of wind energy (p11, EP21) for various sites. From these data the typical variation can be found so that the average wind speed for a particular month (V(m)) is known given the average annual wind speed (V_a).

$$V(m) = V_a \, (1+0.16\cos(0.5235\,(m-1))) \qquad (ms^{-1})$$

where m is the number of the month.

The graph below depicts the annual wind speed variation.

Figure A3.3 Annual wind speed variation



The average annual wind speed coincidently turns out to be

$$V_a = (E/(0.623\ Y))^{0.333} \qquad (ms^{-1})$$

where E is the annual incident energy (Jm^{-2})

and Y is the number of seconds in a year.

The wind speed will be calculated from the data for Shoeburyness , a high wind energy site (p11, EP21). This shows the variation of 1:2.2 in incident energy from July to January. This implies a variation in wind speed of 1:1.3. Since the average annual incident energy is 2.2 $MWhm^{-2}$, the average wind speed (V_a) is 7.4 ms^{-1}. The monthly average ($V_a(m)$) varies from about 6.4 ms^{-1} in July to 8.4 ms^{-1} in January. This variation may be approximated by:

$$V(m) = 7.4\ (1.0 + 0.16 \cos(0.523(m-1))) \qquad (ms^{-1})$$

where m is the number of the month.

(NB all angles in radians)

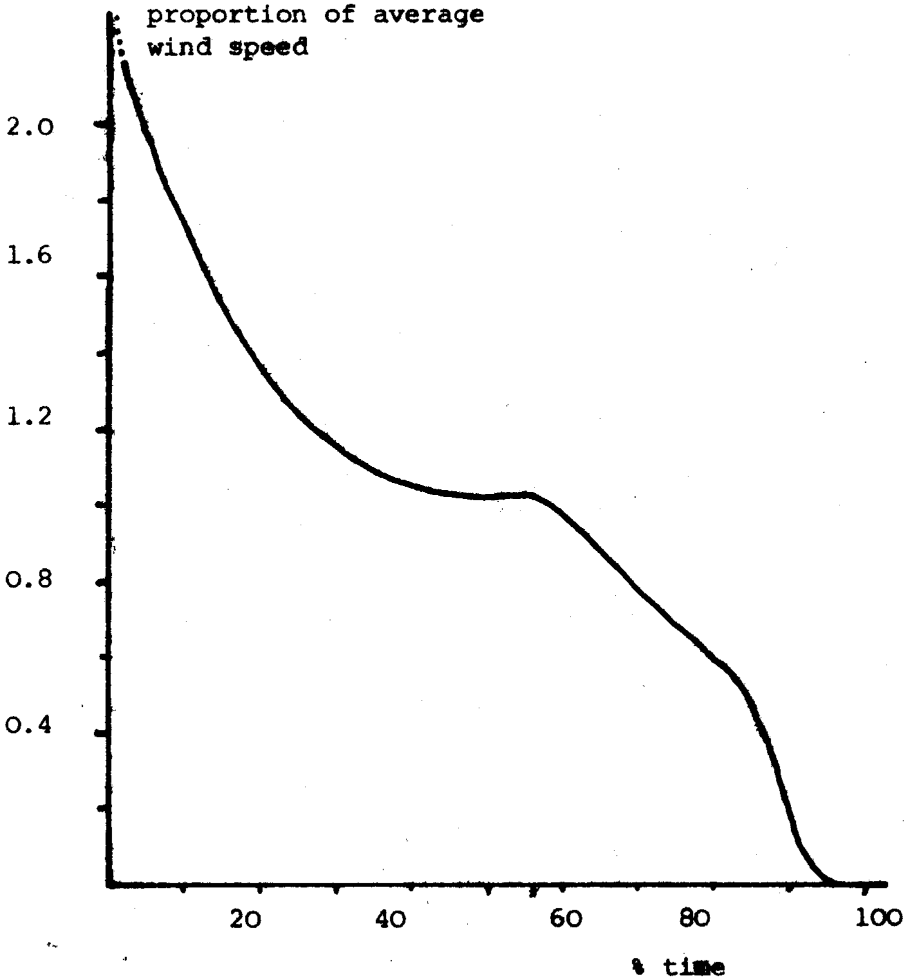
The diurnal variations may be simulated by multiplying the above function for $V_a(m)$ by a factor f(h) dependent on the hour of the day (h), to give the speed in any hour (V(h)):

$$V(h) = V_a(m)\ f(h) \qquad (ms^{-1})$$

where $f(h) = 1 + 0.125 \sin(0.262(h-8))$

The above equations establish average values for the wind speed; unfortunately the wind speed varies widely from these averages in "real time", from dead calm (about 10% of the time)to over 15 ms^{-1} (about 5 % of the time). These very large variations can cause large changes in the overall efficiency of the aerogenerator. The wind speed varies considerably from these long term averages V_a and $V_a(m)$. Analysis of the frequency of different wind speeds (see EP21) gives the following spectrum for the proportion (P) of the average wind speed occurring in any time interval (I) of 10% of the total time, thus

Figure A3.4 Wind speed spectrum



The variation in wind speed from the average can be simulated by simply multiplying the average wind speed by each of these proportions in each hour over ten hours. This obviously gives an unrealistic cyclical variation, but it is not a diurnal cycle and hence no spurious correlations with loads will occur.

In typical areas within a boundary surface layer of 280 m. thickness (flat open country) and 500m. (urban area) the mean wind speed increases approximately as follows (from IHVE, 1976) ;

$$V_2 = V_m \, (H_2/H_m)^a \qquad (ms-1)$$

where

V_2 is the wind speed at H_2

V_m is the recorded speed at H_m (=10 m.).

a = 0.143 (flat open) (this is assumed in the model)

= 0.286 (suburbs)

= 0.5 (towns)

This wind speed will be that assumed to drive the windmill, where the height H_2 is assumed to be the height of the hub of a horizontal axis machine. For a 23 m. radius machine (as considered in EP21) the hub of the machine would be at least 31 m. above the ground since 8 m. clearance of the blades is assumed; the wind speed at this height would be 1.176 times the speed encountered at 10 m.

A3.3.2 Calculation of wind intensity

The kinetic energy of a mass M of air moving at a speed V is given by

$$KE = 1/2\ M\ V^2 \qquad (J)$$

The intensity (or power density) of this wind may be calculated from the mass flow rate at speed V per unit area perpendicular to the wind direction. The mass flow rate per unit area is

$$F_m = D\ V \qquad (kg.s^{-1}m^{-2})$$

where D is the density of air.(=1.246 kgm^{-3} at 10 C and 1.012 bar)

If F_m is substituted for M in the equation above, we obtain the intensity of the wind, I_a, thus

$$I_a = 1/2\ D\ V\ V^2 \qquad (Wm^{-2})$$

$$I_a = 1/2\ D\ V^3 \qquad (Wm^{-2})$$

$$I_a = 0.623\ V^3 \qquad (Wm^{-2})$$

A3.4 Wave energy

The calculation of incident wave energy is dogged by two problems; the limited availability of measured data in terms of sites, recording periods and detail and the use of these data to estimate the actual incident energy.

Wave intensities vary with time and geographical location. Temporal variations are considerable over periods greater than a few hours; this variability is large diurnally, seasonally and, "unfortunately" inter annually. Thus even if good wave records were available for various sites in the reference year 1976 (which they are not) it is unlikely that these recorded intensities would be "typical". A dilemma is thus presented: short term "real time" records would enable the effects of short term variations to be examined but would not represent annual averages; or average data for several years could be employed which would be inadequate in a contrary way. Ultimately it might be best to use statistical data manipulated by random selection in the probability distributions of the wave conditions as analysed from records. Effects such as autocorrelation could be incorporated.

The physical coupling between wind and waves necessitates some correlation of their intensities (although it is not necessarily an instantaneous correlation); for example it may be found that powerful waves arrive about twenty hours after strong West winds. Such a correlation would have significant effects if electricity were derived from wave machines and aerogenerators. This coupling is being investigated, the wave conditions being calculated from wind conditions by "hindcasting" techniques. If such methods are proved reliable and relatively simple it would eliminate the need for acquiring great quantities of wave data, and historical wave records could be generated from the well recorded wind data. In the meantime it has been assumed that the wave heights and periods are influenced by the wind at some previous time, this is decribed below.

A3.4.1 Calculation of wave heights and periods

Actual waves are a complex superposition of wave heights and periods. Wave recordings do not usually measure the complete spectrum of incident waves. This does not usually lead to great errors since it is mostly the small, low power waves that are neglected. However, even the measurement of the significant waves show complex relationasips between height and period for different times of the year; these are often shown in scatter diagrams (see for example, Salter, 1978). However these diagrams do not show the actual spectra involved and there is no indication of direction. Waves through a sequence of intervals tend to show significant autocorrelation; this could obviously be an important feature with regard to power generation. D. Mollison, of Edinburgh University, amongst others, has analysed some of these relationships using statistical methods. It is unfortunately beyond the scope of this report to give an account of such an analysis.

The modelling of incident waves will take into account the type of wave machine assumed. The ducks have an efficiency function such that the mechanical power output is largely independent of the wave period and linearly dependent on the wave height; at least up to the torque limit.

At present there is some recorded wave data for certain sites in 1976, although the data is difficult to use. Until it is available in a simple form, the model will use average data from several years recording for the wave measurement site Station India, off to the NW of the Hebrides. This data has been analysed by Jardine and Latham (1979). They derive functions for the expected wave height through the year and also variances and autocorrelations. Given some correlating function between the wave height and wave period the wave energy may be estimated.

The annual variation in average wave height may be expressed analytically (after Jardine and Latham) as

$$H(m) = 4.04 + 1.16 \cos(0.52\ m) \qquad \text{(m)}$$

where m is the month number.

If it is assumed that the wave period is a constant 10 s. all year round one can calculate the intensity of the wave. For the type of machine considered here the wave period is not very important in terms of efficiency. The realisation that wave machines must be near the shore because of cost and practicalities makes the energy resulting from the above heights and periods too high - near shore intensities must be used. Harrison, Jenkins and Mortimer (1978) show that estimates of practically useful incident wave energy have almost halved over the past five years; a reduction from about 90 kWm^{-1} annual average to about 50 kWm^{-1}.

To allow for this decrease in near-shore intensities the intensities calculated from Jardine and Latham's analysis will be diminished by reducing the mean wave height from 4.04 to 3.0 and the height variation from 1.16 to 0.85.

$$H(t) = 3.0 + 0.85 \cos(0.52\ m) \qquad (m)$$

This gives an average power of 58 kWm^{-1}. However, a reasonably complete description of actual ocean waves awaits further analysis of their periods.

It would be relatively simple to incorporate a function which would randomly "wobble" these heights and periods according to some probability distribution (incuding autocorrelation) - this would be included in a future development of the model and would rely on future statistical analysis. Since the variations in wave power are so important to the system and the lack of variation would lead to an overestimate of the firm power available a simple method has been utilised. This uses the method of varying the wind speed (see above); except that the variations are smaller and lag behind the wind by some specifiable period of time, say five hours.

If the wave machines were geographically dispersed the total power availability would increase, although the energy output per metre of machine would probably diminish. This could improve the technical and economic performance of wave machines. This refinement, important as it is, is beyond the scope of this report and model.

A3.4.2 Calculation of incident wave intensity

The power density, or intensity, (I_w) of a monochromatic sinusoidal water wave may be calculated as follows. The specific mass (M) per metre wave front, of a half sinusoid above sea level is

$$M = D\ (W/2)\ (H_{tc}/(2\sqrt{2})) \qquad (kgm^{-1})$$

Where D is the density of sea water ($kg\ m^{-3}$)

W is the wavelength (m.)

H_{tc} is the height trough to crest (m.)

The centre of gravity of this half sinusoid falls from $H_{tc}/(4\sqrt{2})$ above sea level to the same distance below. Thus the change in potential energy of the wave during each cycle (E_p), when M falls through this height is

$$E_p = g\ D\ (W/2)\ ((H_{tc}/2\sqrt{2})^2) \qquad (Jm^{-1})$$

where g is gravity ($9.81\ m.s^{-2}$)

$$E_p = D\ W\ g\ (H_{tc}{}^2)\ /16 \qquad (Jm^{-1})$$

The frequency of gravity waves in deep water (F) is

$$F = (1/W)\ (g\ W/(2\ \pi))^{0.5} \qquad (Hz)$$

Hence the intensity of the wave is

$$I_w = F\ E_p$$

$$I_w = D\ g\ (H_{tc}^2)\ ((g\ W)^{0.5})\ /(16\ \sqrt{(2\ \pi)}) \qquad (Wm^{-1})$$

This equation for the incident wave intensity applies only to a regular sine wave at a deep sea site. It has to be modified to account for "random" seas which are neither monochromatic nor unidirectional. Furthermore the limited accuracy and extent of the measurements must be accounted for. Measurements of ocean wave height are often of the significant wave height (H_s), which is defined as the average height of the highest third of the waves measured in any particular sampling period (Edinburgh University, 1978).

H_{tc} in the equation above can be converted from H_s using the root mean square displacement, D_{rms}:

$$H_{tc} = 2\sqrt{2}\ D_{rms} \qquad (m.)$$

$$H_s = 4\ D_{rms} \qquad (m.)$$

$$H_{tc}^2 = (H_s^2)/2 \qquad (m.)$$

The wavelength W can be calculated from the measured zero crossing period (T_z), as follows:

$$W = (g/2\ \pi)\ T_z^2 \qquad (m)$$

Therefore the intensity (I_w) becomes

$$I_w = D\ (g^2)\ T_z\ (H_s^2)\ /(64\ \pi) \qquad (Wm^{-1})$$

(NB The author is indebted to S.H. Salter (1975) for this analysis, although the author accepts all responsibility for this presentation).

D. Mollison (1978) argues for the use of an energy period T_e for the calculation of wave intensities. He shows how a mixture of different waves each with different root mean square heights H_i and periods T_i define the energy period T_e, thus

$$T_e = \sum(T_i H_i^2)) / (H_{rms}^2) \qquad (s)$$

where $H_{rms}^2 = \sum (H_i^2)$

He then considers an infinite spectrum of waves and shows that

$$I_w = D g^2 H_{rms}^2 T_e /(4 \pi) \qquad (Wm^{-1})$$

and that if it is assumed that T_e is 15-20 % higher than the measured T_z, I_w is estimated as

$$I_w = 0.57 T_z H_s^2 \qquad (kWm^{-1})$$

where $H_s = 4 H_{rms}$ from the equation above

Mollison then proceeds to a discussion of the nature of the spectra of sea waves and their directionality. However such considerations are beyond the level of detail possible in this report. Therefore the equation above will be used to calculate the intensity of ocean waves. It is assumed that there is no alteration in the estimated intensity for reasons of directionality, or because the energy period T_e is not in fact 20% higher than T_z. The measured wave and wave machine data are limited to the extent that such alterations can not yet be estimated accurately anyway.

A3.5 Tidal energy

Energy may be extracted from the tides in two ways. Firstly by the direct conversion of the kinetic energy in tidal streams by a water mill of some kind, no storage being involved. Secondly, tidal streams may be used directly and to charge storage reservoirs with potential energy for later conversion to electricity. The former use is omitted and therefore the tidal height (rather than the tidal stream size and speed) may be used to calculate performance.

A3.5.1 Calculating the height of the tide

The height of the tide ($H_t(t)$) can be calculated for any particular hour at locations where some measurements have been taken of the harmonic constants characterising that location.

The height, $H_t(t)$, of the tide is calculated thus:

$$H_t(t) = \sum \{ H_i \cos(V_0 + S_i t - K_i) \} + H_{tmean} \qquad \text{(m)}$$

where

S_i is the angular velocity (rad/solar hour)

V_0 is the start angle (rad)

t is the time (solar hours)

H_i is the amplitude (m.)

K_i is the phase angle (rad.)

H_{tmean} is the mean tide height (m.)

V_0 and t are identical for all harmonic components ; but H_i, S_i and K_i have separate values for each component, these being measured for many tidal sites. The values of H_i are basically determined by the gravitational attraction between the astronomical bodies involved and the peculiarites of the basin in which the water mass is moving. S_i and K_i are angular velocities which determine the astronomical geometry with time.

For most sites four harmonic components are sufficient for our purposes, the amplitudes of the other components being negligible. The table below shows the values for these components at Cardiff, this being near the site of the proposed barrage of the scheme modelled here.

Table A3.1 Harmonic components of Cardiff tides

i	1	2	3	4
H_i(m)	4.09	1.42	0.094	0.067
S_i(r/hr)	0.50587	0.5236	0.2625	0.24335
K_i(r)	3.333	4.171	2.513	0.105

These values are taken from Lisitzin (1974).

Although these values enable the present high tides at Cardiff to be predicted some account should be made of the possible changes caused in the tides by a sizable tidal power scheme. A barrage would alter the resonant properties of the Severn basin; some studies have indicated that a small change in the flow impedance could cause relatively large changes in the tide heights.

It must be said that these calculations are not sufficient for design purposes since local meteorological conditions can have a considerable influence on the height of the tide. Thus, like most similar technologies the barrage would have to be designed to meet the worst conditions that can be envisaged.

Introduction

Little is known about many energy converters, particularly concerning details of their energy performance in real operating conditions. Often the regulation of converter performance (such as with British Standards) concentrates on other aspects (such as safety) or fails to set criteria which ensure efficient operation other than in a laboratory. For example, domestic gas boilers have to attain 70 % efficiency at full load. In practice, this figure is not very relevant since they are installed oversized and operated at part load. Thus the actual average operating efficiency is probably 55 % (for space heat) and 30 % for water heat. This must be compared with the potential efficiencies of 80 % and 95 % for non condensing and condensing boilers respectively.

Often the only information available is from manufacturers or by inference from regulations. Therefore I deem many of the efficiencies quoted here to be overestimates of actual efficiency; especially for industrial and commercial converters. The only solution to this problem is careful testing and surveying of converters in situ.

A4.1 Domestic converters

A4.1.1 Transport

(i) Petrol cars

Petrol cars are cars using relatively high octane petroleum in an electrically ignited internal combustion engine to produce work and heat. The mechanical output from the engine is transferred to the wheels via a transmission system where it is used to accelerate the car and overcome tyre friction and air resistance. The car is decelerated by converting its kinetic energy into heat by friction in the brakes. The heat generated by the engine, which is about 80% of the fuel input, is rejected through the exhaust and cooling system, which uses an air or water medium. Petrol for the car is stored in a petrol tank.

In 1976 the total population of cars was 14 million (IIED, 1979).

The efficiency of internal combustion engined cars is defined as the useful power produced at the wheels for overcoming tyre and air resistance and accelerating divided by the thermal content of the petrol consumed. Estimates vary, but an average figure, including all the losses incurred by idling, starting and so on, is 0.12. This figure, reported by the IIED (1979) was produced by the US Environmental Protection Agency. I have not yet found an equivalent analysis for UK cars.

(ii) Electric cars

These cars carry electrical energy stored in batteries which is converted by an electric motor into mechanical power which is in turn transferred to the wheels via a transmission system. It is in some respects analogous to a petrol car, in that the batteries are equivalent to the petrol tank. However unlike the petrol car, some of the kinetic energy of motion can be recuperated by generating electricity from the braking energy required; this is called regenerative braking. In addition the electric vehicle has no idling losses (some types of battery may however require small steady energy inputs). These features mean that its efficiency, the ratio of energy delivered to useful energy output, is much higher than for the petrol car (roughly five times better delivered to useful or 1.3 times better primary to useful). Electric vehicles can also use low grade fuel sources via power stations and use ambient sources of electricity. Pollution and noise in conurbations can be reduced.

The main problem to overcome in electric vehicles is their limited performance in terms of range and acceleration. It does appear that these limitations would not be too severe for most users and technical improvements may alleviate the problems. Many groups (such as the Lucas and Chloride battery manufacturers) are presently developing electric vehicles.

The bulk of the assumptions for the performance of electric vehicles has been taken from Chapman et al (1976). The variables defining the gross energy flows in electric vehicles are the efficiencies of battery charging and discharging (η_c), of the electric motor and transmission system (η_m), the average power of the motor (P_m), and the maximum energy capacity of the batteries (Q_{mb}) and the maximum input power (P_e) to each set of batteries. Note that the motor and transmission system efficiency includes savings due to regenerative braking.

The electrical energy put into the batteries in time t is

$$\Delta Qb = \eta_c \, P_e \, (1 - Q_b/Q_{mb}) \, t \qquad (J)$$

Note that the power input to the batteries increases as the charge level diminishes, and will only occur in times when other electricity demands are low. If the demand for useful power is P_d , the electricity drawn from the batteries in time t is

$$\Delta Qb = P_d \, t \, /(\eta_m \, \eta_d) \qquad (J)$$

These two simple equations model the performance of electric vehicles. The total electricity demand for battery charging is simply calculated if the number of cars is known; it is assumed that there are the same number of battery sets as cars. There are three major omissions in this model.

Firstly, there may be more sets of batteries than cars to enable battery charging when the cars is in use or immediate refuelling by battery exchange at the electrical equivalent of petrol filling stations. Secondly, it has been assumed that there are no energy losses from the batteries, which may not be the case if certain types of battery are used, such as high temperature sodium-sulphur batteries. Thirdly, the heating requirements for electric vehicles have been ignored; these may be sizeable.

The technical data assumed below are derived from work by Chapman et al (1976) and Considine (1977). The electrical capacity of the battery set assumed corresponds to perhaps 1 to 2 tonnes of battery. Roughly half of this set would be mounted in the car.

Efficiency battery (dis)charge (η_c) = 0.9

Efficiency of motor and transmission (η_m) = 0.8

Capacity of battery set (Q_{mb}) = 150 MJ

Max. power to each battery (P_e) = 2000 W

In my opinion it is likely that the best car/taxi option will be a light low drag hybrid diesel electric vehicle. Such a vehicle combines the desirable qualities of range, efficiency, regeneration, dual fuelling and environmental soundness. This technical appraisal does not account for social or other effects of such vehicles. Perhaps the main problem would be to achieve safety in a light vehicle sharing roads with vehicles sixty times its mass. Urban consumptions in excess of 150 m.p.g. are feasible.

A4.1.2 Miscellaneous electrical appliances

There is a demand for electricity to drive an assortment of domestic electrical appliances not used for heating or cooking: televisions, kettles, irons, curling tongs etc. are all included in this demand for miscellaneous electricity.

In general the appliances may be improved so that less electricity is used in the accomplishment of the same task. Thus for example, the power consumption of colour televisions has fallen from about 250 W to 125 W due to the use of more efficient electronic components. It is not meaningful to use a typical value for all the appliances and so the efficiency is arbitrarily assumed to be 1.0.

A4.1.3 Lights

High energy efficiency and good colour rendering are both desirable qaulities for a light to possess, unfortunately these desirable characteristics produce a conflict. High energy efficiency is obtained by emitting as much light as possible with a wavelength near to that the eye is most sensitive to, about 555 10^{-9}m. Good colour rendering, or naturalness, is obtained by matching the light output spectrum to that the human eye has evolved to use, namely the solar spectrum. The compromise between high energy efficiency (as in a high pressure sodium discharge lamp) and reasonable colour rendering or palatability (as in an incandescent lamp) is subject to the individual's taste. The useful light output of a light is subjectively measured. Innovatory designs of lights claim to achieve both high efficiency and good colour rendering.

The energy efficiency of lumieres is assumed to be the same as the luminous efficacy, which is the ratio of luminous flux produced to the electrical power supplied to it (see Boyce, 1976).

(i) Incandescent

Incandescent lights work by electrically heating a high resistance wire in an inert atmosphere. The heated element reaches about 3200 K and its spectrum, which approximates a black body spectrum, is consequently more red than the solar spectrum. It is unlikely that major improvements in the efficiency of such lights will be made since these would only be achieved by operating the element at a temperature close to that of the sun's surface, i.e. at a about 6000 K, and there are obvious technical problems in doing this.

The efficiency of incandescent lights falls in the range 0.08 to 0.18, an intermediate figure of 0.13 will be used (see Boyce, 1976).

In 1976 all households possessed incandescent lights; hence the population was 19.5 million (IIED, 1979).

(ii) Fluorescent

Fluorescent lights work by exciting the molecules of a low pressure mercury vapour with electrons from incandescent electrodes. The radiation the molecules emit on discharging this energy is predominantly in the blue and green parts of the visible spectrum. A coating of some fluorescent substance is deposited on the inside of the tube. This transforms the original emitted spectrum. By using different coatings the light spectrum can be manipulated. In theory, such lumieres should be capable of nearly 100 % efficiency.

The efficiency of a tubular fluorescent light (Northlight) is assumed to be 0.4; the range is from 0.35 to 0.55 (see Boyce, 1976).

In 1976 6.51 million households possessed fluorescent lights (IIED, 1977).

A4.1.4 Cookers

The type of useful energy a cooker has to provide is particularly difficult to define and thus so is the efficiency. In my opinion the usual quotes for cooker efficiency adopted are probably overstimates. The use of better controls and insulation against conducted, convected and radiant losses in an electric cooker and its cooking utensils would reduce the electricity needed to do the same cooking by factor of three or more. In the UK gas and electric cookers predominate and so solid fuel or other cookers will be omitted.

It is worthwhile noting that cookers play a significant role in forming diurnal demand peaks and that simple measures such as insulated ovens or better controls could reduce their consumption dramatically.

(i) Gas

Since gas cookers consume an average of about 6.5 GJ delivered gas per annum (IIED, 1979) to produce a useful 0.74 GJ, their efficiency (η) is 0.11. There were 10.7 million gas cookers in 1976 (IIED, 1979). P_m is calculated from the annual gas consumption (Q) and the average use level, $\overline{U}_c$, and the efficiency (η), thus

$$P_m = \eta\, Q / (\overline{U}_c\, Y) \quad \text{(W)}$$
$$= 0.11\ (6.5\ 10^9)/Y \quad \text{(W)}$$
$$= 24.0 \quad \text{(W)}$$

where Y is the number of seconds in a year.

(ii) Electric

Electric cookers consume about 3.7 GJ of delivered electricity per annum. The Electricity Council (1978) reckon that microwave cookers consume about 20% of the electricity used by conventional cookers; therefore the latter are at most 20% efficient, conventional electric cookers are thus assumed to have an efficiency of 0.2. The useful cooking energy delivered by a conventional cooker is 0.74 (= 0.2 3.7) GJ/a. The assumption will be that the useful energy required from an electric cooker is the same as for gas cookers, which is probably innaccurate because of the different control and response of the appliances and the fact that gas cookers are more frequently used for boiling kettles. In 1976 there were 8.8 million electric cookers (IIED, 1979).

A4.1.5 Hot water heaters

It should be noted it is assumed that houses derive useful energy for space and hot water heating from one type of conventional heater. Thus all the hot water or space heating is performed by one particular converter for each house. In reality many houses use a mixture of converters; for example gas heating may be used as "background" central heating with some "top up" from on peak electric heating in certain rooms or during an exceptionally cold spell. A common switch of fuelling is from solid fuel water heating via a backboiler in winter to electric immersion heating in summer. The National Fuel and Heating Survey (Field, Hedges, 1977) provide interesting information on this subject. Their survey results for main form of heating are used to estimate apliance populations.

There are two notable exceptions to this rule. Solar water and space heaters require some auxiliary heat from time to time and thus houses with solar systems are "dual-fired"; such systems are dealt with in the relevant section. In addition off-peak electric sometimes require supplementary heating, particularly late in the day.

Since hot water cylinders are not explicitly included, the efficiency of domestic heaters will include any losses from the cylinder. This overall efficiency, called the system efficiency, may be defined as:

$$\text{Efficiency} = \frac{\text{(enthalpy of water at tap)} - \text{(enthalpy of mains water)}}{\text{thermal content of fuel in}}$$

(i) Gas individual

This category includes all gas heaters solely employed for water heating; the main types are "instantaneous" and circulators. These former heat the mains water by burning gas in a small wall mounted boiler and passing the heated water directly to demand - there is no storage. Gas circulators heat water in a hot water cylinder. On average such heaters are more efficient than gas C/H boilers for water heating since they are better matched to the load.

An average efficiency of 0.43 will be assumed for these heaters; a figure derived from a report by Whittle and Warren (1978). They give efficiencies of 0.47 for instantaneous and 0.39 for circulators respectively. The population of these heaters was 4.14 million in 1976 (IIED, 1979).

(ii) Gas central heating

Whereas the individual gas fire or room heater directly transfers the heat from the burning gas into the room via a heat exchanger; gas central heating incorporates a pumped heat distribution medium, either air or water. Thus the whole system needs to be considered if a realistic value for the efficiency of such systems is to be found. The efficiency of such systems is the subject of many studies.

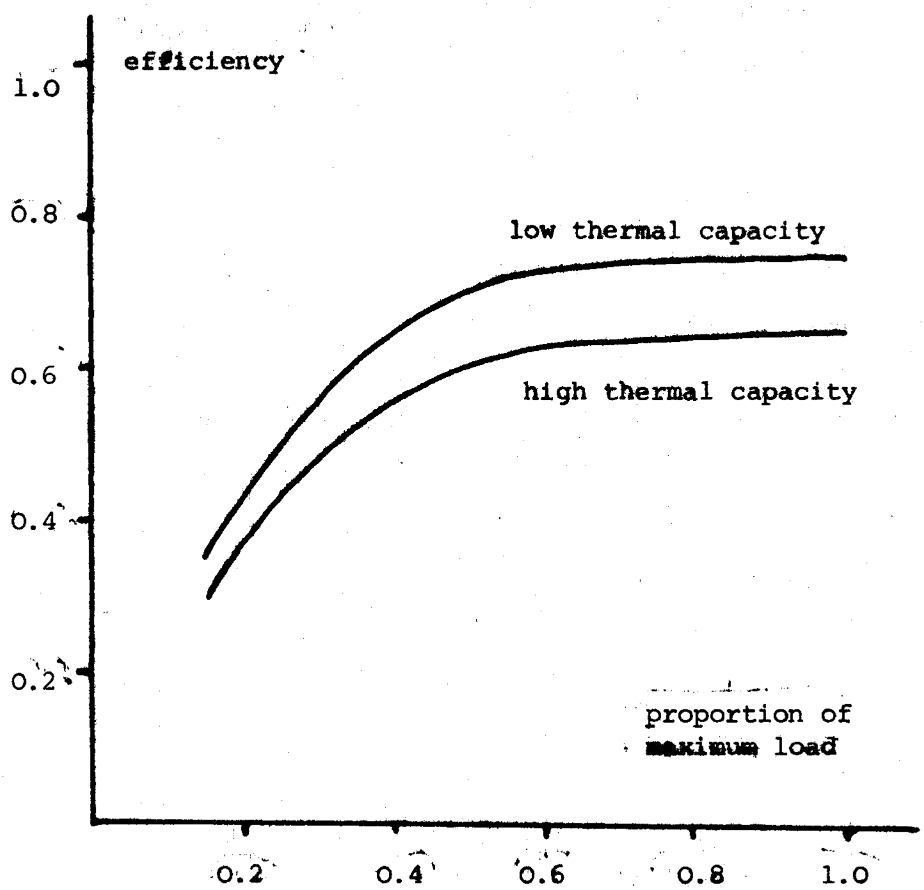
The efficiency of a gas central heating system will depend predominantly on the load pattern, the design of boiler and distribution system, the operating temperature , the control method and the level of maintenance. There are other heat flows which should be considered, such as useful losses in the heating season which may arise from the boiler casing, the flue and pilot lights.

The efficiency of gas boilers is defined as

$$\text{Efficiency} = \frac{\text{useful heat from heat emitters}}{\text{thermal content of gas supplied}}$$

There is a British standard relating to the required efficiency of boilers at full load, but no restrictions as to the efficiency (or inefficiency) at part load. Since the drop in efficiency is substantial at part load the part load curves depicted below will be used (from Romig, Leach, 1977).

Figure A4.1 Domestic boiler efficiencies



These curves may be expressed as

$$\eta(L) = \eta_0 \left(1-\left((1-L)^4\right)\right)$$

where L is the proportion of full load

η_0 is the efficiency at full load

Because thermal mass is ignored in the simple modelling of houses the maximum loads the heaters have to meet are low; a figure of 6000 W rather than 10000 W is assumed.

The base efficiency, η_0, is assumed to be 0.75 for the low thermal capacity boiler and 0.65 for the high thermal capacity boiler. These figures are likely to be optimistic since the efficiency obtained under testing conditions is likely to be better than the in situ efficiency. Innaccuracies will also occur because there is no consideration of losses due to pilot lights or pipework; these may or may not be useful.

The population of gas central heaters used for water heating in 1976 was 4.0 million (note that this implies that 0.68 million gas central heaters do not provide hot water). It is assumed that all the boilers then were of the high capacity type.

(iii) Gas fuelled heat pump

A gas fuelled heat pump works on the same principle as an electric heat pump except that the compressor is powered by a gas-fuelled internal combustion engine and a proportion of the waste heat from the engine is supplied to the load. This gives an overall primary energy to useful energy ratio greater than that of the electric heat pump.

This ratio, which may be called the system efficiency, S, is defined thus:-

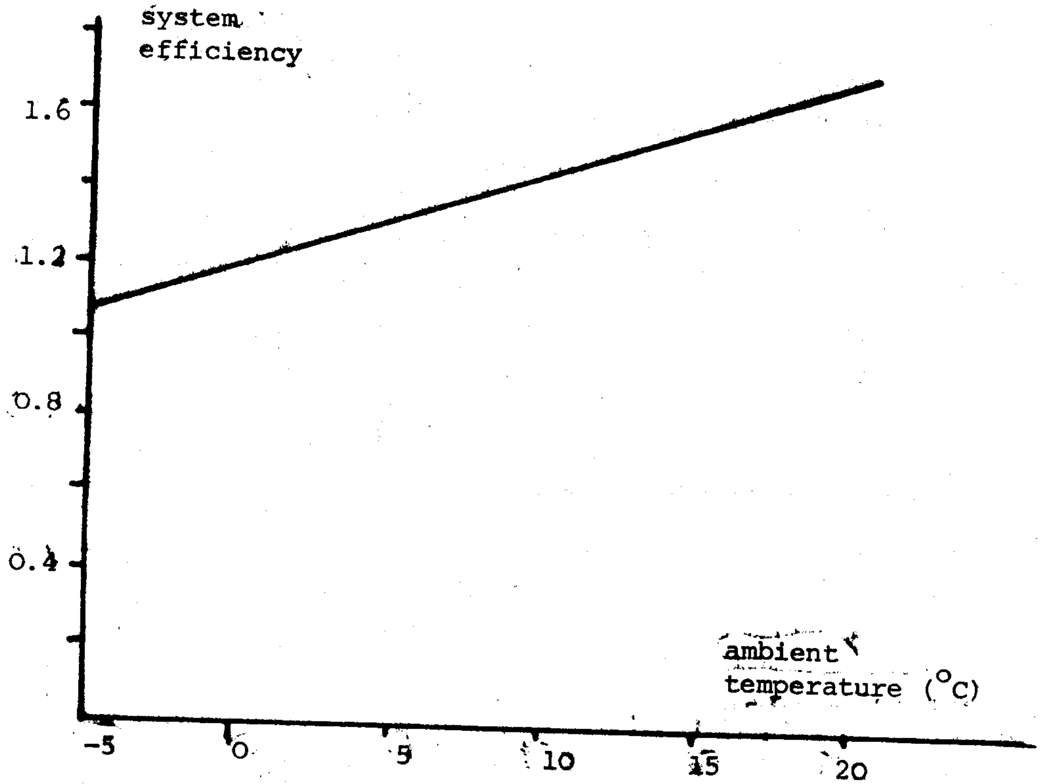
$$S = \frac{\text{total useful energy from system}}{\text{delivered energy input}}$$

(note that atmospheric heat is neglected in this efficiency)

At present there is a dearth of performance data relating to the performance of such heat pumps in the UK climate. However theoretical calculations coupled to the experimental data that does exist lead to an estimate of the temperature dependency of the system efficiency shown below. The actual nature of the curve obviously depends on the design of the particular machine used. The efficiency curve given is considered to be applicable to a gas heat pump system supplying a load equivalent to the combined space and water loads for upward of ten houses. The economies of scale involved with such systems makes their use in individual houses unlikely. The condensing temperature is assumed to be between 40 and 50 centigrade, with the power output being that sufficient to meet the peak loads encountered in the particular housing type under consideration.

A prototype gas-fired heat pump has been developed and tested at the OUERG. The machine tested did not quite match up to predicted performance, but it seems that the theoretical system efficiency could be in a "second generation" machine. These, and other aspects of such machines, are discussed by the principal researcher at the OUERG, Cheryl Phillips (1980). Robert Critoph (Warwick University), who initiated the OUERG heat pump experiment, is developing and improving the gas fired heat pump at Warwick University. The system efficiency assumed will be the estimated, not the experimental, value for the reasons noted above. The figure below depicts the estimated variation of the system efficiency with ambient temperature. This is based on information from R. E. Critoph (private communication).

Figure A4.2 System efficiency of a gas fired heat pump



The performance curve may be expressed analytically:-

$$S = 1.3 + 0.02\ T_a$$

where T_a is the ambient air temperature (C).

(iv) Oil central heater

Oil central heaters are similar to gas central heaters except that of course they use oil as a fuel. Their part load characteristics are much the same as for gas central heaters (see IIED, 1977). The efficiency of these appliances is assumed to be the same as for high thermal capacity gas boilers (see above).

In 1976 there were about 0.19 million of these systems used for heating hot water.

(v) Solid fuel central heater

This category covers a multitude of different designs; but their common feature is hot water radiators run from a central solid fuel fire. Their efficiency can be very high (up to 0.8); but a fairly conservative value of 0.65 will be assumed. Ths is perhaps much too high an efficiency for water heating with these appliances. In 1976 there were about 2.72 million of these heaters (Field, Hedges, 1977).

(vi) Solid fuel heater

Solid fuels are used to heat water in a number of appliances. Back boilers and indirect cylinders are the common types. A description of these is not possible here. The average efficiency of such water heaters is assumed to be 0.40 as assumed by the IIED (1979). In 1976 there were about 2.45 million of these.

(vii) Electric immersion heater

An electric immersion heater is simply an insulated electrical resistive heating element placed in a domestic hot water tank. Control is by a thermostat and possibly a time switch. Although the electric heating is 100 % efficient the useful efficiency is less due to tank and pipe losses. The model presently assumes a useful efficiency of 0.70 (Warren, Whittle, (1978), and OUERG, (1978)) and neglects the control and storage effects. Should these effects be seen to be large a more detailed model will be written.

In 1976 there were about 6.18 million immersion heaters.

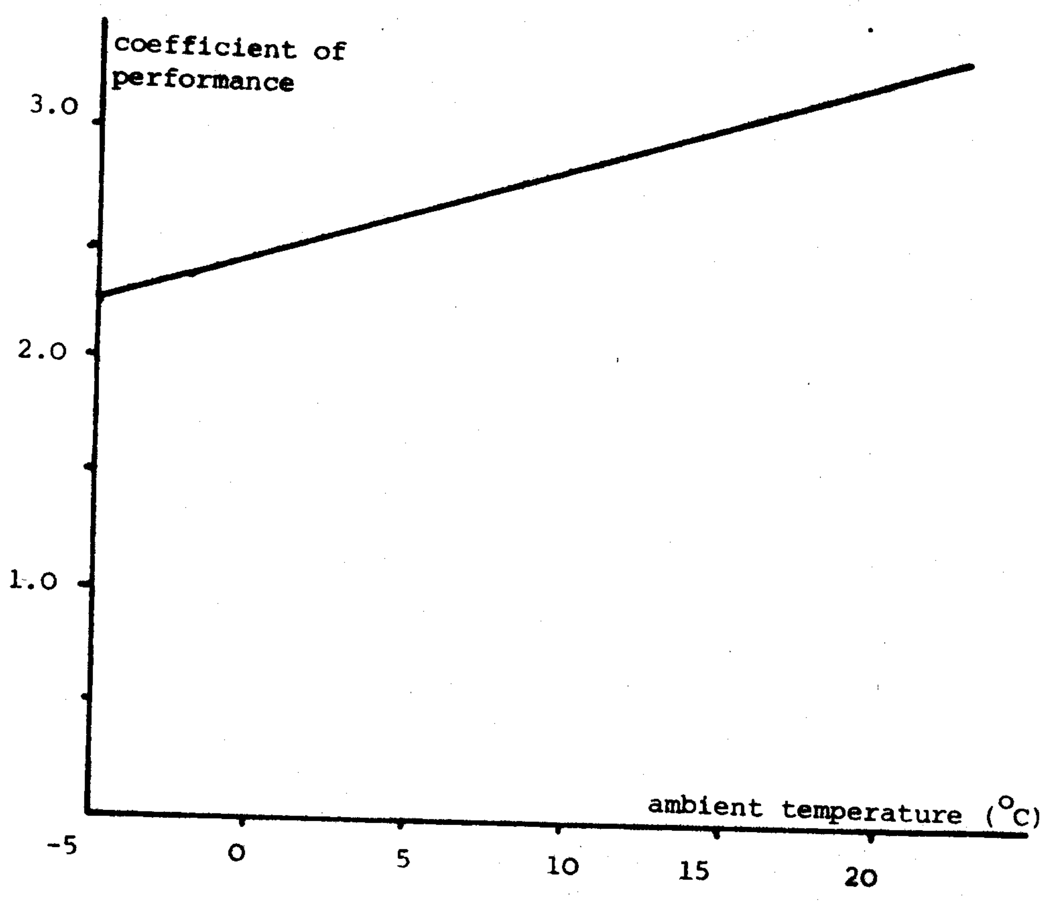
(viii) Electric heat pump

An electric heat pump consists of an electrically powered compressor which drives a working fluid through a set of heat exchangers. The fluid expands through a throttle and then expands and cools whereupon it absorbs heat from a low temperature reservoir. It is then compressed, rises in temperature and releases heat into a high temperature reservoir. Such devices have not been used to any extent for space and water heating in dwellings in this country. Consequently it is possible that the perfomance of these machines will be improved. The heat pumps considered here will use atmospheric heat as the low temperature heat source. The medium constituting the high or low temperature reservoirs affects the temperatures and heat flow rates through the heat exchangers and consequently the coefficient of performance (COP) of the electric heat pump. The COP is defined as

$$COP = \frac{\text{useful heat output}}{\text{electricity delivered}}$$

The curve for the variation of the COP of such a heat pump coupled across reservoirs at different temperatures is given below, this being derived from data given by Blundell (1976), Heap (1975) and Sumner (1976).

Figure A4.3 COP of an electric heat pump



This curve may be expressed as the analytic function:

$$COP_e = 2.4 + 0.04\ T_a$$

The COP of a heat pump obtained in practice is generally of the order of 30 to 40% of the theoretical maximum. It seems possible that extended, low temperature difference heat exchangers plus better control of the heat pump might allow average COP' s in the range 5 to 10 for space heating purposes. This possibility is being examined by P. L. Johns (OUERG) and others.

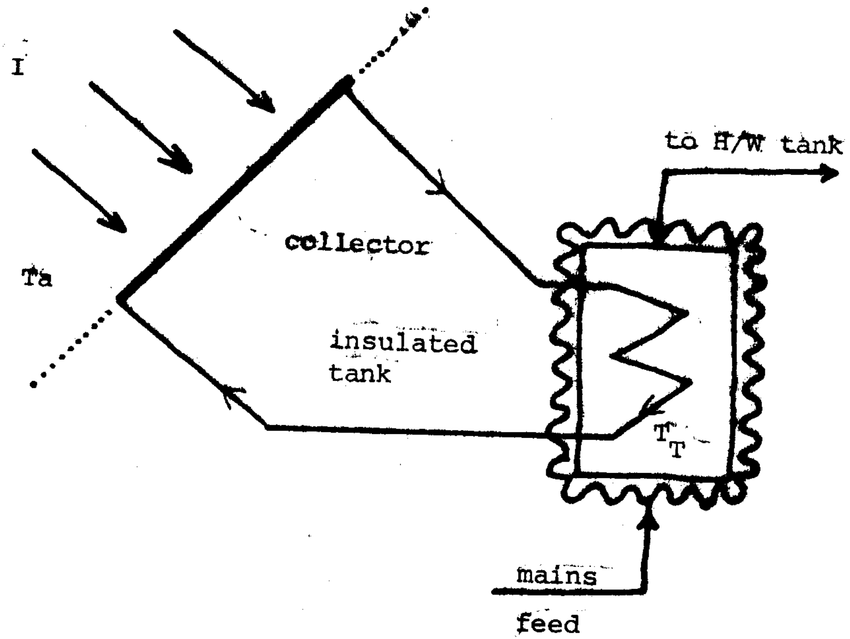
(ix) Combined heat and power

Hot water and space heating loads are met by a combined heat and power scheme. It is assumed that the efficiency of the district heat transmission system is a constant 0.9 (this tallies with typical transmission losses estimated by Courtney and Macadam (1976) and EP 34 (HMSO, 1979)) although of course it will in fact vary according to the particular scheme, load and ground temperature at the time of year (assuming the pipes are buried).

(x) Solar water heater

A conventional design of pumped solar hot water heater will be used in the model (see diagram below).

Figure A4.4 Solar hot water heating system



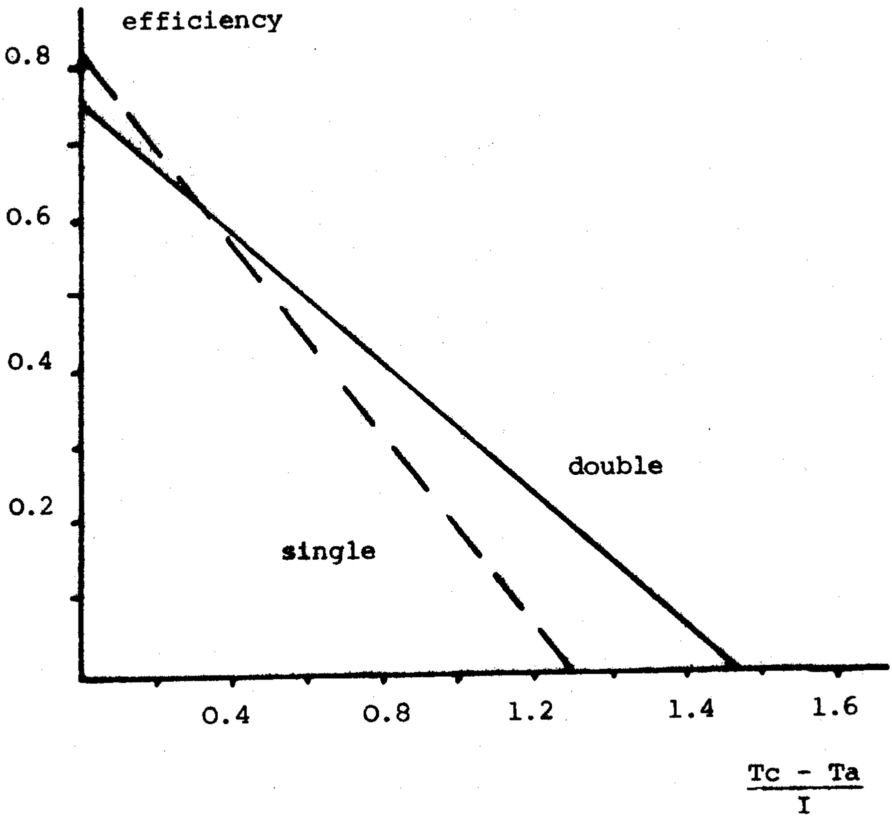
An array of double glazed solar collectors (area A_c) is coupled to an insulated water tank (volume $V_t(l)$) by an indirect pumped circuit. The efficiency of the solar collectors (η_c) is determined by the construction of the collector, the tank temperature ($T_T(C)$), the ambient air temperature ($T_a(C)$) and the incident radiation on the collector surface ($I(Wm^{-2})$), i.e.

$$\eta_c = \eta_c(T_T, T_a, I)$$

This assumes that the average collector temperature is the same as the average tanke temperature ($T_c = T_T$).

This function is generally rather complicated (see for example Duffie and Beckmann (1974)) and so a simple linear function will be used. This does not cause large errors due to the peculiar "negative feedback" [1] behaviour of solar collectors. The figure below shows the curves assumed for single and double glazed collectors.

Figure A4.5 Solar collector efficiency functions



These curves may be approximated as follows:

Single glazed

$$\eta = 0.83 - 6.3\ X$$

Double glazed

$$\eta = 0.76 - 4.3\ X$$

where $X = (T_c - T_a)/I$

---

[1] This is because the efficiency of a thermal solar collector decreases as the storage temperature increases. Thus an overestimate of efficiency in the first period will lead to a high value for the tank temperature and thence a lower value for the efficiency in the following period.

Given these functions and values for the parameters T_a (from the meteorological data), T_T (from the model) and I the efficiency η_c may be calculated.

The system operates as follows. If the efficiency of the collectors is positive heat is transferred to the storage tank at a rate R:

$$R = \eta_c A_c I \qquad \text{(W)}$$

This causes a rise in the tank temperature ΔT_T:

$$\Delta T_T = R\ t\ /(S\ V_t) \qquad \text{(C)}$$

where t is the running time (sec)

S is the specific heat of water ($Jl^{-1}C^{-1}$)

When a volume of hot water demand (V_d) is drawn from this storage (or pre-heat) tank, mains water at a temperature (T_m) is mixed in and the new tank temperature is

$$T_T = ((V_t - V_d)T_T + V_d\ T_m)/V_t \qquad \text{(C)}$$

The tank will also cool if it is hotter than the surrounding air, at temperature T_b. Since the thermal mass of the storage tank is large and its area (A_t) and U-value (U_t) relatively small its rate of cooling may be approximated linearly over small time intervals (one hour). Thus after a time t the drop in tank temperature will be

$$\Delta T_T = t\ U_t\ A_t\ (T_T - T_b)/(S\ V_t) \qquad \text{(C)}$$

If the tank temperature is less than the demand temperature auxiliary heat (Q_a) from another source is required, this being

$$Q_a = S\ V_d\ (T_d - T_T) \qquad \text{(J)}$$

It is assumed that this auxiliary heat will be provided by a low thermal capacity gas boiler.

This submodel is crude because it ignores the following effects:

-the electrical consumption of the pump.

-the non linearities of collector performance.

-the precise nature of the insolation.

-the angle dependence of transmittance and aborptance.

- heat exchange losses.

- tank stratification.

However from the author's previous experience in the detailed simulation of such solar systems (Barrett, 1976) and discussions with R. Everett (OUERG) it would seem that such a crude model will be sufficiently accurate for our present purposes. The values of the system defining parameters are given below.

Collector area (A_c) = 5 (m^2)

(Double glazed)

Storage volume (V_t) = 200 (1.)

Storage loss coefficient ($U_t\ A_t$) = 1.2 (WC^{-1})

A4.1.6 Space heating

Note that with a few exceptions only one type of converter per house is assumed. The exceptions are electric off-peak and solar systems; this aspect of domestic converters is discussed more fully under hot water

(i) Gas individual

Gas individual space heaters are those gas fuelled space heating appliances in the domestic sector that do not use either an air or water heat distribution system. There is a wide range in the types of such heaters and details of the exact populations and operating characteristics of each type are hard to come by. Therefore an attempt at a weighted efficiency over all the different types will be used. An estimate of 0.5 will be used (see OUERG, 1979).

The population of these appliances was about 4.14 million in 1976 (IIED, 1979).

(ii) Gas central heating

The population of these heaters was about 4.14 million in 1976 (IIED, 1979).

(iii) Gas heat pump

See relevant appendix.

(iv) Oil central and individual heating

In 1976 there were about 2.85 million oil central heating systems and 0.6 million individual oil heated households. It will be assumed that both these systems operate at the same efficiency as a high capacity gas boiler. These converters are thus modelled as an aggregate 3.45 million central heating systems.

(v) Solid fuel individual

These are individual open and closed solid fuel fires that deliver heat directly into the dwelling from the fire itself or via the surrounding brickwork or masonry. The efficiency is difficult to define since the usefulness of the heat from the fire's surrounds is subjectively estimated.

Therefore ranges of between 0.1 to 0.35 for open fires and from 0.4 to 0.85 for closed fires are applicable. All one can do is to use central estimates; these will be 0.25 for open and 0.65 for closed fires respectively. These estimates are chosen to lie near figure provided by workers in the industry and the average efficiency is assumed to be 0.46 (IIED, 1979).

In 1976 there were about 2.45 million households using this type of heater.

(vi) Solid fuel central heating

About 2.71 million households used these heaters in 1976.

(vii) Electric on peak

Electric on peak heaters are assumed to be the category of electric space heaters which do not include any storage and thus have to be operated at on peak times. Thus radiant bar fires, fan heaters, convector heaters are all included. It is assumed that such fires have an instant heating effect and an efficiency of 1.0.

In 1976 about 0.44 million households used on peak electric heaters for their main source of heat.

(viii) Electric off peak

In 1976 about 1.36 million households used off peak electric storage heaters and 0.77 million used some other off peak system, such as underfloor or hot air. It will be assumed that <u>all</u> these systems are storage heater systems, unrealistic though this is, so the combined off peak population is 2.13 million. This simplifying assumption is necessary because it is beyond the scope of the model to disaggregate these heating systems and they can not be regarded as on peak systems. Field and Hedges (1977) found that the average off peak heating system consisted of 2.5 storage heater units. It is such a system which will be described below.

Electric storage heaters consist of a storage mass of thermally insulated high thermal capacity bricks heated by electrical resistance heating. Electricity is input at times of generally low electricity demand (i.e. off peak) thus raising the temperature of the bricks. The heat stored thereby is gradually released in the house by unassisted conduction, convection and radiation and sometimes with fan assisted convection in addition. An unassisted type of heater will be assumed.

The performance and control of a set of 2.5 storage heaters is determined by the thermal capacity of the bricks (C_t (JC^{-1})), its specific loss coefficient (S_l (WC^{-1})), the temperature of the bricks (T_b (C)) and the house (T_h (C)), the electrical heating power per set (P_e (W)) and the times defined as being off peak.

The useful heat output of the heater will be

$$P_o = S_l\ (T_b - T_h) \qquad \text{(W)}$$

and the corresponding temperature drop in the bricks over one hour's cooling, given the assumption that the linear approximation will suffice, is given by

$$\Delta Tb = P_o\ 3600/C_t \qquad \text{(C)}$$

The exponential law of cooling (Newton's law) is approximated reasonably accurately over hourly intervals by such linear equations, as is true for most thermally massive insulated heat stores.

The storage heaters will demand an electrical input in the off peak period between 12 p.m. and 9 a.m. provided the temperature of the bricks is less than some maximum (T_{bm} (800 C)) and there is a space heating demand. In addition, "real" storage heaters accept charge in a topping up period between 3 p.m. and 5 p.m.; at present this is ignored in the modelling. It is assumed that the number of heaters which will be switched on in off peak times is proportional to $(1-T_b/T_c)^{0.5}$; where T_c is the control temperature set by the consumer. If he thinks it will be cold on the following day T_c is set high. In the model T_c is set to the value $800(1-T_a/T_i)$, where T_a is the average monthly ambient temperature and T_i is the desired house temperature. Thus the lower the temperature of the bricks the more heaters will be turned on. Thus the total electrical power demanded by N sets of storage heaters is given by

$$P_{te} = N\, P_e\, (1-T_b/T_{bm})^{0.5} \qquad \text{(MW)}$$

If these conditions are met the temperature rise of the store will be

$$\triangle T_b = 3600\, [P_e - S_1(T_b - T_h)]\, [1 - T_b/T_{bm}] \qquad \text{(C)}$$

Note that it is assumed that electrical heating is 100 % efficient.

If insufficient heat is emitted by the set of storage heaters it is assumed that on peak elecric heating is used as a supplement. This auxiliary power requirement (P_{ae}) is

$$P_{ae} = ds - P_o \qquad \text{(W)}$$

where ds is the space heat load of one house. The total auxiliary power needed is simply N P_{ae} (MW).

Storage heater specifications

This refers to the average set of about 2.5 storage heater units per house (see Field, Hedges, 1977).

Total specific loss	= 4.0	(WC^{-1})
Total thermal mass	= 85.0	(WhC^{-1})
Total input power	= 7.5	(kW)
Maximum temperature	= 800.0	(C)

It is assumed that there were 2.13 million such heaters in 1976.

(ix) Electric heat pump

See appendix above

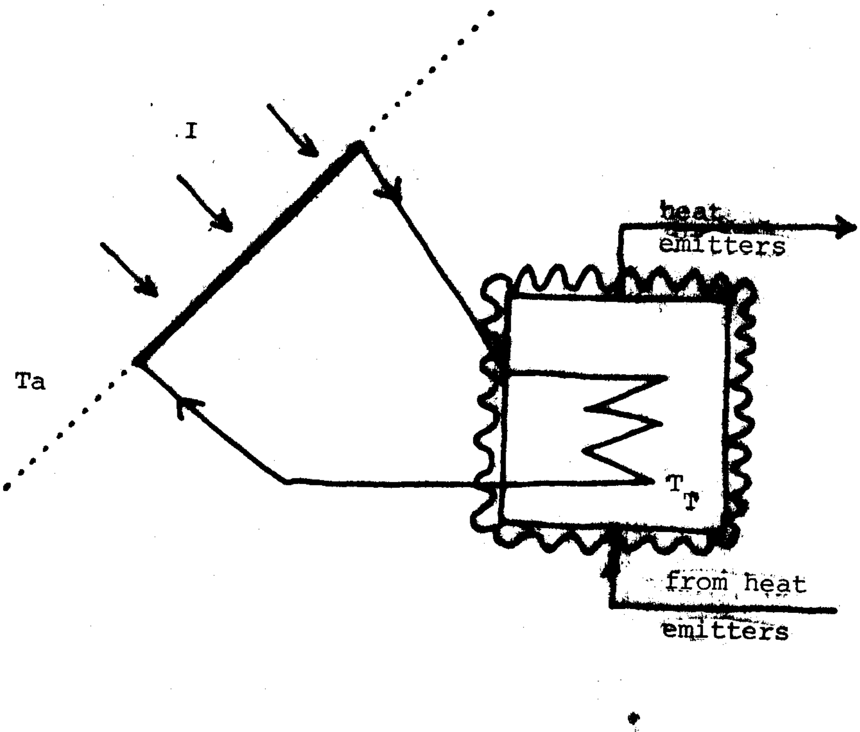
(x) Combined heat and power

See appendix above.

(xi) Active solar house

Active solar houses consist of an array of solar panels connected to a heat storage and distribution system. Typically such houses in the UK use ordinary single or double glazed flat plate collectors coupled by a pumped water circuit to a storage unit consisting of a large insulated tank of water. If the heat output from this tank to the space heat emitters (usually low temperature radiators) is less than the demand an auxiliary gas heater is brought into play. A detailed description of such a house may be found in work by Duffie and Beckmann (1974). For the purposes of the model the system is defined by the schematic shown below.

Figure A4.6 Active solar space heating system



The physical performance of the components and their control are described below.

The collectors are assumed to be double glazed (as described for water heaters) and their operation is basically the same. If the efficiency is positive, solar energy is collected and the storage temperature rises. If there is a demand for space heat and the storage temperature exceeds the minimum operating temperature for the space heating emitters (this is assumed to be 30 C) heat is taken out. The drop in temperature arising from this demand is simply calculated.

If the tank temperature is less then 30 C at a time of demand the auxiliary gas heater is used. This is assumed to be a low thermal capacity gas boiler.

Values defining an active solar house are :

Collector area (A_c) = 20 (m^2)

(double glazed)

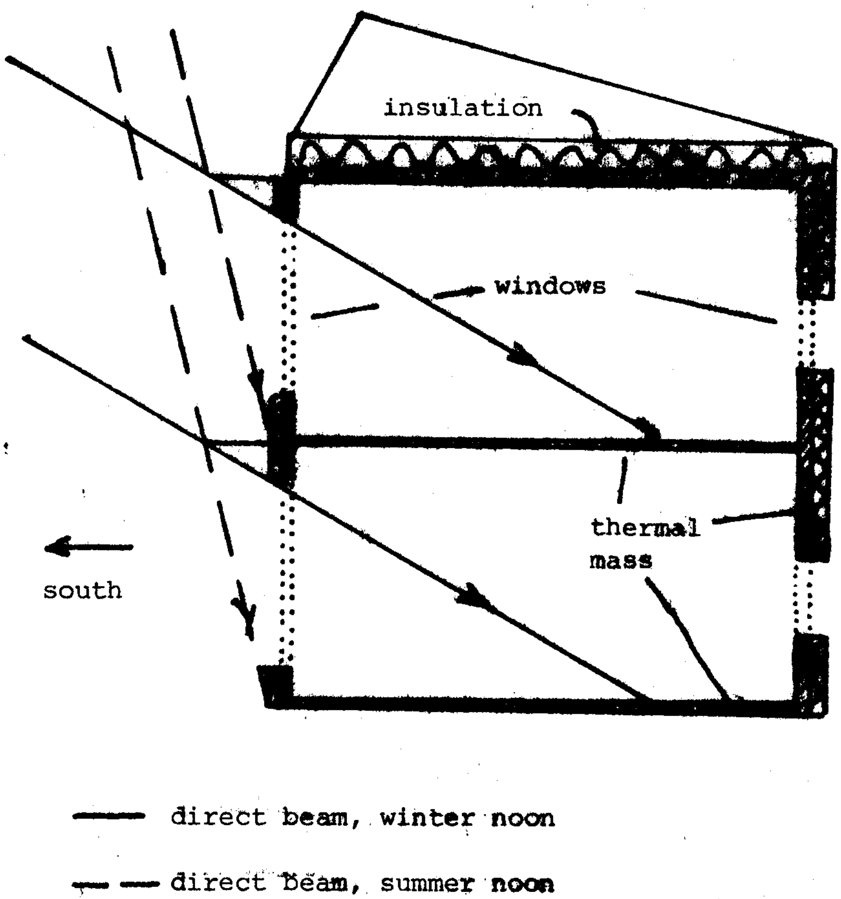
Volume of storage tank (V_t) = 30 (m^3)

Heat loss coefficient of tank ($U_t A_t$) = 20 (WC^{-1})

(xii) Passive solar house

A passive solar house differs from an active solar house because the solar energy collection and storage system is "architecturally integrated" into the house. Essentially the collection areas are composed of south facing fenestration and some storage is accomplished by using the thermally massive elements of house construction. High levels of thermal insulation are necessary throughout since a large proportion of the savings in heat load (as compared with a "normal" house) is due to conservation. A schematic diagram of such a house is given below. Descriptions of such houses are given by Franta and Olson (1977). In addition to this the ERG is conducting the biggest passive solar housing trial in Europe; results from this experiment will be used to validate the extremely simple model described below.

Figure A4.7 Passive solar house



The heat flows through the house are calculated as if the house had some thermal capacity. The role of thermal storage in the fabric and furnishings of such houses will be important; both for avoiding sudden overheating or wild temperature variations and for storing some excess daytime solar energy for use in the evening.

The total heat loss is the sum of the fabric and ventilation losses, Q_f and Q_v respectively. Free heat gains arise from the sun (Q_s) and from incidental sources (Q_i). Thus the amount of auxiliary heating required (Q_a) is

$$Q_a = (Qf+Qv) - (Qi+Qs) \qquad (W)$$

Q_f, Q_v and Q_i are calculated as for normal houses except that the thermal characterisics of the passive solar houses are different.

The solar gain through the south facing glazing is estimated from the total insolation on the south glazing and the transmiitance of the glass, thus

$$G_s = A_g \, I_s \, T \qquad \text{(W)}$$

where A_g is the glazing area (m^2).

I_s is the insolation (Wm^{-2})

T is the transmittance.(angle dependence ignored)

The solar gain is assumed to be absorbed in the thermal mass of the house directly and then to heat the house by thermal transfer to the air of the house. Radiation effects are not explicitly included. The thermal mass (2200 Wh C^{-1}) denoted M_p, is equivalent to 1 m^3 of concrete. The temperature rise of this mass after t seconds of solar heating at G_s (W) is:

$$\Delta T = G_s \, t \, / M_p \qquad \text{(C)}$$

The useful heat output from this mass to the house, Q_s, is

$$Q_s = A_w \, U_w \, (T_m - T_i) \qquad \text{(W)}$$

where A_w is the area of the thermal mass

U_w is the transfer coefficient of the wall ($Wm^{-2}C^{-1}$)

T_m is the temperature of the thermal mass (C)

T_i is the internal temperature of the house (C)

In this way the passive solar contribution is distributed more realistically than with a zero thermal mass model.

Values for the parameters pertinent to the performance of such a house are given below. It is assumed that the auxiliary useful heat requirement is met by a gas boiler of the low thermal capacity type. Since the house has unusually large glazing areas the change in the overall fabric loss coefficient caused by drawing curtains or closing insulating shutters will be significant and has thus been included.

Values defining a passive solar house are:

Area of southern fenestration (A_g) = 20 (m^2)

Transmittance of glazing (T) = 0.75

House daytime specific loss coefficient (S) = 150 (WC^{-1})

House nightime specific loss coefficient (S) = 120 (WC^{-1})

Area of thermal mass (A_w) = 100 (m^2)

Transfer coefficient (U_w) = 8 ($Wm^{-2}C^{-1}$)

A4.2 Industrial converters

A4.2.1 Transport

(i) Diesel motors

Diesel motors are internal combustion engines with very high compression ratios which obviate the need for spark ignition and facilitate higher efficiencies. Energy losses occur in much the same way as the petrol internal combustion engine, i.e. through the cooling system and friction lossees in the engine and transmission. The technical characteristics of such motors is described by Blackmore and Thomas (1977). A typical value of 0.17 is taken as being representative of the efficiency (delivered to useful energy) of contemporary diesel motors and transmissions in lorries, vans and buses.

A4.2.2 Kinetic

(i) Electric motors

IIED (1979) reports on page 43 the findings of an analysis by Murgatroyd and Wilkins (1976) of the efficiency of industrial electric motive power production. They estimate an average of 65 % of the electricity delivered to electric motors is lost through drives and controls.

The efficiency of electric motors is therefore assumed to be 0.35 (but note that transmission and control losses are included).

(ii) Oil motors

It is assumed that stationary motors using oil as a fuel will have the same efficiency as a transport diesel motor (and transmission), namely 0.17.

A4.2.3 Lighting appliances

The average efficiency of lighting appliances in industry will be assumed to be 0.4; this is the same as for fluorescent lights.

The following sections of this appendix attempt to deal with the remaining industrial converters. The extreme diversity of processes found in industry involves some diversity in the energy converters employed; however these converters are often similar in nature since they produce similar types of useful energy. The detailed surveying of these technologies and their associated efficiencies is incomplete as yet. There has been some effort expended in remedying this lack, but the complexity of the task and problems such as commercial confidentiality are difficult to surmount. Data on industrial and commercial converters are generally the least accurate and reliable data used in the model. However, a fairly small and identifiable number of types of useful energy are required in industry such as process heat within a certain temperature range or electricity for electrolysis. This, coupled with the fact that many of the energy converters would be mass produced, means that the efficiencies estimated may not be wildly in error.

There are figures for efficiencies of various industrial converters given by EP 39, the IIED study (1979) and other assorted sources. Perhaps the most detailed survey of industrial energy conversion equipment is that being done by the Science Policy Research Unit (Sussex University), but it is limited to boilers. Their results are still only preliminary, but it does seem that average effiencies quoted by other people are not wildly innaccurate; however the empirical basis is slight.

A4.2.4 High temperature heat

IIED (1979) estimates that 20 % savings may be achieved in direct fired (or high temperature) plant. If it is assumed that these savings were due to improved efficiency of the actual burners thought economic, and that the maximum technically attainable savings were 40%; a nominal efficiency of 0.6 could be assigned to processes directly fired by fossil fuels.

On this assumption I may list these efficiencies.

(i) Gas

Efficiency assumed to be 0.6

(ii) Oil

Efficiency assumed to be 0.6

(iii) Coal

Efficiency assumed to be 0.6

(iv) Electricity

Since it is the problem of exhausting the combustion products of fossil fired processes that incurs heat losses one can assume that direct electric firing is 100 % efficient because there are no such waste products.

Efficiency of direct electric fired plant is 1.0.

(v) Combined heat and power

From the ETSU industry study for 1976 (IIED, The ETSU industry study (IIED , 1979) reports that 209 PJ of heat and 42.2 PJ of electricity were produced by the combustion of 111.2 PJ of gas, 203.4 PJ of oil and 61.9 PJ of coal; a total 376.5 PJ of fuel. If it is assumed that this heat and electricity production occurs in CHP plant one can calculate the average efficiencies of producing electricity and heat; thus

Efficiency of producing electricity is electricity out divided by fuel in:

Efficiency = 42.2 /376.5

= 0.11

The efficiency of producing heat is heat out divided by fuel in:

Efficiency = 209.0/376.5

= 0.56

A4.2.5 Low temperature heat

IIED (1979) estimates that an increase in efficiency of 0.25 may be made in process boilers which are the main sources of low temperature heat. If it is assumed that the maximum efficiency of fossil fuelled fired boilers is presently 0.75 (although there is no reason why it should not ultimately approach 1.0), the savings imply a present efficiency of about 0.6. This is the value that will be assumed for all fossil fired industrial and commercial boilers; both for process heat and for space and water heating. The effiencies or efficiency ranges quoted in brackets are those given in EP 39 (1979).

(i) Gas

Efficiency assumed to be 0.6. (0.73)

(ii) Oil

Efficiency assumed to be 0.6. (0.71)

(iii) Coal

Efficiency assumed to be 0.6. (0.64)

(iv) Electricity

Since there are no wasteful exhaust gases electrically heated boilers are assumed to have an efficiency of 1.0.

(v) CHP

Efficiency fuel to electricity is assumed to be 0.11, and to heat 0.56.

A4.2.6 Space and hot water heaters

At present the use of "alternative" energy technologies for the provision of space and water heat in the industrial sector is ignored. This is simply because the model has to be limited for reasons of time. The efficiencies of these space and hot water heaters are taken from the relevant appendix.

(i) Gas

The efficiency is 0.6.

(ii) Oil

The efficiency is 0.6.

(iii) Coal

The efficiency is 0.6.

(iv) Electricity

The efficiency is 1.0.

(v) CHP

Efficiency fuel to electricity is assumed to be 0.11, and to heat 0.56.

Perhaps the most important low temperature heat provider here is CHP (often termed cogeneration industrially). Industrial heat less than 120 C could be provided by such a device, assuming that transmission or load matching problems were not insoluble. The low temperature industrial heat demand averages about 7 GW(th); if all this were produced by cogeneration an average of 1.7 GW of electrical power might also be produced. This represents about 6 % of total electrical demand.

A4.3 Commercial converters

A4.3.1 Transport

(i) Oil

Converters in this section are ships and aircraft. Motors for these are predominantly diesels or steam or gas turbine motors for ships and aeroplanes respectively. Overall motor and transmission efficiencies are assumed to be an average 0.3 (Simon, 1975). The efficiency of motors for ships and aircraft might perhaps be defined as the the amount of work done in thrusting the craft through the fluid medium divided by the thermal content of the fuel delivered.

A4.3.2 Miscellaneous electric

(i)Electricity

A nominal efficiency of 1.0 will be ascribed to these converters, but it must be noted that reductions in their electricity consumption are often feasible.

A4.3.3 Light

(i) Electricity

Fluorescent lights with an efficiency of 0.4 are assumed.

A4.3.4 Cooking

Cooking appliances in the commercial sector are assumed to be twice as efficient as in the domestic sector because of their design and use patterns.

(i) Gas

The efficiency is 0.2.

(ii) Oil

The efficiency is 0.2.

(iii) Coal

The efficiency is 0.2

(iv) Electricity

The efficiency is assumed to be 0.4.

A4.3.5 Space and hot water heaters

The efficiencies of space and water heaters in commercial premises are assumed to be the same as in the industrial sector. The comments in brackets are based on figures given in EP 39 (1979).

(i) Gas

Efficiency is 0.6. (space: 0.55 to 0.6, water: 0.52)

(ii) Oil

Efficiency is 0.6. (space: 0.59, water: 0.52)

(iii) Coal

Efficiency is 0.6. (space: 0.35 to 0.57, water: 0.5)

(iv) Electricity

Efficiency is 1.0. (space: 1.0, water: 0.7)

Innovatory technologies such as heat pumps and solar systems are not considered here for application to commercial and institutional buildings. Their role could be a large one since those buildings have large space and water loads and are used predominantly during the day when high insolation levels and ambient temperatures makes them amenable to ambient energy supply. Indeed, the UK made one of the earliest successful applications of passive solar energy and conservation at Wallasey school, Liverpool. In this school sufficient space heat is provided by solar energy, lights and occupants; the conventional space heating system is redundant.

A4.4 Iron and steel

A4.4.1 Introduction

The efficiencies of the processes embodied in the manufacture of iron and steel are difficult to define in terms of energy flows. This is mainly because the roles of carbon as a fuel and as a chemical feedstock (as a reducing agent) coexist in iron manufacture. Furthermore, as with all industries, the technologies used involve a range of effiencies. Therefore the effiencies will be defined in terms of the potential fual savings per unit output. Thus if it is estimated that the maximum fuel saving is 30% when all improvements have been made, the present efficiency is assumed to be 70%. The values given below are estimated from the figures given by R. E. Critoph, 1976.

To some extent fuels are substitutable in this industry and this is included in the figures below. It must be stressed that these figures are obtained by comparison with ideal engineering practice given the best new technologies.

The figures in brackets are some relevant information from EP 39 (1979) concerning the efficiencies of various technologies.

A4.4.2 Coal

Average efficiency = 0.43. (Blast furnaces 0.47)

A4.4.3 Oil

Average efficiency = 0.54. (blast furnaces: 0.55, basic oxygen furnace: 0.25)

A4.4.4 Gas

Average efficiency = 0.78. (blast furnaces: 0.43(NG) and 0.85, basic oxygen: 0.2)

A4.4.5 Electric

Average efficiency = 0.30. (for work: 0.65, basic oxygen: 0.6)

A4.5 Energy industry converters

A4.5.1 Introduction

Energy industry converters are those converters operated by public concerns (CEGB, NSHEB, SSEB, NIES, BGC, NCB, BNOC) as well as various companies which may or may not be wholly private (e.g. Shell, British Petroleum etc.). The common factor is that they all operate within the UK and provide certain fuel supplies to the UK.

It is appropriate to define two efficiencies here.

Extraction efficiency is defined as the thermal content of the fuel extracted (from the coal mine or gas field) less the energy put in to extract the fuel, divided by the thermal content of the fuel extracted.

The transmission/distribution efficiency is the thermal content of the fuel delivered by the transmission/distribution system divided by the fuel input to that system.

These definitions are not always too useful since much of the fuel used in the extraction of primary energy will be as secondary delivered fuels from elswhere, rather than from the particular "mine" in question. For example, coal mining requires electricity. It might be better to include these self uses of energy by the energy industries as energy demands; but it was simpler to include them as efficiencies.

It is worth remarking that although attention is usually focussed on the "generation" of fuels, the capital value of transmission/distribution is a significant proportion of the total capital assets for the fuel industries. It might therefore be worthwhile giving more extensive consideration to things like transmission capacity in the future.

A4.5.2 Gas

(i) Gas extraction

The efficiency of extracting natural gas in the UK is assumed to be the same as that for oil, namely 0.96 (see below). The maximum extraction rate is assumed to be 100 GW for 1976.

(ii) Gas transmission/distribution

The efficiency of extracting the gas from the gas field and transmitting it to the consumer is between 0.91 (Romig, Leach, 1977) and 0.94 (private communication, BGC, 1979). However it would seem that all these estimates are calculated from the gas input to the system and the gas output as measured by the consumers' meters. EP 39 (1979) states estimates that only 3 % of the input gas is actually physically lost; the rest is due to consistent underestimation of consumption by the meters so that any errors are favourable to the consumer. Therefore a gas transmission/distribution efficiency of 0.97 will be assumed. The problem with this assumption is that there will be some discrepancy between the results of the model and reality; where reality is defined by statistical data on metered consumption. This problem must necesssarily be borne in mind when validating the model's calculations of physical gas flows against the metered flows.

(iii) Coal to gas conversion

There are many routes to the production of gas from coal. The method used will depend on the gas required, the coal used and any other economic or environmental factors. The following therefore describes in general terms a common conversion process; a process of the type germane to the UK. Coal may be reacted with water and oxygen to form methane and carbon dioxide. This reaction, or series of reactions, which produces synthetic natural gas, or methane, usually occurs in two stages. The first stage, at high temperature, produces carbon monoxide, hydrogen and some methane endothermically. The second stage, at a lower temperature, produces methane exothermically from carbon monoxide and hydrogen. In reality the process is not this simple since coal is not just carbon and hydrogen but a complex mixture of chemicals and thus many by-products, some undesirable, are produced.

Although many types of gas synthesisers have been developed it seems unlikely that the efficiency (defined as the thermal content of the synthetic natural gas produced over the thermal content of the coal input) of synthesisers will exceed 0.75. An estimated value of 0.70 will be used. If coal is converted to both gas and oil the overall efficiency may change; the efficiency depends on the types and proportions of the products required. If a use for the heat wasted in the in the exothermic part of the reaction is found the efficiency might be improved. Accounts of the technical details may be found in work by Erikson, Forrester et al (1977).

A4.5.3 Oil

Separate figures for the extraction and delivery efficiencies are hard to come by. Values for the overall efficiency for extracting and distributing the oil are 0.92 (BGC, private communication), 0.92 (Romig, Leach, 1977) and 0.9 (Chapman et al, 1976).

(i) Oil extraction

The efficiency of oil extraction varies from 0.98 to 0.99 for the southern North Sea (Hemming, 1978) to perhaps 0.96 for the northern North Sea. A value of 0.97 will be used. It will be assumed that the output power of oil extraction was 150 GW in 1976.

(ii) Oil refining

The efficiency of oil refining depends on the nature of the crude oil input and the range of liquid (or other) products required. Energy is used to subject the oil to certain conditions of pressure and temperature in the presence of suitable catalysts. Using data for the UK (from Digest of Energy Statistics) an efficiency of 0.93 may be calculated; this may change substantially if the quality of the crude oil input changes or different products are required.

(iii) Oil distribution

Efficiency of distribution of liquid fuels is assumed to be 0.98.

(iv) Coal to oil conversion

Oil is manufactured from coal in much the same way as synthetic gas; basically hydrogen has to be combined with the carbon present in coal. Most published data on efficiencies refer to US coals and to product mixes (types of oil and gas produced) which might not be relevant to the UK. Estimates vary from 0.65 (Chapman et al, 1976) to 0.75 depending on the type of process used and the coal type used as feedstock. A value of 0.68 will used for future, advanced oil synthesisers using UK coal.

It is assumed that the product is synthetic crude oil; this must be refined before distribution.

A4.5.4 Coal

(i) Coal mines

Chapman et al (1976) estimate that the extraction efficiency for coal is 0.95; this will be assumed in the model. The output power of coal mines is assumed to be 100 GW for 1976.

(ii) Coal distribution

Since Romig and Leach (1977) give the overall extraction and distribution efficiency as 0.92; the distribution efficiency can be found by dividing the overall efficiency (0.92) by the extraction efficiency(0.95). The distribution efficiency is thus 0.97.

From data given by Mooz (1973) one can estimate that the distribution efficiency of coal by train over a 60 mile journey is 0.998; however more detailed analysis is required to justify this figure as being right for the overall efficiency of coal distribution.

A4.5.5 Electricity

The UK operates one of the largest centralised electricity supply networks in the world. From the modelling point of view this has the disadvantage that it is complex because of the diverse nature of the power stations and the advantage that no regional modelling is required, since it is a coherent system (the justification for this is that England and Wales constitute 87 % of UK electricity demand and that there is some trading of electricity between Scotland and England). Furthermore there are plans to increase the total power of our electricity exchange links with France from the present 100 MW to a total 2100 MW. Considering how the diversity of electricity demands, supplies and stores might increase with a better integrated Anglo-French system it is surprising that this idea has not been examined more fully. But, as they say, this would be another "bouilloire de poissons" altogether. [2]

The UK aims to plan and operate its mix of power stations in such a way as to minimise its total cost of supplying a certain amount of electricity over a certain period. In order to do this they must account for the variability in demand and the capital and running cost associated with each type of power station. Power stations supplying electricity a large proportion of the time (i.e. having a high load factor) tend to have high capital and low running costs, the latter comprising fuel, maintenance and operational costs. This leads to the notion of the merit order which is an ordering of the power stations available according to the criterion below (where i refers to position of the power station in the merit order as defined by the load factor).

$$(C_i+M_i)+K.lf.P_i/\eta_i < (C_{i+1}+M_{i+1})+K.lf.P_{i+1}/\eta_{i+1}$$

where C is the annual capital cost ($£.kW^{-1}.a^{-1}$)

M is the annual maintenance cost ($£.kW^{-1}.a^{-1}$)

K is a constant (31.536)

---

[2] In fact the electricity industry is considering links with other countries too, such as Belgium.

η is the efficiency

P is the fuel price ($£.GJ^{-1}$)

lf is the annual load factor

for all i=1, (n-1), where n is the total number of the stations.

There is no reason to presume that the above criterion will be used in future times. In general all the costs and performances that determine the merit order are variable. Maintenance schedules, transmission or station failures, start up times and so on make the merit order vary with time. It is obviously out of the question to attempt a detailed simulation of the system since the real system requires very large amounts of manpower and computing facilities. However the merit order presented below integrates what seems to be a logical sequence of electrical generators utilising ambient energy sources with the mix of conventional power stations. The merit order for this mix is determined as outlined below.

It is interesting to note that the "spiky" output from ambient electrical generators would require a correspondingly "spiky" out-of-phase output from switchable sources (nuclear, coal, oil, gas and pumped storage). Most switchable stations are thermal power stations which can not vary their output rapidly without a loss in thermal efficiency. Furthermore, the load factors of thermal power stations would necessarily drop. Thus ambient and thermal power sources are in many ways mutually incompatible (unless storage is large). A high ambient component would probably require rapid response low capital high fuel cost thermal power stations as back-up (e.g. gas turbines).

A4.5.6 Merit order

The power stations highest in the merit order consist of these which must necessarily operate, namely combined heat and power, and those which are not switchable, namely ambient power stations. These latter are of high priority since they have high capital and zero fuel costs. Furthermore they do not have fuel stores.

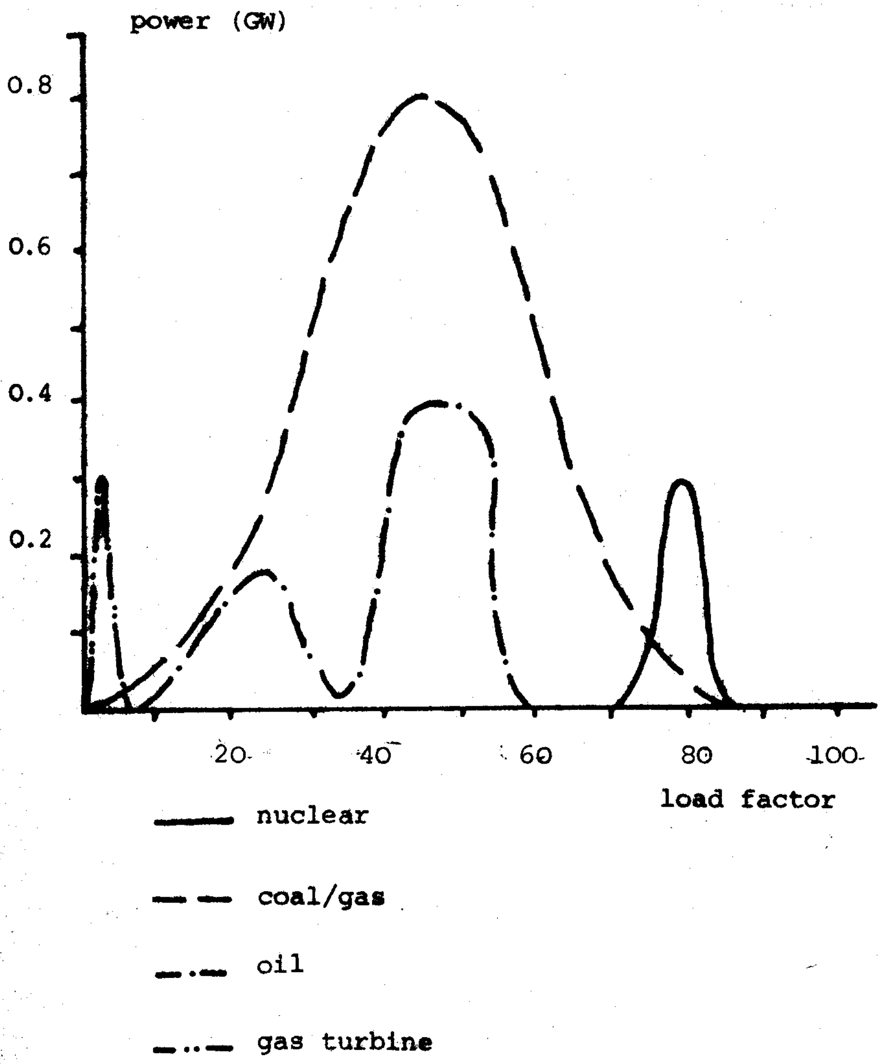
Thus a reasonable guess at a future merit order might be as follows.

MERIT	TYPE	REMARKS
1	CHP	Essential for human needs. Electricity produced pro rata with heat demand.
2	Aerogenerators	Geographically dispersed, no storage.
3	Wave machines.	Most distant, non storable.
4	Tidal power	Some storage, but tides must be used available.
5	Freshwater hydropower.	Output storage only, cheap.
6	Pumped storage.	
7-11	Conventional thermal.	Merit order described below.

The position of pumped storage in the merit order varies according to a fairly complex algorithm, which is described in the appendix on pumped storage. Given some demand for electricity the power sources are brought into action in the merit sequence until demand is satisfied. Each power station type increments its power by some amount. Ambient generators produce electricity in increments of electric power of 10% of the total available output from that particular type of device, until demand is satisfied or the output limit is reached. Thus if there were 1563 MWe available wave machine output, each increment would be 156.3 MWe. The exception is tidal power; this is always incremented by 250 MWe each time.

The merit order of the conventional power stations is roughly estimated from the power at each load factor; these are shown in the figure below. Note that the load factors assumed for nuclear stations is for the more reliable sets. Some of these stations operate at load factors far below design levels because of technical problems.

Figure A4.8 UK power stations: power vs load factor



The power is taken incrementally in steps of 250 MW; the merit in steps of 1 GW. Firstly the nuclear is brought on stream, then half the coal, then natural gas, then coal and oil and finally gas turbine (oil fired). This procedure is illustrated in the example below.

Example

Suppose there were 5 GW nuclear, 10 GW coal and oil, 2 GW natural gas, and 2 GW gas turbine. The merit ordering would be -

Merit

1 -5 nuclear.

6 - 10 coal

11 - 13 natural gas

14 - 23 coal and oil equally.

24 - 28 oil.

29 - 33 gas turbine.

A more accurate ordering would require excessive computing time. The 1976 merit order has been estimated from data. One problem encountered in merit ordering is dual fired stations, particularly coal/natural gas fired stations. These are modelled by dividing the declared net capability of the dual fired stations equally between coal and natural gas. (The merit order of thermal power stations can be defined exogenously if desired.)

The model simulates this merit order by flipping through the merit order summing the total power output until supply meets demand in the particular hour being simulated. The first five generator types (CHP, wind, wave, tidal and pumped storage) provide a variable output whereas the remainder always increment 250 MW at a time. The exceptions to this rule are gas turbines and pumped storage. The former are brought on stream if either the total load necessitates their usage (i.e. if all other thermal stations are in use) or if the rate of change of demand exceeds a certain amount. Pumped storage is also turned on if the rate of change of demand exceeds a certain amount. Thus gas turbine and pumped storage are used as rapid response stations.

A4.5.7 Technical description of electricity generators

(i) Combined heat and power

Modern power stations are approaching the maximum efficiency for the production of mechanical work (and thus electricity) as determined thermodynamically, given the temperatures the heat engine presently operates between. No further large improvement can be expected barring breakthroughs in material properties or the use of topping cycles. As is usual with energy converters, the efficiency is calculated from the useful energy output and the total fuel energy input. If heat is rejected from the power station heat engine at 100 C. rather than a few degrees above ambient temperature it can be used to meet low temperatue demands, such as for space and hot water heating. However thermodynamic contraints mean that less work will be produced. This is exactly what a combined heat and power station does. The rejected heat is piped as hot water to the point of demand with some transmission loss, generally of the order of 10 % (Courtney, Macadam, 1976). The electricity is sent to the grid as normal. The efficiency of the station at producing work (i.e. electricity) falls because of the increased temperature of the low temperature reservoir; however the efficiency of the power station at producing useful energy is roughly doubled, because useful heat as well as work is now produced.

The technicalities of such stations can not be included here. The combined heat and power station assumed here is a back pressure turbine system. A fuller account of such machines are to be found elsewhere (e.g. Energy Papers 20, 34, 35; and Robinson(1979)). The details of operation that concern us are given below.

Efficiency of electricity production = 0.25

Efficiency of heat production = 0.50

Overall station efficiency = 0.75

Heat transmission efficiency = 0.9

The system is operated such that electricity is only produced on a fixed pro rata basis with heat, i.e the efficiencies are constant. This performance would correspond to a back pressure rather than a variable ITOC [3] CHP machine.

Combined heat and power is also used to some extent in industry for private supply; it is often called cogeneration. The efficiencies of industrial CHP are assumed to be 0.11 (fuel to electricity) and 0.56 fuel to heat. The basis for this is described in the appendix on industrial converters.

(ii) Aerogenerators

Aerogenerators are devices which convert some of the kinetic energy in the wind into electricity. Wind power can also be used to produce mechanical power, as in the old grain windmills, or to produce heat. It is assumed that wind is used to produce electricity for the centralised electricity grid for the following reasons. Firstly, the wind is a high grade source of energy, namely work, and unless aerogenerators were very cheap it would be economically wasteful to produce heat, which can be sold for less than electricity. A large proportion of the capital cost of wind devices is in the supporting structure; this generally makes it worth while installing the conversion gear necessary to produce electricity. Secondly, there are reasons why aerogenerators would be remote from centres of demand. Wind intensities tend to be greater and more reliable at coastal or high altitude sites where there are rarely large populations. Furthermore it seems likely that aerogenerators could cause a disturbance if sited near people because of noise and unsightliness. Their impact on ecological systems must be examined.

The conversion pathway to electricity from wind energy involves the conversion to mechanical power and thence the generation of electricity in a form suitable for the electricity distribution system.

---

[3] ITOC means intermediate take off and condensing.

The power of the wind (P_w (W)) passing through an aerogenerator of swept area $A_s(m^2)$ at a speed V_w (ms^{-1}) is :

$$P_w = 0.623\ V_w^3\ A_s \qquad (W)$$

Theoretical studies find that the maximum mechanical power that may be extracted (P_m (W)) is a proportion C_p of P_w. Estimates for C_p are 0.593 (as usually assumed) and 0.687. The values require experimental validation; 0.593 will be assumed here. Thus

$$P_m = 0.593\ 0.623\ V_w^3\ A_s \qquad (W)$$

In practice, an overall maximum power coefficient C_{op} is used. This pertains to the maximum mechanical power under optimal conditions. Some values are shown below.

Table A4.1 Technical characteristics of aerogenerators

C_{op}	TYPE	$\eta_a = C_{op}/C_p$
0.415>0.475	Horizontal	0.7>0.8
0.15>0.3	Vertical	0.25>0.5
(0.62)	(tracked)	(1.04)

C_{op}/C_p may be thought of as the aerodynamic efficiency, η_a. The electrical output P_e (W) is calculated from P_m by using the combined electromechanical efficiency, η_{em}, thus

$$P_e = \eta_{em}\ \eta_a\ 0.593\ 0.623\ V_w^3\ A_s \qquad (W)$$

The aerogenerator design used in the model will be based on the 23 m. radius machine described in EP21 (1977). The machine starts to operate at some "cut in" wind speed (V_c) and reaches maximum electrical output at the rated wind speed, V_r. EP21 concludes that the optimal values for V_c and V_r are

$$V_c = V_r / 2 \qquad (ms^{-1})$$

and

$$V_r = 2.3\ V_a \qquad (ms^{-1})$$

where V_a is the annual average wind speed.

For the wind speed site chosen V_a is 7.4 ms^{-1}, allowing for the height of the generator; V_r is therefore 20 ms^{-1} and V_c is 10 ms^{-1}.

η_a is assumed to be a constant 0.75 for these machines. η_{em} is also assumed to be a constant 0.8.

The rated or maximum electrical output, P_{er}, at the rated wind speed is

$$P_{er} = \eta_{em}\ \eta_a\ 0.593\ 0.623\ V_r^3\ A_s \qquad (W)$$

$$= 0.83\ 0.75\ 0.593\ 0.623\ (20)^3\ 1661 \qquad (W)$$

$$= 3.06 \qquad (MW)$$

At wind speeds greater than 20 ms^{-1} excess power is shed.At speeds less than 20 ms^{-1} P_e is calculated from the equation above, but note that η_a is assumed constant.

The total electrical power available P_{et} (W) from S_a such generators is simply

$$P_{et} = S_a\ P_e \qquad (MW)$$

(iii) Wave machines

Wave machines convert some of the energy in waves to a useful fuel. Since the energy in waves is high grade mechanical energy and the siting of such machines is necessarily distant from land based energy demands, it will be assumed that wave machines will be used to produce electricity for input to the electricity transmission system. It is possible that other conversions might be appropriate, such as to hydrogen gas via electrolysis. The environmental impact of large arrays of wave machines has yet to be discussed and investigated in any detail.

The efficiency of wave machines is defined as the ratio of the electricity output to the wave energy incident on the wave machines. In general the overall efficiency of wave machines in the production of electricity (η_w) is the product of the wave-mechanical efficiency (η_w) and the mechanical-electrical efficiency (η_{me}). In general the efficiency of wave machines (η_w) is determined by the energy periods and root mean square heights of the waves, i.e.

$$\eta_w = \eta_w (T_e, H_{rms})$$

The useful electricity output ($P_e(t)$) at any time from a length (L_w) of such machines when the intensity of the incident wave power is I_w, is accordingly

$$P_e(t) = \eta_w I_w L_w \qquad \text{(W)}$$

There are maximum values for the incident intensity I_w at which the mechanical or electrical power capacity of the wave machine will be exceeded: it will thus start to shed any excess wave power. The fact that the financial cost of the machines, whatever their design, is largely dependent on these power capacities (i.e. the cost in £/kW is high) and that high intensity wave conditions, such as in a storm, are relatively rare means that it is uneconomic to catch the largest, most powerful waves.

The determination of this optimum power capacity is complex as it will vary according to the machine and installation site.

Many designs of wave machines have been proposed and some of these have been developed to the small scale prototype stage (e.g. at Edinburgh and Southampton Universities). They operate in a number of different ways; from the direct mechanics of Cockerell's rafts (being studied at Southampton University) to devices in which the wave energy drives turbine generators via compressed air (at Lancaster University). At the time of writing the most developed and documented is the type under development at Edinburgh University in the Department of Mechanical Engineering. The project is directed by S. H. Salter. The machine being developed is called a "duck".

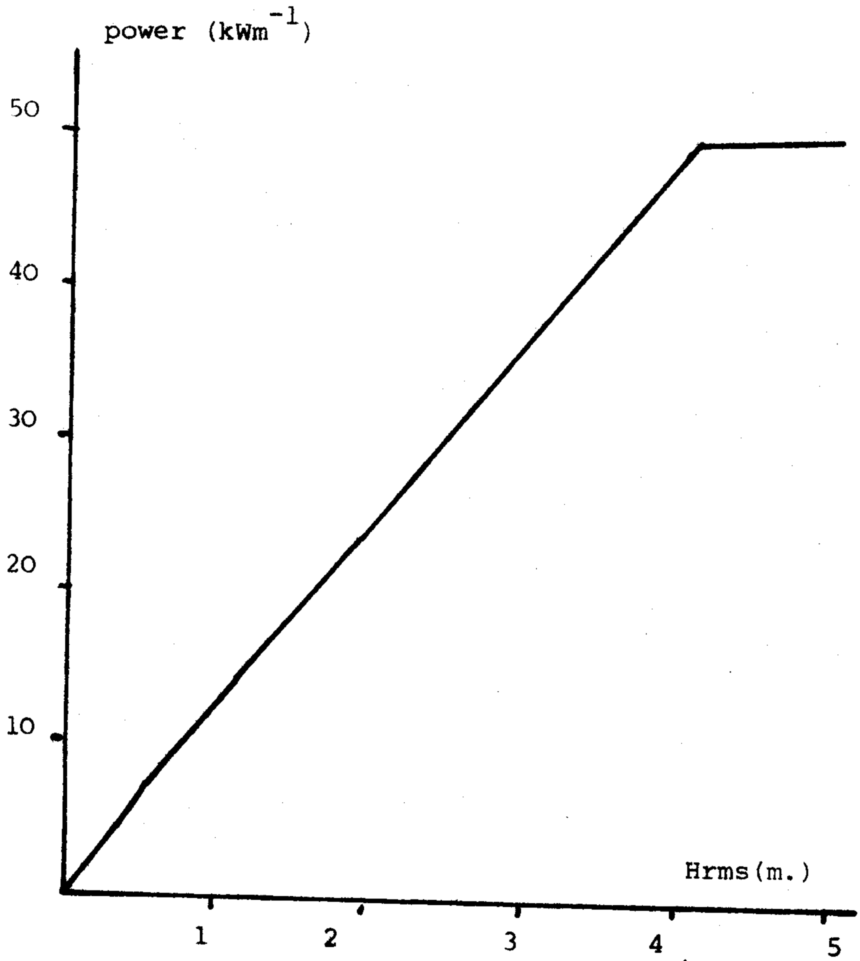
It is only because of the relative abundance of data on ducks that they are used in the model; it would be premature to choose one particular design now.

The functions for efficiency given below are all derived from the experimental results of the performance of scale model ducks given by Edinburgh University (1978). These results relate to ducks with fixed and moveable mooring (called fixed and unfixed rig), various torque limits and diameters in a variety of simulated seas. The maximum torque limit allowable approximately determines the maximum mechanical power output; the correlation being roughly 100 kWm^{-1} ouput per $MNmm^{-1}$ torque (although this conversion factor is slightly different depending on whether the rig is fixed or unfixed). The optimum choice of duck diameter and torque limit is affected by the seas likely to be encountered at the site of installation and the capital costs of the wave machine. However it seems likely that for the type of seas extant to the NW of Scotland a 10 m. diameter with a torque limit of 0.5 $MNm.m^{-1}$ and an output of 50 kWm^{-1} might be near the optimum.

The overall efficiency of a 10 m. duck with a 0.5 $MNmm^{-1}$ limit is such that the power output of the duck is largely independent of the energy period (T_e) of the waves and strongly dependent on the root mean square height of the waves (H_{rms}). The mechanical power output from such ducks (P_w) is depicted in the figure below; it is an approximation to the family of curves for different periods shown on page 2.9 of the Edinburgh wave power report(1978).

The figure below depicts how the power output of the duck varies with wave height.

Figure A4.9 Power output vs wave height for a Salter duck



This curve may be approximated by:

$P_w(t) = 12.5 \ H_{rms}(t)$ ($MWkm^{-1}$)

for $0 < H_{rms} < 4$

$P_w(t) = 25$ ($MWkm^{-1}$)

for $4 < H_{rms}$

The electrical output $P_e(t)$ at any time is obtained by multiplying the efficiency of conversion from mechanical power to electricity (η_{me}) by the transmission efficiency for electricity (η_{et}) ashore and the length of the wave machine array (L_w), thus

$$P_e(t) = \eta_{et}\,\eta_{me}\,P_w(t)\,L_w \qquad \text{(MW)}$$

$$P_e(t) = (0.95)\,(0.70)\,P_w(t)\,L_w \qquad \text{(MW)}$$

This equation will be used to calculate the electrical output from the array of ducks.

These assumptions concerning duck performance are derived from scale models in laboratory conditions. Therefore the usual reservations about the accuracy of such results as applied to real seas at full scale should be made. Perhaps the major uncertainty lies in the response of ducks to waves incident in many directions, unlike the laboratory waves. It does seem unlikely that the error due to this is very large, perhaps a reduction of 5 - 20 % in the expected output.

This very brief description of wave machines largely arises from the research results, methods and thoughts presented in the report by Edinburgh University (1978), although the author acknowledges all responsibility for this presentation.

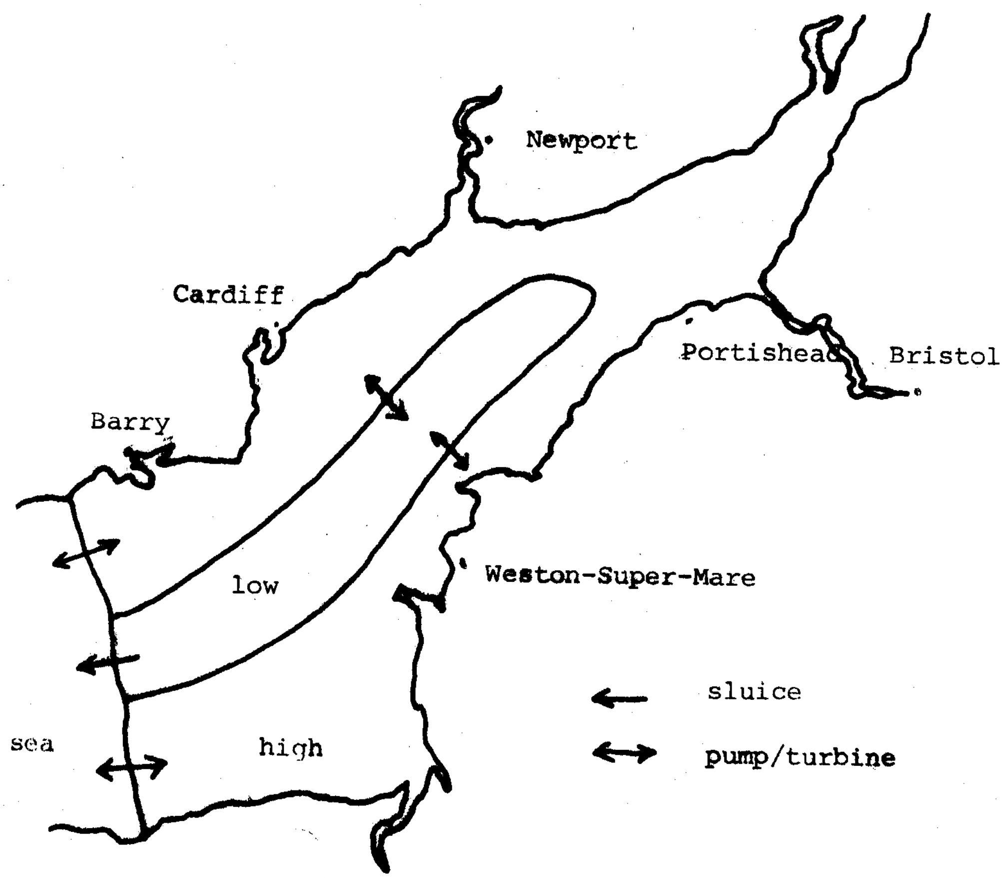
(iv) Tidal power

A Severn tidal scheme will be modelled. E. M. Wilson (1965) presented calculations which indicate that there are other plausible sites for tidal power development; these being at Morecambe Bay, the Dee estuary, the Solway Firth and the Humber estuary. He estimates that these other sites could collectively produce as much as a Severn estuary (or Bristol channel) scheme. Other workers suggest that tidal streams may be directly harnessed by underwater "windmills" of the vertical axis type. Such a technology would not require the large civil engineering works engendered by schemes with storage reservoirs. Fraenkel and Musgrove (1979) estimate that there is an average 14.7 GW of power from four major channels around the UK. Judicious choice of siting might alleviate the load matching problems encountered by such zero storage systems. However this particular technology will not be modelled here.

The tidal scheme included in this model is a two basin combined storage and generation system sited in the Severn estuary. The approximate sizing of the basins, sluices and pump/turbines is taken from other research workers (e.g. CEGB Research, 1979, EP 23).

A schematic plan of such a scheme is shown in the diagram below.

Figure A4.10 Schematic of Severn tidal power system



The performance of such a scheme is determined by the physical characteristics of the basins, sluices, turbines and so on as well as the water levels and the method of control. Research into Severn schemes is yet in its infancy and a thorough assessment of its impact on the local ecosystems and communities will be a lengthy undertaking. However, the model will as elsewhere limit itself to the description of the energy flows likely to be encountered in such a project, although it must be emphasised that the accuracy will be limited by the limited technical data available concerning the hardware characteristics and the essentially crude description by this submodel.

The physical characteristics of the scheme are assumed to be as detailed below. However this scheme may change according to the nature of the electricty demand and the rest of the electricity supply system. Furthermore it is possible that the scheme could be built piecemeal which would ease the problem of designing a technology with such a long lead time.

(A) Reservoirs

The table below details the gross characteristics of the reservoirs that are pertinent to the operation of the scheme.

Table A4.2 Characteristics of Severn tidal scheme

Reservoir	High	Low
Area(km^2)	580	222
Min. Height(m)	0	0
Max. Height(m)	15	15

The total potential energy available from tidal movement in one day may be calculated. This calculation does not tell us how much electrical energy might be produced.

Assume two tides a day (in fact the tidal cycle lasts about 12.66 hrs) causing a 15 m. change in height over 800 km^2. of reservoir. Total potential energy E_p is

E_p = 2(Area dH D g dH/2) (J)

= 2(800 10^6 15 1000 9.81 7.5 2)

(J)

= 74 (TJ)

= 218 (GWh)

The proportion of this potential energy that may be extracted as electricity depends on the operation and control of the pumps/turbines and the scheme's interaction with demands and other supplies.

(B) Reversible pumps/turbines

At present the performance characterisics of low head reversible pumps/turbines suitable for a Severn tidal power scheme are vague. This is because the "optimal" design for the basins and the control system has not been decided. This is hardly surprising since the long construction time involved for such a scheme (up to 30 years) necessitates a long term prediction of the electricity supply and demand systems. However data of the performance of low head hydro machinery used at La Rance (France) and as manufactured by Allis Chalmers can probably be considered similar, although the units are much smaller in power output (30 times less). Since these units are not purpose designed for the Severn scheme the performance assumed might be pessimistic.

The table below gives the efficiency, η, (electrical power in or out/total power of water throughput) of La Rance (LR) and Allis Chalmers (AC) machinery and the calculated values of this efficiency.

Table A4.3 Efficiency of tidal machines

Head(m)	η(gen)	η(pump)	η(calc)
15	0.87(AC)	-	0.87
11	0.77(AC)	-	0.86
10	0.85(LR)	-	0.85
9	0.87(LR)	-	0.84
7	0.84(LR)	-	0.79
6	0.63(LR)	-	0.75
5	0.71(AC)	-	0.69
3	0.54(LR)	0.5(LR)	0.53
2	0.44(LR)	0.38(LR)	0.41
1	0.22(LR)	-	0.26

Assuming that the efficiency of pumping is the same as for generation at any given head (H), the calculated values in the table above were derived from the following function for the efficiency of pumping or generating (η(H)):

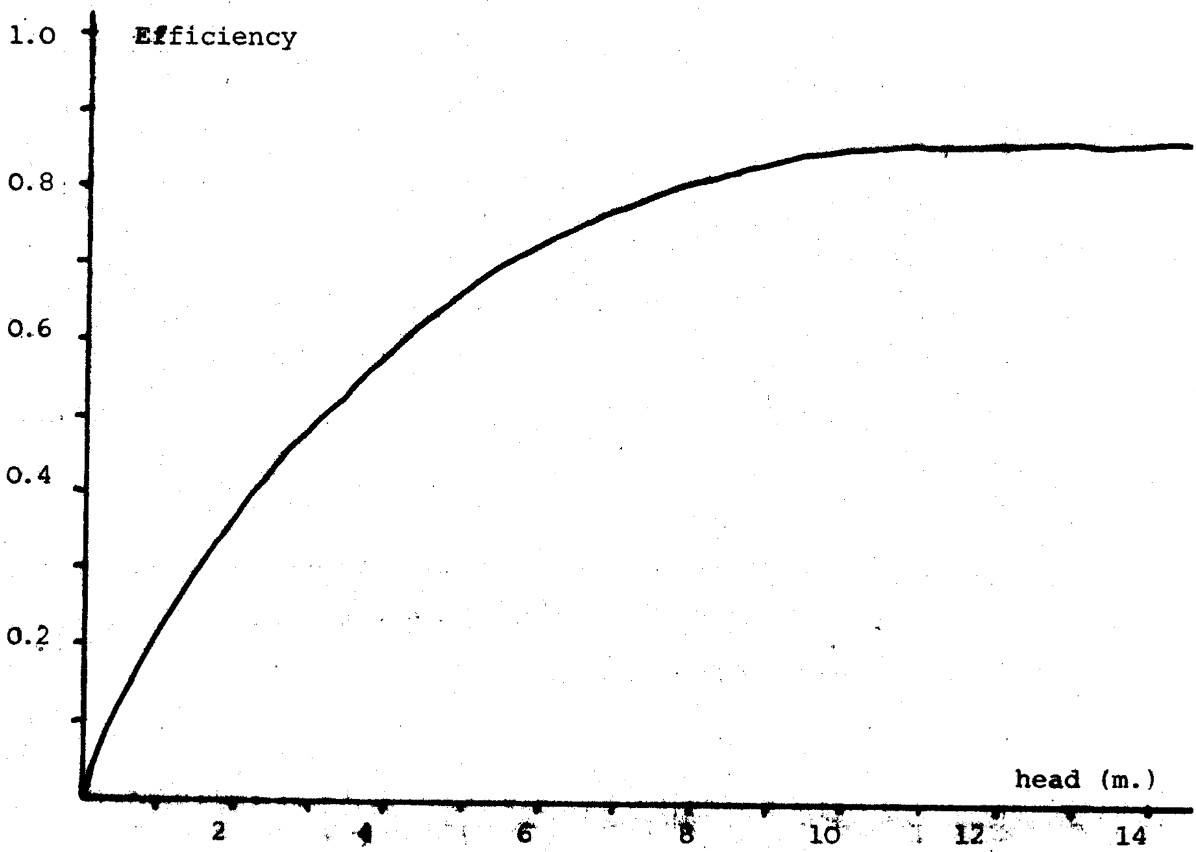
$$\eta(H) = 0.87 - 1.30(10^{-5})\ (16-H)^4$$

for $0 < H < 16$ (m.)

Because the efficiency is so low at low heads and rotational speeds can be too low, there is usually a minimum operating head for turbines/pumps.

The figure below shows the efficiency of the turbines/pumps as based on the function derived from pertaining to operational schemes or equipment.

Figure A4.11 Efficiency of tidal machines



The reversible pumps/turbines are positioned to operate between the high (h) and low (l) reservoirs and the high reservoir and the sea (s). The total maximum electrical capacities of these sets of machinery operating in any mode are P_{hl} (MW) and P_{hs} (MW) respectively.

Generation

The maximum flow rate through the turbines when generating, M_{mg}, as derived from data given by Allis and Chalmers, is:

$$M_{mg} = (1/1000)\ P\ (8.0-0.0092\ C^2) \qquad (1000\ m^3 s^{-1})$$

where P is P_{hl} or P_{hs} (MW)

C 2 15.0 -head (m)

The maximum instantaneous mechanical power is

$$P_m = M_{mg}\ H\ g \qquad (MW)$$

where g is gravity ($9.81\ ms^{-2}$)

The maximum electrical power is

$$P_{em} = N(H)\ P_m \qquad (MW)$$

The electrical power is drawn off in increments of 250 MW; the flow rate in any increment is thus $250/P_{em}$ times the maximum flow rate. If this flow lasts for one hour, the change in height of the reservoir is

$$\triangle H_r = (M_{mg}\ 900)/(P_{em}\ A_r) \qquad (m)$$

where the area of the reservoir is in km^2.

This incrementation continues until either

(i) the maximum electrical power is produced

(ii) sufficient power has been generated

(iii) the reservoir heights reach a maximum or minimum

(iv) the head is insufficient for operation

Storage

Given the electrical pumping power required in any hour (P_r) and the heights of the reservoirs and the tide to give the head (H), the pumping flow rate (M_f (m^3s^{-1}) may be calculated:-

$$M_f = P_r/(g\ H\ \eta(H))\ (m^3s^{-1})$$

The consequent changes in the heights of water in the reservoirs are simply calculated from the flow rates, the reservoir areas and the flow time. The calculations for pumping are done in increments of 250 MW.

(C) Sluices.

Sluices are used to empty the low reservoir when the height of the low reservoir exceeds the height of the tide. The flow rate M_s through N_s Venturi sluices each of area A_s at a head H is (from N. Heaps, 1972)

$$M_s = \sqrt{(2g)}\ (C\ A_sN_s)\ \sqrt{(H)} \qquad (m^3s^{-1})$$

where g is gravity

C is the Venturi sluice coefficient (=1.6)

The sluices must empty the reservoir quickly enough to retain a reasonable working head between the high and low reservoirs. 120 sluices each of area 80 m^2. would give a rate of fall of about 1.5 m/hr in the low reservoir height at a head of 2m.; this should suffice. Calculations for the sluice flow are in increments of 1/5 of an hour.

(D) Operational control

Basically the scheme can operate in a maintenance, an output or an input mode.

(a) Maintenance

If the level of the low reservoir exceeds the level of the tide the sluices are opened. If the tide is higher than the the high reservoir level the sluices between high and sea are opened.

(b) Generation

The order of priority of generation is sea to high, high to low and high to sea. Water is only allowed to flow through the turbines if there is a sufficient head, usually about 3 m., and the reservoir heights are within the allowable range.

(c) Storage

The order of priority for the storage of surplus electricity is low to high followed by sea to high. The reservoir heights must again stay within the allowable ranges.

As with many other parts of the energy system the control aspects of tidal power are only crudely modelled. This is especially so with tidal power since its potential output is predictable in so far as tides are predictable, and experience of the UK electricity demand allows fairly accurate forecasting over periods of a day or more. It is therefore likely that enhanced control strategy of greater sophistication would enable increased electricity production and storage.

(v) Freshwater hydroelectricity

Freshwater hydroelectricity results from the harnessing of the gravitational potential energy of water which can drop through some height, from a high reservoir to a low reservoir or river. The potential energy available (E) is proportional to the height difference (H), the mass of water (M_w) and gravity (g) thus;

$$E = M_w \, g \, H \qquad (J)$$

The height difference and the volumes and catchment areas depend on how the scheme employs the local topology. The mass of water available for generation depends on the rainfall and catchment area of the high reservoir. It is fortunate that rainfall is generally greater in high altitude places. This potential energy can be extracted using high head schemes, usually involving storage, or in low head, "run-of-the-river" schemes with little storage. These latter are ignored, although it may be that such schemes will be found worthwhile now, as in the past.

The actual electrical energy which may be generated from the potential energy depends on the efficiency of the turbogenerators. This efficiency is about 0.85; this being typical for any high head hydro scheme. The technology has not advanced greatly in terms of efficiency in recent years.

Due to the essentially small scale nature of geographical formations in the UK (as compared to countries with large hydro schemes, such as Canada) there is a large number of small schemes. The NSHEB operates 55 hydro stations, the CEGB operates 7; their electrical power capacites range from 20 kW to 130 MW. A detailed account of these generators is therefore not possible here. The contribution of hydropower to electricity supply is assumed to be a 14 hour output extending from 8:00 hrs. to 21:00 hrs. Private communication with the NSHEB indicates that this is a typical operating pattern for this machinery. In reality the output will depend on the other sources of electricity and on whether there has been sufficient rainfall to charge the high reservoirs.

The table below gives the salient details for freshwater hydropower in operation in 1976.

Table A4.4 Freshwater hydropower

BOARD	MAXIMUM OUT(GW)	AVERAGE OUT(GW)	ANNUAL OUT(GWh/a)	STORAGE OUT(GWeh)
NSHEB	1.050	0.333	2912.0	939.3
CEGB	0.111	0.033	292.0	?
TOTAL	1.161	0.366	3204.0	939.3

Pumped storage is not included here. However the Cruachan and Foyers pumped storage schemes actually provide some generation from their own catchment areas; this contribution which amounts to about 135 GWh annually has been added to the NSHEB output. The model assumes that there is one aggregated hydro scheme and that its output is such that it tends to the average annual power output.

Since the development of freshwater hydropower is constrained by a complex of economic, geographical, meteorological, ecological and legal factors it is difficult to guess what its future role might be. It is interesting to note that estimates of the Scottish Highlands hydroelectric potential contribution quadrupled between 1921 and 1965. L. Grainger (1977), in an editorial summary, presents high head estimates that the UK might extract 12 TWhe/a of the total potential 63 TWhe/a in the UK; a fourfold increase in the hydro contribution nationally. Its very high availability (about 95 %), long lifetime (usually at least 50 years) and non-polluting renewable nature coupled with fairly low cost (£300/kW) make it a relatively desirable source of electricity. Many aspects of hydroelectric power are discussed by C. Lippold of the OUERG (Lippold, 1980).

Of particular interest is the low head hydroelectric potential of the UK; an estimate of a possible 4500 MWe for England and Wales has been reported (Observer, 19/10/80). This estimate, from a confidential 1977 Department of Energy report, would correspond to 31 TWh/annum of electricity (assuming an 80 % load factor), or about 14 % of present UK electricity demand.

(vi) Conventional thermal power stations

Conventional thermal power stations convert a fossil or fissile fuel into heat by oxidation and fission respectively. There are some losses in this basic heat production, but for the most part they occur in the extraction of work via a heat engine. The heat engine operates between the high temperature in the "furnace" heat to steam exchangers (about 600 C) and the low temperatures in the waste rejection exchangers (about 25 C).

The net output electrical power of each type of power station (by fuel) and the efficiency characteristics as derived from statistical data enable us to calculate the fuel use by power stations.

Because of maintenance requirements different power station types have different availabilities for electrical power generation. If the total installed capacity of each type is multiplied by the availability the actual available capacity is the result. Because of the maintenance scheduling the winter availability of some stations may be higher than the annual average availability; thus meeting winter demands more efficiently or cheaply. The table below gives these calculations; they pertain to the UK system in 1976. Data is from EP 39, 1979, pages 34 and 223. The load factor assumed for nuclear power is higher than past experience has shown, but the assumed 0.70 is meant to apply to future, more reliable plant.

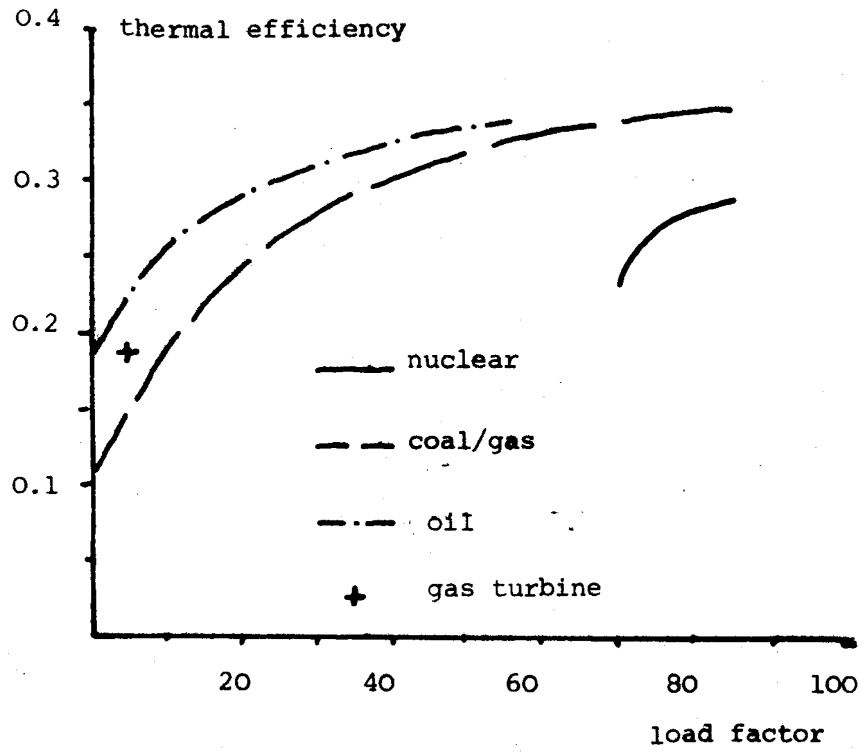
Table A4.5 Conventional thermal power stations capacities

All powers are in GW.

TYPE	CAPACITY	AVAILABILITY	ASSUMED
Coal	45.0	0.70	32.0
Oil	12.0	0.70	11.0
Nat. Gas	1.5	0.85	2.0
Nuclear	5.0	0.70	3.0
(Hydro	1.5	0.95	1.4)
G.turb, dies	2.0	0.85	2.0
(Pumped	1	1.0	0.9)

The fuel requirements for each power station are determined by the power output and the efficiency. The required power output is known so it remains to calculate the average efficiency of each power station when it is meeting a particular load. CEGB data provide figures for the efficiency and power outputs of different station types (after appropriate calculations of the source statistical data). These are derived as functions of the annual load factor. These functions are depicted in the figures below. It is assumed that although these data are from CEGB sources they are generally applicable to UK stations.

Figure A4.12 UK power stations: efficiencies vs load factor



For fossil fuels the thermal efficiency of the power stations is simply the energy content of the electricity produced divided by the thermal content of the fuel burnt. For nuclear power stations efficiency is the electrical output divided by the heat produced by fission in the station. There is no unique value for the heat which may be practically extracted from fissile fuels since it depends on the type of station and fuel. Furthermore the "waste" fuel from nuclear power stations generally contains sufficient fissile energy to warrant reprocessing. The flows of the various radioelements in breeder reactors is even more complex.

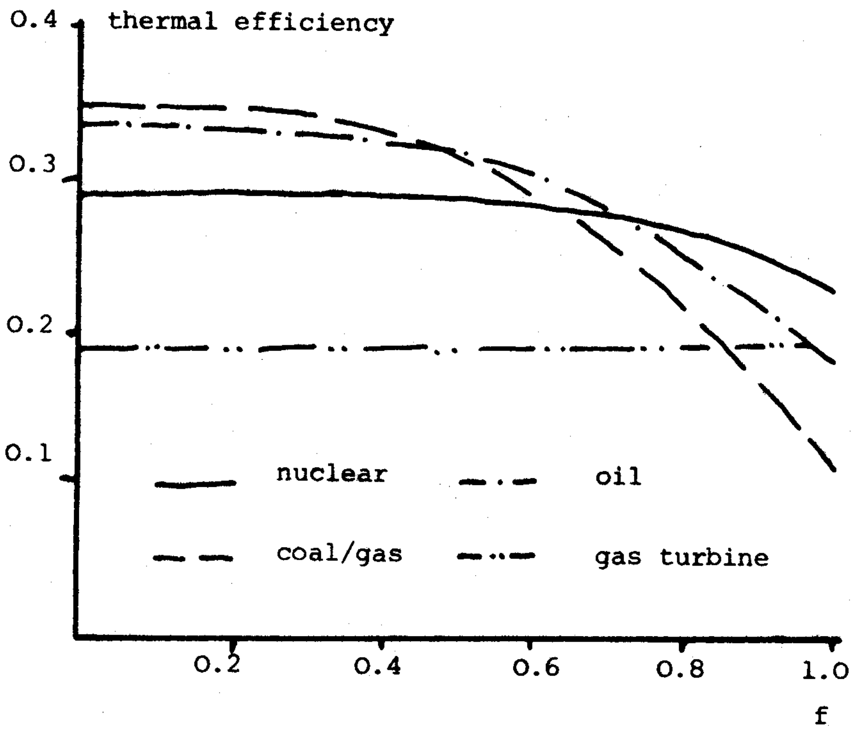
It is because of this complexity that nuclear fuel processing technologies will be grossly simplified. The efficiencies (and other technical characteristics) will be dependent in part on things like ore or waste grade and the type of nuclear fuel required. Import and export of nuclear materials complicates things further.

For thermal stations the thermal efficiency (η_{lf}) and the power (P_{lf}) at each load factor (lf) are estimated from CEGB statistics. These functions may be rescaled as functions of a factor f, where f is

$$f = \pi\,(lf_{max} - lf)/(lf_{max} - lf_{min})$$

The resulting efficiency functions are shown below.

<u>Figure A4.13 UK power stations: efficiency vs factor f</u>



If it is assumed that

(a) the load factors reflect the merit order.

(b) The power distributions are sinusoidal.

(c) The efficiency functions are the same form for all station types.

one can calculate the efficiency N_f of the next station switched on at a total output P_{tf} for that type.

At factor f, P_f, the output power, is

$$P_f = P_1 \sin(f) \qquad \text{(GW)}$$

where P_1 is half the total available power of a particular station type.

Total power up to f

$$P_{tf} = \int (P_1 \sin(f))\, df \text{ between 0 and f} \qquad \text{(GW)}$$

$$= P_1 - P_1 \cos(f) \qquad \text{(GW)}$$

[The total power of the stations in each category, P_t, is thus

$$P_t = P_1 - P_1 \cos(\pi) \qquad \text{(GW)}$$

$$=2\ P_1 \qquad \text{(GW)}$$

and thus $P_1 = P_t / 2$]

So, given P_{tf} (the total instantaneous output of that particular category of station) one may calculate f from the above:

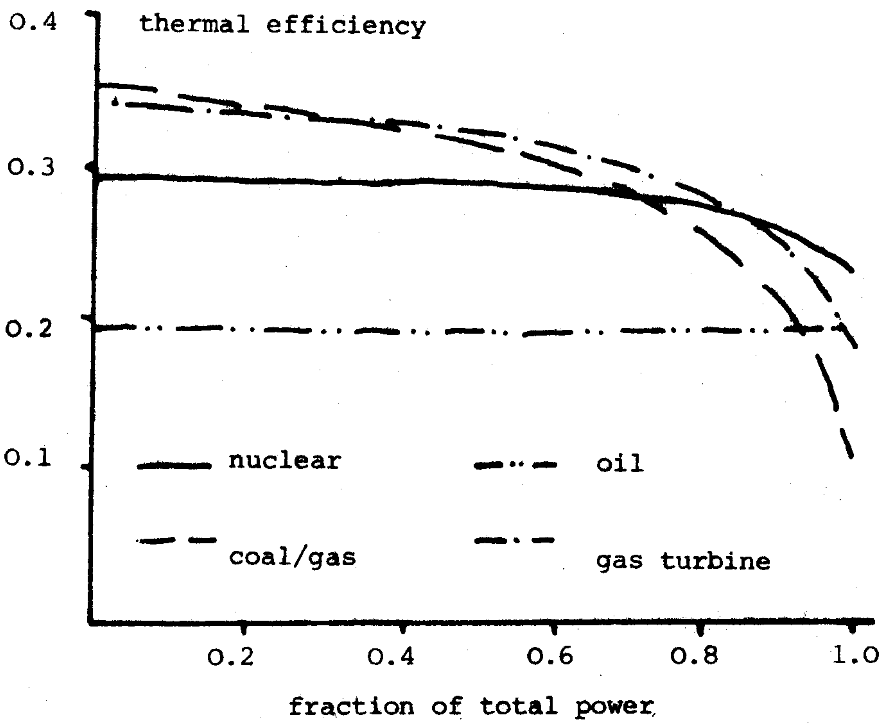
$$f = \cos^{-1}(1-P_{tf}/P_1)$$

Given this value for f and the assumption that the efficiency may be approximated by

$$\eta_f = \eta_{max} - (\eta_{max} - \eta_{min}) (f/\pi)^3$$

The efficiency of any power station type at any load (P_{tf}) may thus be found. These efficiencies are shown below.

Figure A4.14 UK power stations: efficiency vs total power



(vii) Nuclear fuel production

Since nuclear energy is predominantly used for electricity generation it is included here. It is assumed that the processing of uranium ores and the reprocessing of waste fuel has an average efficiency of 0.50. This efficiency is the net useful nuclear fuel (thermal energy potentially liberated in a certain reactor type) divided by the net useful energy produced plus the energy for processing. This definition is perhaps not the best way of dealing with this process.

The power output of the processing plant is assumed to be sufficient to meet the demand for nuclear fuel.

(viii) Electricity transmission/ distribution

The losses in transmitting ex-works electricity to the distribution system are about 2 % and the losses in distribution are about 6 % giving an overall efficiency of transmission and distribution of 0.92 (EP 39, 1979, Vol 1, p45). This overall figure conceals differences for the transmission losses for geograpically remote generators (e.g. nuclear, wave) and those near demand (e.g. CHP). This could be an important omission, both because of the losses involved and because of the capital cost of transmission (about 10 % of total electricity investment in 1979) and distribution and other hardware (about 35% of total).

A4.5.8 Biomass

(i) Plants

Plants convert solar energy into organic materials by photosynthesis; this may be represented by the general process

$$H_2O + CO_2 \xrightarrow{\text{sunlight}} \text{organic materials} + O_2$$

If this process is later reversed by oxidation of some of the organic materials a part of the original solar energy input may be usefully liberated. This section will attempt to estimate the average efficiency of plants in "fixing" solar energy into a form suitable for the production of fuels; this latter production is discusssed in the next section.

Firstly it must be noted that plants themselves use some of the fixed energy for their own metabolism, thus they consume oxygen and liberate water and carbon dioxide; this respiration is particularly noticeable at night when no photosynthesis occurs. Secondly, other minerals besides hydrogen, oxygen and carbon are necessary for plant growth and some of these (e.g. nitrogen and sulphur) are incorporated into the plant by light dependent processes. Thirdly, the metabolism of plants is determined by a multitude of factors including the type of plant and its age, the incident solar radiation, the soil and air temperatures, the effect of neighbouring plants or animals, carbon dioxide concentration, the supply of water (and other minerals), the humidity and the presence of disease or artificial growth regulators. The effect on photosynthesis and metabolism of these factors is presently little understood for a wide range of plants.

The estimation of an average plant effiency will be based on the actual past yields of organic materials suitable for fuels, although it should be noted that plants may be improved artificially or new ones discovered in future giving higher efficiencies. It also looks promising to use marine plants for fuels; this will be omitted in this report.

The average annual efficiency of plants (η_p) is defined as

$$\eta_p = \frac{\text{(useful energy in dry organic products)}}{\text{(total solar energy incident on land occupied by plants)}}$$

The useful energy in dry organic products is the heat which would be liberated if they were burnt in oxygen (cf the gross heat content of fossil fuels). The total solar energy incident on the area occupied by plants is simply the total global radiation incident on the plantations over one year, this being more than that incident on the plants due to incomplete coverage of the land by the plants. It should be noted that any other energy inputs to energy crops (such as for fertilisers, tractors etc) would be included as an industrial demand.

The overall efficiency η_p results from the following conversion chain (note that the values given are typical values).

(a) Plant land coverage (0.3)

(b) Proportion of sunlight in right waveband (0.5)

(c) Losses at leaves (reflection etc) (0.8)

(d) Quantum efficiency of photosynthesis (0.23)

(e) Efficiency from plant self use (0.6)

(f) Proportion of plant harvestable. (0.8)

[(g) Proportion left after drying (0.9), may not be necessary]

(source: mainly Hall, 1979)

The product of these typical efficiencies gives an overall value for η_p of 0.012. The values of η_p for crops in a temperate climate are in the range 0.006 to 0.01, depending on the type of plant. (see table 3, Hall, 1979).

A central figure of 0.01 will be assumed for η_p in the model. It should be emphasised that improvements in this figure are likely to be made due to the development of plants especially "designed" for the production of biofuels.

The use of waste biomass resulting from agricultural or food processing activities is not included in the model. It has been estimated that such wastes might provide about 20 mtce (540 PJ) of primary energy (Energy Manager, Vol 2, No 9, Nov. 1979).

(ii) Biomass to fuels

The variegated organic products (biomass) arising from plants may be used in a number of ways. They may be used directly, as in a wood burning stove, or converted to other solid, liquid or gaseous fuels. Which route the biomass energy takes is dictated by the availability and demands for other fuels. Since biomass represents stored chemical energy it is a highly substitutable fuel; it can be converted to work as well as heat.

Furthermore the fuels manufactured from biomass are generally easily stored, of a high energy density and easily distributed. For these reasons it is asssumed that biomass is converted to synthetic crude oil and gas; with oil having priority over gas. The synthetic crude oil will need refining; this will be done at the same efficiency as natural crude oil - 0.94. It is thus assumed that a premium use for biofuels is in the substituting for natural oils, especially as a transport fuel. This preliminary crude allocation may be altered in the future if it is obviously inappropriate.

The efficiency of converting biomass to oil and gas are simply the ratios of the useful fuel energy out to the biomass energy in. Values for these efficiencies are given below; they are rough estimates based on various sources. Exact figures are not possible since the efficiency depends on the type of biomass and the process of conversion.

Table A4.6 Biomass conversion

CONVERSION	EFFICIENCY
Bio to oil	0.55
Bio to gas	0.50

A5.1 Introduction

As mentioned in the main text, natural stores are included in the model for completeness only. The size of these reserves is such that the annual demands for the fuels in these stores (gas, oil, coal) is negligible in comparison. This is with the exception of biomass; since there is no biomass energy stored for conversion to fuels at present stocks must be amassed. This particular store will be treated in a way described below. It should be emphasised that there is some uncertainty in the estimates of fossil fuel reserves given below, this uncertainty springs from two problems.

Firstly there is the difficulty of accurate measurements of the extent and geological nature of the reserves and secondly there is the difficulty of deciding how much of the underground reserves are economically recoverable now, and in the future when fuel prices will probably rise making it worthwhile extracting fuels from the more inaccessible deposits. The uncertainty in the estimates is indicated by the use of the categories proven, possible and probable. Finally it is assumed that all these reserves are accessible by the UK, whereas in fact the UK may decide to export some part of these fuels in exchange for other imports, possibly including different fuels. At present the rates at which fuels may be extracted from these various stores are assumed to always be sufficient to meet at least the average annual demand for extracted primary fuel. There are actually limits to these rates as determined by such things as mining capacity or the number of wells drilled.

The estimates of the oil and gas reserves, and the conversion factors used to calculate the energy equivalence, are taken from the IIED study (1979).

The specific energy content of a fossil fuel (or any fuel which burns in oxygen) is the amount of heat liberated at 20 C (including latent heats) by the combustion of the fuel in a stoichiometric ratio with oxygen.

A5.2 Gas

The estimated gas reserves for the entire UK continental shelf are given in the table below. This includes possible new finds (but excludes imports from the Norwegian sector) for information.

Table A5.1 UK natural gas reserves

	VOLUME (Gm^3)	ENERGY (mtce)	ENERGY (EJ)
Known	810	1160	30.62
Probable	272	390	10.30
Possible	367	520	13.73
Total	1449	2070	54.65
New finds	80-1410	410-2030	10.82-53.59
TOTAL	1730-2860	2480-4100	65.47-108.24

(NB The thermal content of the gas has been calculated on the assumption that 1 Gm^3 of gas is equivalent to 38.6 PJ of energy.)

This store is decremented by simply subtracting the total natural gas which is required by the next store downstream.

A5.3 Oil

The estimated recoverable oil reserves in the UK licensed area are shown in the table below.

Table A5.2 UK oil reserves

	MASS(Mt)	ENERGY(EJ)
Proven	1350	60.6
Probable	960	43.1
Possible	880	39.5
TOTAL	3190	143.2
		(=17279 TWh)

(NB The conversions to energy from mass were made on the assumption that the oil has the same specific thermal energy content as "crude petroleum", namely 1 million tonnes of oil is equivalent to 44.9 PJ.)

Oil reserves are decremented in the same way as gas reserves.

A5.4 Coal

The table below gives the estimates of the UK coal reserves. The estimates of the total known reserves of coal in the UK (i.e all the coal known to exist) are unlikely to change dramatically since the UK has been extensively surveyed. However the estimates of the amount recoverable might well change considerably depending on the changing economics of mining incurred by new technologies and the burgeoning prices of other fuels.

The estimates below are taken from the Plan for Coal (1974).

Table A5.3 UK coal reserves

COAL	MASS(Gt)	ENERGY(EJ)
Recoverable	45	1188
Total	190	5016

(NB: it is assumed that 1 tonne of coal is equivalent to 26.4 GJ).

A5.5 Biomass

The reserves of energy as biomass for fuels are assumed to be zero at present. The store of biomass energy is enlarged by the output from plants and diminished by the output via conversion to synthetic oil and gas. It is assumed that there is no limit to the amount of biomass that can be stored.

The conversion of solar to energy to biomass and biofuels is described in the relevant appendix.

APPENDIX 6. ARTIFICIAL STORES

A6.1 Domestic

Some information as to the ways in which people use domestic stores is available (Field, Hedges, 1977). Until it seems necessary to refine the filling control; a simple method of control will be assumed for these stores. Each set of stores (e.g. all the coal bunkers) will be modelled as if they were one large store. The instantaneous amount of energy in a store may be calculated from past inputs and outputs. The amount the store is to be filled is decided by the proportion of the store that is empty. The more empty - the more it is filled. If C_m is the maximum energy it can store and C(t) is the current storage level; the quantity $\triangle C$ put in is :

$$\triangle C = (C_m - C(t))^2 / C_m \qquad (J)$$

This method of control will be referred to as proportional control hereafter. For many stores this implies that the maximum input power is one storeful per hour. Where this is not the case (e.g. electric storage heaters) it will be made clear.

(i) Oil tanks

These are household oil tanks storing oil for the purposes of space and water heating. The maximum energy storage capacity (C_m) is determined by the average volume of such tanks (V_t) and the specific volume energy content of the heating oil (S_o), thus

$$C_m = V_t \, S_o \qquad (J)$$

The typical domestic oil tank holds 1125 litres which gives it a maximum capacity of 40.0 GJ assuming a specific energy content of 45 GJ/tonne and a density of 1266 litres/tonne.

The population of oil tanks is the same as the total number of houses consuming oil in central heaters for space and water heating. This was 3.45 million in 1976. This implies a total storage capacity of 38 TWh (120 PJ).

(ii) Petrol tanks

These are modelled in the same way as domestic oil tanks (see above). The average values for the volume (V_t) and the volume specific thermal content are given below. The population of such tanks (P) is obviously the same as the number of petrol driven cars. The proportional filling method is used (see above).

Volume of tank = 45 litres.

Energy storage = 1.6 GJ

Population = 14 million.

The total storage capacity is thus 6.2 TWh (22.4 PJ).

(iii) Coal bunkers

These are modelled like oil tanks (see (i) above), except that the maximum mass of coal (M_m) and the mass specific thermal content (C_m) are used instead of volume and volume specific thermal content. The maximum energy storeable (E_m) is

$$E_m = C_m M_m \qquad (J)$$
$$= 30.7 \ (2) \qquad (GJ)$$
$$= 61.4 \qquad (GJ)$$

Proportional control is used (see above). There were 4.3 million domestic bunkers in 1976, implying a total capacity of 73.3 TWh (264 PJ).

(iv) Electric storage radiators

See relevant appendix on domestic space heaters.

(v) Electric batteries

See relevant appendix on domestic transport converters.

(vi) Solar hot water tanks

See relevant appendix on domestic hot water heaters.

(vii) Hot water cylinders

These are presently omitted.

A6.2 Industrial stores

(i) Oil

No documented information. These stores will therefore be assumed to hold sufficient energy for one month's consumption; this amounts to 30.7 TWh (=110 PJ). Proportional control is assumed.

(ii) Coal

No documented information. It is assumed that one month's store is available; this amounts to 15.8 TWh (=57 PJ). Proportional control is assumed.

A6.3 Commercial stores

(i) Oil

No documented information. It is assumed that one month's store is available; this amounts to 14.4 TWh (= 52 TJ). Proportional control is assumed.

(ii) Coal

No documented information. It is assumed that one month's store is available; this amounts to 0.168 TWh (= 0.608 PJ). Proportional control is assumed.

A6.4 Energy industry stores

A6.4.1 Gas

Despite the fact that gas supplies originate from natural stores of immense size it has been found economic to utilise artificial gas storage to smooth the demand. There are certain constraints imposed on the BGC by their suppliers; these often include restrictions on the rate of extraction at different times of year (their interests are often mutually competitive). Also, the capital cost of transmission capacity is high in terms of $£W^{-1}$ and the reduction in the maximum transmission capacity that arises from the implementation of storage reduces the overall cost. It is interesting to speculate what the requirements for artificial storage may grow to in the future if the gas is supplied from synthesisers rather than natural reservoirs; the gas system will then be more similar in its loading problems and generating and transmission problems to the electricity system. This is because synthesisers will be analogous to power stations The power cost of a synthesiser is much higher than that of a natural gas well. In addition, the cost of gas storage is relatively high, although not as high as that for electricity. These high power and storage costs for the synthetic gas case will have an effect on the optimality (in economic terms) of the system, just as power and storage costs are a large consideration in electricity system planning.

Gas is stored in gaseous or liquid form in a variety of material envelopes. The type of store used generally depends on the storage duration required. Gasometers, high pressure gas bullets, pipe nests and line packing (i.e. packing more gas into the transmission system) are used for short term storage. Liquefied gas, on the other hand, is the form used to store gas for periods of several months, this is because the storage density is higher. This type of storage can easily provide a large output; but it takes much longer to restock because of the compression and cooling of the gas that is required; work has to be done on it. Thus in general it takes about 200 days to fill liquid stores and about 20 to discharge them.

The capability for storing gas in enlarged and sealed salt caverns is under development. Such stores can be depleted and restocked fairly rapidly. It should be noted that line packing, which presently accounts for about 50% of the short term storage, will decrease in capacity if the average demand for gas is such that a larger proportion of the transmission capacity is used.

The short and long term storage capacities for 1977 are given below (from ERG 027, 1979). The model uses an aggregated storage capacity which does not differentiate between the different types; this is especially important since the very large stores of liquid gas can not be used for rapid load following. It is assumed that an appropriate mix of stores will be developed for the future; large salt caverns are one type under development. BGC is also negotiating for the purchase of a depleted gas field for the long term storage of gas (Guardian, 9.11.79); this closely follows reports that a 15 % shortfall in gas supplies is possible in the 1979/80 winter. The use of depleted gas fields for storage would probably solve problems of seasonal variation. However, there is little experience with such stores; aspects such as the in/output rates to such stores and the in/out efficiency will need examination.

The table below summarises artificial gas storage.

Table A6.1 Artificial gas storage

Millions of cubic feet is abbreviated to mcf.

PERIOD	TYPE	VOLUME(mcf)	ENERGY(TJ)
Short	low p	45	4.86
	high p	2	0.22
	line pack	48	5.18
	Total	95	10.26
Long	liquid	7500	810.00
	TOTAL	7595	820.26 (=228 GWh)

This assumes that 1 mcf = 108 GJ.

A6.4.2 Oil stores

Oil is generally stored in large quantities for strategic political reasons and not to enable a varying demand to be met. In 1976 the peak stock levels were 998 PJ of oil stored at refineries and 50 PJ at power stations. The total storage was thus 1048 PJ (= 291 TWh).

A6.4.3 Coal stores

The coal industry stores about 300 PJ of coal, power stations about 550 PJ and other stores about 85 PJ, a total of 260 TWh (935 PJ); This was the maximum in 1976. Proportional control is assumed.

A6.4.4 Nuclear fuel stores

Since nuclear fuel has such a high energy density, storage is not a technical or economic problem, and is therefore assumed to be adequately large.

A6.4.5 Electricity stores

The generating boards facilitate the storage of electrical energy by converting it to mechanical power in a reversible pump turbine and raising water vertically in the earth's gravitational field; thus the energy is stored as potential energy. To deplete the store the water is allowed to flow downwards back through the turbine/pump converting the potential energy to electricity once more. There are obviously losses associated with these flows, the main ones relating to friction and pump/turbine effiency. To date this type of storage has had a limited storage capacity as compared to the average daily electricity consumption. However new pumped storage schemes are possible, especially if tidal schemes are included, although the environmental impact of such schemes can be considerable. The bulk of this section will relate to conventional pumped storage as opposed to tidal storage since their characteristics are quite different (mainly due to the height of the working head). Innovatory methods of electricity storage are under consideration; these include energy storage by compressed air in underground caverns and more exotic schemes such as ones incorporating flywheels.

Since the change in the working head of a conventional pumped storage scheme is quite small the pump/turbine effiencies show a negligible variation. Hence the performance of such a scheme can be modelled using three variables; the maximum storage capacity (C_m), the overall in/out efficiency (η_{io}) and the maximum in/out electrical power load of the pumps/turbines (P_m). It is assumed that all the conventional storage units can be considered as one large unit (but note the exception of tidal schemes).

The control of pumped storage as simulated is relatively simple. If electricity demand is very low or if there is a surplus of electricity, it is fed to the storage at the maximum power P_m until either the store is full (i.e. at level C_m) or the surplus has been absorbed, or the maximum electrical load on the pumps is reached. Conversely, it is depleted as rapidly as possible until the demand is met or the store is empty. Pumped storage is also used in output mode if there is a large rate of increase in electricity demand, as a rapid response station. However, there is a storage merit order if tidal schemes are included. For filling the stores, surplus electricity is channelled to the conventional pumped units, then to tidal. When being depleted, tidal storage is used first; the reverse order. The reason for this is that storing electricity in the tidal scheme can reduce the effective use of potential tidal power by reducing head differences. This is not always the case, but to determine a strategy which optimises this subsystem according to expected demand and tidal heights as well as current tidal and pumped storage levels is exceedingly difficult. There are also other parameters which should also be taken into account such as the amount of output from thermal power stations and the expected output from other ambient sources such as wind and wave.

The values for C_m , η_{io} and P_m are given below. Details of pumped storage in tidal schemes may be found in the relevant appendix.

The table below summarises pumpred storage in the UK.

Table A6.2 UK pumped storage

SCHEME	POWER(MWe)	STORAGE MWmh	EFFICIENCY
Ffestiniog	300	2024	0.82
Cruachan	400	11470	0.85
Foyers	300	15747	0.87
TOTAL	1000	29100	0.86(av)
Future			
Dinorwic	1675	600000	
Craigroyston	3200		

A6.4.6 Electricity storage strategy

The unpredictable sources of electricity may provide electricity surplus to demand at any time. It is obviously desirable to store as much of this for later use as possible. The operation of storage for improving the economics of electricity generation is not explicitly included. Since all the ambient energy intensities and the demands can be predicted fairly accurately some hours in advance it is likely that a good control strategy could be evolved. This might significantly enhance the contribution and role of storage and income energy sources.

The geographical proximity of storage to electricity surpluses may be an important factor.

If any of the unpredictable sources (CHP, wind or waves) produce a surplus it is stored according to the following merit order and constraints.

(i). Domestic off peak storage heaters.

Surplus is supplied to these if there is spare storage or charging capacity at the heater and if space heating is required.

(ii). Electric car batteries.

If there is spare storage and charging capacity.

(iii). Pumped storage

If there is spare storage and charging capacity.

(iv). Tidal scheme.

As the power capacities and reservoir heights will allow.

In addition to the function of storing surpluses, pumped storage is also used to diminish the fluctuations in the required output from the large nuclear and coal fired power stations. When the difference between demand and CHP plus ambient electricity is increasing rapidly pumped storage is operated in output mode and vice versa when the difference is decreasing. The variations in output of the large thermal power stations are thus kept within reasonable limits over small time periods.

REFERENCES

ABOTT M.M., VAN NESS H.G., 1972, "Thermodynamics", Schaum"s Outline Series, McGraw - Hill Book Co.

ADDISON R.A., GOLDSMITH K., WONG L., 1976, "Improving the load characteristics of power systems", Vol 202, No 22, Electrical Review International.

BARRETT M. A., EVERETT R., 1977, "Cost-effectiveness of grouped solar heating schemes", OUERG.

BIRKETT D. G., 1979, "Review of potential hydroelectric development in th Scottish Highlands", Electronics and Power, pp 339-346.

BLACKMORE D. R., THOMAS A. (editor), 1977, "Fuel economy of the gasoline engine", Macmillan.

BLUNDELL C. J., 1976, "Domestic heat pump design for the British climate". Heating and Ventilating Engineer, June 1976.

BOYCE P. R., 1978, "Concise notes on interior lighting", ELectricity Council Research Centre, Job No. 025, January 1976, ECRC/N888.

CEGB, 1975, "Tidal power", from "CEGB Research", May 1975, pp 36-39.

CHAPMAN P. F., MORTIMER N. D., 1974, "Energy inputs and outputs for nuclear power stations", ERG 005, OUERG.

CHAPMAN P. F., CHARLESWORTH G., BAKER M., 1976, " Future tranport fuels", SR251, Transport and Road Reasearch Laboratory, Crowthorne, Bucks.

COLLINGBOURNE R. H., Meteorological Office, Eastern Rd., Bracknell, Berks." Ten year meteorological tape".

CONSIDINE D.M., 1977, " Energy technology handbook", McGraw Hill,

COURTNEY R. G., MACADAM J. A., 1976, " An economic assessment of long distance heat transport and the utilisation of power station reject heat for district heating". BRE Current Paper, CP 46/76.

COURTNEY R. G., 1977, "A computer study of solar water heating", CP 30/77, BRE.

CRITOPH R. E., 1976, "Industrial energy use required to maintain living standards with especial reference to the UK iron and steel industry". Ph. D. Thesis, Southampton University.

DESSON R. A., 1976, "Energy conservation: the intermiittent occupation of dwellings and domestic energy consumption", CP 37/76, BRE.

DIXON J., LOWE R., 1981, "Economics of Large Wind Turbines", paper presented to an IEE colloquium on Integration of Renewable Energy Sources, 3.11.1981, IEE, London. (Available from the OUERG).

DUNN J. B., HUTCHINGS I. J., 1969, "The distribution of traffic in Great Britain through the day in 1968", LR295, Road Research Laboratory.

ECONOMICS ADVISORY GROUP, 1981, "Domestic Energy Conservation and the UK Economy", ACE, 3 Pleydell St., London EC4.

EDINBURGH UNIVERSITY, "Edinburgh wave power project", Fourth year report, Volume 1, July 1978.

ELECTRICITY CONSUMER'S COUNCIL/NATIONAL CONSUMER'S COUNCIL, 1981, "Improving Insulation in Existing Dwellings", available from ECC, 119 Marylebone Rd, London or NCC, 18 Queen Annes Gate, London SW1.

ELECTRICITY COUNCIL, 1978, " Microwave Cookers", Electricity Council, London.

ENERGY PAPER 20 (EP 20), 1977, "District heating combined with electricity generation in the United Kingdom", HMSO.

ENERGY PAPER 21, 1977, "The prospects for the generation of electricity from wind energy in the UK", HMSO.

ENERGY PAPER 23 (EP 23), 1977, "Tidal barrages in the Severn estuary", HMSO.

ENERGY PAPER 34, 1979, "Heat loads in British cities", Report of the Heat Load Density Working Party of the Combined Heat and Power Group, HMSO.

ENERGY PAPER 35 (EP 35), 1979, "Combined heat and electrical power generation in the United Kingdom", HMSO.

ENERGY PAPER 39 (EP 39), 1979, "Energy Technologies for the United Kingdom", Volumes I and II, HMSO.

ERG, 1978, "Energy in the home", OUERG.

ERG, 1979, "The gas supply industry", ERG027, OUERG.

ERIKSON S., FORRESTER III R., JOHNSTON R., TEPER M., 1977, "Economic and technical criteria for coal utilisation plant", Part II, "Gasification Processes", Part III, "Liquefaction processes". IEA, 14/15 Lower Grosvenor Place, London, SW1W OEX.

FIELD J., HEDGES B., 1977, "National fuel and heating survey", Social and Community Planning Research, 16 Duncan Terrace, London.

FOX L., MAYERS D. F., 1968, " Computing methods for scientists and engineers", 1968, Clarendon Press, Oxford.

FRAENKEL P. L., MUSGROVE P. J., 1979, "Tidal and river current systems", from "Future Energy Concepts", Conference Publication No 171, IEE.

FRANTA G. F., OLSON K. R., 1977, " Solar architecture", Ann Arbour Science Publishers.

GARNISH J. D., 1976, "Geothermal energy: the case for research in the UK", EP 9, HMSO.

GRAINGER L.(editor), 1977, "Energy resources: availability and rational use", A Digest of the 10 th World Energy Conference, Istanbul, 19 -23 September, 1976.

GRAY T.K., GASHUS O.K. (editors), 1972, "Tidal power", Plenum Press, New York, 1972.

GREEN M. B., PATTISON J. R., RICH J., 1976, "Utilisation efficiency of heating appliances". Institute of Gas Engineers, 1976.

GRYLLS W., 1978, "Preliminary study of wind power availability in the SW", Exeter University.

HALL D. O., 1979, "Solar Energy use through biology-past present and future", Solar Energy, pp 307-328, Vol 22, No 4, 1979.

HARRISON R., JENKINS G., MORTIMER N.D., 1978, "The energy analysis in the assessment of the UK wave energy programme", Energy Workshop report No 18, Sunderland Polytechnic.

HEAP R. D., 1975, "Domestic heat pump operation". Heating and Ventilating news, August 1975.

HEAPS N.S., 1972, "Tidal effects due to water power generation in the Bristol Channel", from Gray & Gashus, op cit.

HEMMING D.F., 1978, Private communication.

HMSO, 1976, "Digest of UK Energy Statistics".

HMSO, 1976, "Annual Abstract of Statistics".

HOFFMAN E.J., 1976, "The concept of energy", Ann Arbour Science Publishers Inc, PO box 25, Mich 48106.

HOLLANDER J.M., SIMMONS M.K., 1976, "Annual Review of Energy: Volume 1", Annual Review Inc, Palo Alto, California.

IIED (LEACH G., ROMIG R., BUREN A., LEWIS C., FOLEY G.), 1979, "A Low Energy Strategy for the United Kingdom", Science Reviews, London.

INSTITUTE OF HEATING AND VENTILATING ENGINEERS, 1976, Guide A2-21.

JARDINE T. P., LATHAM F. R., 1979, "Forecasting the height of ocean waves", from "Future Energy Concepts", Conference Publication No 171, Institute of Electrical Engineers.

JOHNS P.L., (Due 1981), "Fuel use in space heating", OUERG.

LEACH G., ROMIG F., 1977, "Energy conservation in UK dwellings: domestic sector survey and insulation", IIED.

LIPPOLD C., 1980, "Global assessment of hyropower", ERG Working Paper 3.

LISITZIN E., "Sea level changes", Elsevier Oceanography, Series 8, Elsevier Publishing Company, 1974.

LOWE R.L., ALEXANDER G.A., 1981, "The effects of clusters of wind generators", OUERG.

McBRIDE R., 1978, "A chemical heat pump/storage device and its applications", OUERG.

MITCHELL H.G., PARKER L.C., HASLETT G., 1971, "Storage heating systems", ECR/N375, Electricity Council.

MONOGUE P. J., 1977, "Occupancy patterns and energy use in housing", Symposium:Thermal performance and energy use in housing. The National Institute for Physical Planning and Construction Research. Gresham Hotel, Dublin, April 5-6 th., 1977.

MOOZ W. E., 1973, "Energy Trends and their future effect on transportation", The Rand Corporation, Santa Monica(Ca).

MORTIMER N. D., 1974, " Gross energy requirements of marine transport", ERG007, OUERG.

MORTIMER N. D., 1975" Gross energy requirements of air transport", ERG008, OUERG.

NATIONAL COAL BOARD, 1974, "Plan for Coal", NCB, Hobart House, Grosvenor Place, London, SW1X 7AE.

OKE T. R., " Review of urban climatology 1968-1973", WMO Technical Note No.134

PETHERBRIDGE P., " Sun position, solar radiation and solar cooling load data", BRE internal note.

PHILLIPS C., 1980, "Evaluation of the design, construction and operation of a gas fuelled engine driven heat pump", OUERG.

PICKUP G.A., MILES A.J., 1979, "Energy conservation - field studies in domestic heating", 116th Annual General Meeting of the Institute of Gas Engineers.

ROBINSON P.J., 1979, "Transmission and distribution networks and the consumer - the potential for development", Whole City Heating Conference.

SALTER S. H., 1974, " Wave Power", Nature, Vol 249, No 5459, pp 720 -724, June 21, 1974.

SIMON A. L., 1975, "Energy resources", Pergammon Press.

SUMNER J. A., "Domestic heat pumps", Prism Press, 1976.

SYSTEMS ANALYSIS RESEARCH UNIT, 1979, "UK Energy Demand Projections", Directorate General of Research, published by the Departments of Environment and Transport.

WHITTLE G. E., WARREN P. R., 1978, "The efficiency of domestic hot water production out of the heating season", CP44/78, BRE.

WILSON E.M., 1965, "Energy from the tides", Science Journal, July 1965.