PLANNING ENERGY SYSTEMS FOR SMALL, RURAL COMMUNITIES (INCLUDING ECONOMIC, TECHNICAL AND THERMODYNAMIC CRITERIA)

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ABSTRACT

The work described in this thesis develops a strategy for planning domestic energy supply systems for small, rural communities.

Two methods for system optimisation are proposed: economic optimisation and thermodynamic optimisation. Both methods are applied to the small Scottish island of Eigg, as an example of a small community. It is shown that, for the range of energy equipment studied, the two methods are generally complementary.

Economic theory and choice of parameters are discussed, as is the theoretical background to thermodynamic modelling. The net present value method is used to determine unit energy costs, which are used in the economic model as the parameter by which different energy sources are chosen. For thermodynamic assessment three parameters are used: exergy, second law efficiency and energy quality. Energy quality against quantity diagrams (on which areas represent exergy) are shown to be a useful way of visualising thermodynamic system performance.

This work also develops methods which can be used to determine model inputs. These include: an energy census of the island of Eigg to determine the current energy system, development of a hydrological prediction model for determining hydro power potential, use of computer models to determine house space heating demands, and development of methods for predicting meteorological parameters from long term data.

The application of the economic planning model to Eigg allows a much improved energy supply system for the island to be proposed. This makes energy more available, improves comfort (with regard to energy usage), and gives 30% higher energy usage for a lower unit cost than the islanders currently pay. The thermodynamic optimisation process improves the thermodynamic efficiency of the energy system on Eigg by more than 100%, and shows which areas of energy technology should be investigated to harmonise economic and thermodynamic optimisation.

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Guide to the Thesis.

This thesis covers several different topics which, although they form parts of the overall energy planning method, are separate subjects. Each topic, presented as a different chapter or section, has its own introduction, literature review and discussion. The Introduction of Chapter 1, and the Conclusions of Chapter 7, therefore, give only an overall introduction and general conclusions for the whole thesis.

The literature review of each section covers work of other researchers, showing their methods and conclusions. The methods used in this thesis are often compared with those of others in the literature review rather than in the main text, to save unnecessary duplication.

Because several different topics are covered, it is not possible to give a list of symbols covering the whole thesis. Therefore each section has its own list of symbols, in which standard symbols for that subject have been used wherever possible. This occasionally leads to the same symbol having a different meaning, or a variable having a different symbol, in different sections. Non-standard units (for example kWh/y instead of watts) are used in some sections, when these are easier to understand.

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CHAPTER 1 INTRODUCTION

1.1 Small, Rural and Remote Communities

It is estimated that nearly 50% of the world's total population live outside urban areas; in the countryside, or in small villages or towns (Ward & Dubos 1977). Yet in 1800, as few as 5% lived in cities of over 2500 people. The movement of people from the country to the cities has brought with it considerable problems: overcrowding, strain on public services, increased pollution in and around cities, and uneven distribution of labour. These problems are more apparent in the developing countries of the world, but they can be overcome by encouraging people to remain in rural areas.

The problems of remote, rural areas are well known: poor employment prospects, bad communications, poor health care and educational facilities, costly imports of necessary goods and poor energy supplies. This latter is a critical factor in the survival of rural communities, since the provision of good energy supplies brings with it the possibility of improving agriculture (hence nutritional standards), of establishing industries, and of increasing the comfort and standard of living of the people.

Yet the provision of energy supplies, especially if they have to be 'imported' from outside the area, does not necessarily improve the situation; it might be too expensive to be viable, or might place the community more at risk to influences and prices outside their control. A better situation may exist if the community can provide its own energy supplies, so reducing its reliance on external supplies (see, for example, Lewis 1981). It is the study of how best to supply this energy that this thesis covers.

Although a large percentage of people still live in rural areas in developing countries, many remote communities in developed countries have suffered population decreases. For example, in the Highlands and

Islands of Scotland, many communities have declined, partly because of poor, and expensive, energy supplies, and also because of poor facilities and lack of employment opportunities. This thesis studies a small Scottish island, with a view to developing a method for planning energy systems for many small communities throughout the world.

1.2 Which Energy to use?

The cheapest, or most easily available, energy sources are not always the best to use. The widespread use of wood as fuel in developing countries has brought with it considerable problems of deforestation in these regions (Eckholm 1980 and Van Dieren & Hummelinck 1979). Similarly, the use of fossil-based fuel and nuclear energy in many countries also leads to problems of resource depletion and environmental pollution. Such supplies, in addition, are not widely available in remote areas, without costly transportation. Energy planning should therefore always consider energy supplies which are locally available, and sustainable.

The recent accident at the Chernobyl nuclear reactor (New Scientist 1986), as well as public fears, threaten to slow this method of energy generation. In any case, current costs show that nuclear energy generation is not practical on the level of small communities (Pooley 1984). Fossil fuels too have prompted much recent debate about their acceptability, particularly with regard to their environmental effects. In addition, despite often conflicting claims, the supply of fossil fuels is ultimately limited, and since they provide raw materials for many other purposes than energy, their careful use is very important. These factors, combined together, suggest the more widespread use of renewable energy sources.

Renewable energies, being derived from the naturally occuring environment, are available in almost all areas of the world in varying quantity. The west coast of Scotland is well favoured in its supplies of economically-viable renewable energy, having solar energy and good wind energy potentials in many areas, hydro energy potential in some areas and wood fuel available in some areas but with the possibility of further development. This work studies ways of making communities more energy self-reliant, by using these sources to provide a large proportion of the energy requirements, and by minimising reliance on expensive imported fuels.

Cheaper energy supplies will benefit remote communities, and such areas have factors which give potential for the successful use of renewable energy sources. Imported energy, whether by mains electric cable, or as solid, liquid or gaseous fuels in discrete quantities, is often expensive (Twidell & Pinney 1985), thus making the economics of renewables more favourable. Much of the energy demand, particularly on Scottish islands, is for space heat, which is comparatively easily supplied by renewable sources, being not highly time dependent. Because there is usually a positive correlation between the availability of renewable supplies (hydro and wind energy) with demand for space heat, it is suitable in their circumstances.

1.3 Possible Methods for Energy Planning

The most common method of assessing projects, including energy systems, is on the basis of cost. The cheapest solution, or the one which maximises the profits to the operator, is the one usually chosen. This method is likely to persist until such time, for example, that resources become scarce, or people become more aware of other factors, such as environmental pollution, personal satisfaction or resource allocation. Therefore one of the methods proposed by this thesis is to minimise energy costs to the user.

Sections 2.1 and 4.1 present a computer based model for studying the economics of energy supply systems. This uses unit energy costs (£/kWh) as the basis for comparing different energy sources. Other researchers (see Literature Review in sub-section 4.1.3) have used cost per unit of power (£/kW rated output) as the basis for decision, but this does not allow direct comparison between locally produced energy and imported energy (which would be sold on a unit energy cost basis), nor does it show which non-renewable sources (the most expensive ones) should be substituted by cheaper sources first. Although the calculation of unit energy costs depends on the amount of energy produced by a piece of equipment, using unit costs is the best and most consistent way of comparing one energy supply with another. It helps show which energy technologies are worth investing in, and allows direct comparison between locally produced energy, and energy, such as electricity, imported into the community.

After calculation of unit costs, the model works on the basis of using the cheapest energy supplies first. The cheapest renewable energies are used by the model to substitute for the most expensive non-renewable supplies first, so that the optimum use is always made of a particular energy system.

The economic planning model developed by this project is based on the well accepted technique of net present value analysis. This allows direct comparison of various future money transactions at different times, by referring all costs to one point in time (the initial investment point). It allows for the fact that money does not have a constant value with time; it either increases or decreases in value because of interest and/or inflation. The technique also allows a direct comparison between investment in energy equipment and investment in other projects or savings. Net present value analysis is a common, and well-proven method of assessing investments (Simpson et al 1985).

Since the economics of an energy supply system can change rapidly with time, for example the rapid fall in oil prices at the beginning of 1986 (Financial Times 1986), and because the increasing pressure of environmental issues might change the basis for assessing energy production, the economic planning model allows two methods of systems' assessment. The first is to minimise total systems' cost, using whichever energy sources are cheapest. The second is to maximise renewable energy usage, using a cheapest-first basis and still replacing the most expensive non-renewables first. This work will show that the latter option, when applied to Scottish islands in particular, maximises the energy self-sufficiency of a community, by replacing as much imported fossil fuel as possible. Maximising renewable energy usage in remote areas is often consistent with minimising costs, so the second option is the one chosen for the study of Eigg.

Conventional economic analysis, although widely accepted, is not always the best way of assessing energy projects, for several reasons:

1) As mentioned above, energy prices can fluctuate rapidly, often as a result of unpredictable political changes at national and international level, which change the results of economic planning.

2) Even with stable prices, energy costs, as well as labour and equipment costs, vary between countries and regions, making economic planning specific to certain areas only.

3) Conventional economic analysis of resources (although not covered in this thesis) is unable to cope adequately with resource shortages (Simpson et al ibid). It assumes (Ayres & Nair 1984) that: a) the price mechanism will always control shortages, b) that other resource (labour or capital) can substitute for energy, or c) that scientists and engineers will be able to increase, indefinitely, the efficiency with which energy is used.

4) Standard economics take no direct account of energy 'quality'; that high temperature heat sources, or supplies of shaft energy (those with high work potential) are more useful and adaptable, and hence more valuable, than lower temperature heat sources.

Therefore methods which overcome these difficulties are useful in giving results which apply consistently to all areas, regardless of energy costs, and which are not variable with time.

Two main methods of analysis can be used to overcome these difficulties: (a) General system dynamics modelling (IFIAS 1981, reviewed in section 4.1.3), in which other factors, such as nutrition level or greater self-sufficiency in energy, are optimised separately from economic factors. (b) Thermodynamic modelling (Twidell & Pinney 1985) in which the thermodynamic quality of energy supplies is accounted for, and systems are optimised on the basis of thermodynamic (different from energy) efficiency (Thermodynamic assessment can actually be divided into four categories: exergy efficiency, exergy economics, resource allocation and net energy analysis. These are all reviewed in section 4.2.3). This thesis proposes the second method, and uses it as a comparison between thermodynamic and economic performance.

Two important concepts are used in thermodynamic analysis: exergy (the work potential of an energy supply or demand) and exergy efficiency (the exergy used to satisfy an energy demand divided by the exergy of the energy supply). Exergy efficiency is the factor used in this thesis to judge thermodynamic performance. Exergy can be used to determine another property, energy quality, defined as exergy content divided by energy content. Energy quality is used to construct diagrams of energy quality against quantity (which do not appear to have been used before); these prove very useful for visualising thermodynamic performance.

Exergy efficiency differs significantly from the more often used energy efficiency. Energy is, by definition, conserved, whereas exergy is not. Studying energy on its own does not account for the fact that all real processes degrade energy (reduce its work potential), or that low quality energy supplies (such as warm water) cannot be directly or efficiently used to supply high quality demands (such as electricity). It gives no limits, in theory, to the number of times energy can be used for different processes. Exergy analysis, on the other hand, does account for these real limitations and hence gives a much more realistic picture of energy usage.

Exergy analysis can be used entirely independently of economic factors, but it can also be combined with unit costs to determine exergy unit costs (Gaggioli & Wepfer 1980). This thesis adopts an intermediate approach, testing thermodynamic efficiency improvements in the economic planning model described above. Successful thermodynamic improvements must therefore also be economically viable if they are to contribute significantly to the energy system. Thermodynamic optimisation results are compared with economic results, and the two methods are shown to be generally complimentary for the range of energy equipment appropriate for small, rural communities.

1.4 Model Inputs

It is not sufficient only to develop an energy planning model if no data exist to use in the model. Data collection is as important, if not more so, than the development of the model, since the results of modelling are only ever as accurate as the input data. Although this project concentrates on the planning strategies, much work was done on obtaining data with which to test the models.

Data requirements for energy planning fall into three main categories: (1) energy demand, (2) potential energy supplies and cost and (3) performance data for energy equipment. The latter are relatively easy to obtain from standard manufacturers' information, but (1) and (2) require careful assessment and are not easy to determine.

The obvious way to collect energy demand data for a community is by energy census or survey, asking inhabitants how much energy they currently use. However, this approach, although used as an initial data collection method in this project, has several drawbacks. Firstly the expense of fuels can make energy consumption lower than it would be if fuels or energy were cheaper. High cost can also lead to lower levels of comfort (regarding energy usage) than might otherwise occur. Secondly, poor levels of building insulation, energy conservation measures, and equipment efficiencies, all lead to higher than necessary energy consumption. Finally the inconvenience of collecting fuel, or of running equipment (for example if a diesel generator must be manually started, and is some distance from the house) can restrict energy usage. Therefore to plan energy systems based on survey data can be misleading and inaccurate, and in such cases other methods must be found to determine more realistic energy demands.

For the island of Eigg, space heating is the largest single energy demand, even though many houses on the island are underheated by mainland standards of comfort. This work studies three computer based building models which predict space heating demands, and uses the results from one of these in the planning model. Another important energy demand is for electricity. Since nearly half of the houses on Eigg have no electricity supply (but would like a supply if it was cheaper) data from another small community are used to determine realistic demand levels to be used in the planning work.

An assessment of potential energy supplies are equally important. To assess renewable energy potential implies knowing meteorological parameters: solar radiation for solar energy, wind speed for wind energy, and water flows for hydro potential. Wood fuel potential can be assessed from other studies of wood fuel yields in similar areas.

It is important, when obtaining meteorological data, to ensure that they relate to a 'typical' period rather than to a specific period. This cannot be done by short term measurements. Therefore this thesis shows how recorded data from other sites similar to Eigg can be used to determine a typical year for the island. In addition, methods are proposed for simulating mean daily wind speeds from monthly or yearly mean values and for calculating hourly solar radiation and air temperature from mean daily values. These could be used to simulate data for sites for which detailed data are not available.

Measurement of rainfall alone is not sufficient for determining hydro potential, since rainfall must be related to water flows in rivers or burns. However, to attempt to measure flow rates in rivers is not easy, and can involve considerable expenditure of money or time. Therefore this work proposes a method for using recorded rainfall to predict river flows. To this end, a simple hydrological prediction model is developed, which is relatively insensitive to catchment area properties. The catchments on Eigg are all small (less than 4 km^2), allowing several simplifying assumptions to be made in the model. The model developed does not require accurate knowledge of catchment properties, but is shown to be reasonably accurate in predicting potential hydro power both for Eigg and for another, larger catchment in the north-west of Scotland.

The economic and thermodynamic assessment methods, together with the methods of determining input data, allow a complete energy planning strategy to be proposed, starting from initial selection of the community, through data collection or selection, modelling and optimisation of the energy system, to recommendations on which equipment to be installed. Using the strategy, suggestions for improvements to existing energy supply systems can be made. The thesis applies these methods to the island of Eigg, and makes recommendations for improvements to their supply system, resulting in increased energy usage for a proportionately decreased cost.

It is stressed throughout the thesis that its main aim is to propose and develop the methodology of energy planning and data acquisition, and this is achieved by the work presented. The intention is not to model accurately the island of Eigg, because of the assumptions which have to be made when obtaining data. Therefore, although there are undoubtedly several very useful recommendations that can be made for improving the current energy system on the island, great accuracy is not claimed for the detailed results.

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CHAPTER 2 ECONOMIC AND THERMODYNAMIC THEORY

Two different methods of energy systems' planning are investigated in this thesis: economic evaluation and thermodynamic evaluation. The equations required for these two methods are developed and presented in this chapter.

Net Present Value analysis is used as the basis for the economic evaluation of energy systems. Section 2.1 shows how net present value can be used to determine the unit costs (£/kWh) of energy output from various energy sources. Section 4.1 shows how these unit costs are used by the economic planning model.

Three concepts are introduced for thermodynamic analysis (section 2.2), and their definition and formulation discussed. The concepts are: exergy, energy quality and second law or exergy efficiency. Section 4.2 shows how these can be used in the study of energy supply systems.

A literature review of the theoretical thermodynamics used to calculate exergy is presented, as is a brief review of economic analysis of energy systems. Examples of the application of the economic and thermodynamic methods to energy systems are given.

Section 2.1 Economic Analysis of Energy Systems

2.1.1 INTRODUCTION

The most common method of analysing any type of project is by what might be called 'profit analysis'. The money invested in the project is compared with the money made from the project, and those projects which make most money in relation to the investment are usually those selected.

A most important aspect of financial analysis (often called cost benefit analysis or capital investment appraisal) is the fact that money does not have a purchasing value constant with time. Money can be put into savings from which a known rate of interest will be received, meaning that at the end of each year (or whenever interest accrues) the money is hopefully worth more than it was when it was invested. An investor can put his money into a capital project (installing an energy system, for example) or into savings. He should only chose the capital project if it earns more money than putting money in savings.

Similarly, a sum of money invested now is worth more than the same sum invested in the future, as that invested now will have gained interest in the period between the first and the second investment. Inflation also makes money more valuable now than in the future, as it has more buying power now than later. This 'time value of money' has led to methods of economic analysis known as 'discounting' techniques, whereby all money flows are referred to one point in time. Other methods, not allowing for the time value of money, exist, but these all have limitations when applied generally.

Economic analysis can also be applied to a person in a remote community installing an energy supply device for his own use. In such a case, the person is paying himself for the energy he produces, so the methods can be used to calculate how much he must pay himself, or how much the system is costing him.

Economic assessment methods depend greatly on values chosen for interest rates. This section does not attempt to investigate this in detail, but does give a brief summary of rates used by other researchers.

Most assessment methods deal only with those aspects of a project which can be evaluated in purely monetary terms. Social benefits, environmental aspects, etc. are often difficult to assess, and so are not always included. It is beyond the scope of this section to discuss these in detail, but with reference to other people's work such factors, particulary as they relate to renewable energy supplies, are discussed briefly.

2.1.2 SYMBOLS AND UNITS

Symbol	Description	Units
C	Yearly capital cost	£/y
F	Yearly fuel cost	£/y
M	Yearly maintenance cost	£/y
NPV	Net present value	£
P	Yearly energy output	kWh/y
Q	Unit energy cost	£/kWh
R	Revenue	£/y
S	Net cash flow	£/y
V	Present value	£
e	Energy inflation rate	y^{-1}
i	General inflation rate	y^{-1}
j	Relative energy inflation rate	y^{-1}
n	Project or equipment lifetime	y
p	Money or market rate of interest	y^{-1}
r	Discount rate	y^{-1}
r*	Internal rate of return	y^{-1}

Subscripts and superscripts

1,2..k	Year number
e	Equipment
f	Fuel
o	Initial, at time zero
t	Total
'	Corrected for inflation

2.1.3 LITERATURE REVIEW

Many references cover the analysis of capital investment projects, but most repeat the same widely accepted methods. Few deal specifically with the analysis of energy systems, and only very few deal with the analysis of renewable energy systems.

This review concentrates mainly on the general appraisal methods, taken from Hawkins & Pearce (1971) and Lumby (1981), as these can easily be applied to energy systems. Most of these methods can be used to calculate unit costs simply by dividing yearly or discounted cost by the equipment's energy output. More specific applications to renewable energy systems are discussed, taken from Sorensen (1979), Frean (1983), and Simpson et al (1985). This last reference is excellent in its thorough analysis of the economics of energy systems, good literature review and explicit discussion of renewable energies.

METHODS OF ECONOMIC ASSESSMENT

All methods use the notation of subscript zero to indicate the start of the first year (year 1). All costs, fuel, maintenance and replacement parts, are bought at the start of each year; all returns, profits and interest, come at the end of the year.

Simple assessment methods

Most analysts nowadays would only use 'discounting' techniques to assess capital projects. However, simple methods, by their nature, are easy to use, and do give some insight to project performance. The three main methods are: the pay-back method, the peak-profit method and the average profit method. Hawkins & Pearce (ibid) cover these methods, and give examples showing their limitations and resulting errors.

Discounting Methods

All discounting methods allow for the time value of money. This review deals both with money interest rates and inflation effects, the latter being covered once the techniques have been introduced.

Net present Value Technique

If a person or firm can invest money in savings and receive guaranteed interest at 10%, this is an example of a discount rate r. For example, £ 100 invested now will in one year be

$$100(1 + r) = 100(1 + 0.1) = £110 \qquad (2.1.1)$$

Similarly, to receive £121 in year 2, the investor must now invest

$$121/(1 + r)^2 = 121/(1 + 0.1)^2 = £100 \qquad (2.1.2)$$

The basis of discounting methods is to equate all future money flows back to their value at the start of year 1.

Given an initial investment in a project of C_o in year 1, with revenues (net of tax, maintenance costs, fuel cost, etc.) in each year of S_k, the Net Present Value (NPV) of the project is defined as

$$NPV = [S_1/(1+r) + S_2/(1+r)^2 + \ldots S_n/(1+r)^n] - C_o \qquad (2.1.3)$$

or

$$NPV = [\sum_{K=1}^{n} S_k/(1 + r)^k] - C_o \qquad (2.1.4)$$

A project with an NPV greater than zero indicates that its profits will, over the project's lifetime, more than cover the cost of the investment in the project (allowing for the fact that the initial investment could have been put into savings giving a guaranteed return of r% per year, the choice of a value for r being discussed on page 21). Projects with negative NPVs should be rejected.

Net terminal value

This method is virtually the same as NPV, except that instead of discounting all values back to the start of the project, this method calculates what each cash flow will be worth at the end of the project if it has been reinvested at the firm's interest rate. This is the approach used by Frean (ibid).

Internal rate of return

A variation on the net present value method is called Internal Rate of Return. The NPV in equation is set to zero, and the equation

$$[\sum_{K=1}^{n} S_k/(1 + r^*)^k] - C_o = 0 \qquad (2.1.5)$$

solved to determine the value of r^*. This value is compared with the investor's stated discount rate r: if r^* is greater than r, the project is better than investing money in savings at interest rate r, if r^* is less than r the project should be rejected.

There are some problems with the application if IRR to all projects, but since these do not apply to this work they are not discussed here. The reader is referred to Hawkins & Pearce (ibid) or Simpson et al (ibid) for a full discussion of these problems.

The Effects of Inflation

Two types of inflation are considered here: general inflation, when all prices rise by the same relative amount each year, and energy inflation, when fuel or energy costs rise faster than other prices.

General inflation

If an investor invests £100 today, rather than spending it, it is because he hopes his invested money will be worth more later. At the end of a year, his money, having been invested at r per year will be worth £100(1 + r). However, if the annual inflation rate is i per year, his money will have less purchasing power at the end of the year, by an amount $1/(1 + i)$. For a future cash flow S_k in year k, it follows that its present value V is

$$V = S_k/[(1 + r)(1 + 1)]^k \qquad (2.1.6)$$

The discounting factor $(1 + r)(1 + i)$, with reference to eqn. 2.1.4, can be replaced by an equivalent discount factor p, where

$$1 + p = (1 + r)(1 + i) \qquad (2.1.7)$$

or $$p = r + i + ri \qquad (2.1.8)$$

This value, known as the money or market interest rate (Lumby ibid), can be used in the NPV equations. However, if fuel and maintenance costs are expressed as values at the start of year 1, and if there is no capital investment after year 1, eqn. 2.1.21 shows that inflation effects cancel each other out, and so need not be included.

Relative Energy inflation

If energy prices rise faster than those of other goods or services, the discount rate also changes. If e is the energy inflation rate (in real terms) per annum, the relative energy inflation rate j (relative to other prices) is given by

$$j = e - i \qquad (2.1.9)$$

If F_k is the estimated yearly cost of fuel in year k gross of all inflation, the cost allowing for relative energy inflation will be

$$F'_k = F_k(1 + j)^k \qquad (2.1.10)$$

(the Current Purchasing Power, Bass & Twidell 1986). Discounted back to year 0, the present value of the fuel is

$$V_f = F_k(1 + j)^k/(1 + r)^k \qquad (2.1.11)$$

The same result occurs if an effective rate p is used in 2.1.4, where

$$1 + p = (1 + r)/(1 + j) \qquad (2.1.12)$$

$$\text{or } p = (1 + r)/(1 + j) - 1 \qquad (2.1.13)$$

This is the discount rate arrived at by Sorensen (ibid). It is easy to see that if the energy inflation rate is the same as the discount rate r, the effective discount rate p = 0.

Choice of Values for the Various 'Rates'

It is most important that the values of discount and inflation rates, and equipment lifetimes, are chosen carefully. The analyst must be completely disinterested in his work, or he will be accused of picking parameters which favour his preferred energy source. High discount rates proportionately favour projects with relatively low initial capital costs and high decommissioning and waste disposal costs (the case for many non-renewable sources), low rates proportionately favour high initial capital cost projects (which applies to most renewables). Several examples comparing renewable energy systems with non-renewable ones are given by Simpson et al (ibid), which clearly show how parameter choice effects the NPV of the different systems.

This review does not enter the debate concerning values for discount rates, other than superficially. The range of values used is illustrated by the following list (some values account for inflation, some do not): Sorensen (ibid) suggests 0%; the CEGB suggest 5% (Jenkin ibid), as do ETSU (1982); H.M. Treasury requires 5% return in real terms on its investments in the public sector (1984) but suggests a discount rate (r) of 10% for the private sector. The International Solar Energy Society suggest 2.5% in real terms (ISES 1976), while ETSU (ibid), although suggesting 5%, have used values up to 30% (for projects requiring pay-back periods of 2 or 3 years). Finally the Commission of the European Community (CEC 1984) used 7% in their study of new energy technologies, and for assessing which energy research projects to support.

In addition there is the difficulty of predicting both general inflation and relative energy inflation rates. Again a wide range of relative energy inflation rates have been proposed, from 0% (OECD-IEA 1985, covering the period 1983 to 2000), through 3.5% (Commission of the European Community ibid, for the same period) to 8% (Dept. of Energy 1985, for the period 1990 to 2000).

Some researchers propose different rates for renewable and non-renewable energies, and different inflation rates for different fuels. It has been suggested that social benefits (for example employment, reducing pollution, reducing the risks of serious accident and accounting for personal preference) can be accounted for by varying discount rates in real terms. The reader is referred to Simpson (ibid) or Sorensen (ibid) for a more detailed discussion of this subject.

Finally in this review, although not discussed here, the reader is referred to work by Lipman et al (1982), Galt (1984), Bandopadhayay (1982), Bass (1986) and Frean (ibid) for a discussion of the application of appraisal methods specifically to renewable projects.

2.1.4 EXAMPLES OF APPLYING THE NET PRESENT VALUE TECHNIQUE TO ENERGY SUPPLY EQUIPMENT

The type of analysis undertaken here is relatively simple. All energy supply equipment requires a capital investment at the start of year 1, after which the only costs are fuel costs (if applicable), and operating and maintenance costs. Unit energy costs are constant in real terms throughout the equipment's lifetime (ie there is no relative energy inflation), and there is no scrap value or decommissioning cost. Therefore both net present value and internal rate of return could be used, but net present value was chosen as it is easier to calculate.

Parameter choice and assumptions

This work is intended to be applicable to small, remote communities where likely levels of investment in energy equipment are low in comparison with many other energy projects. Therefore the methods of raising investment capital are likely to be different to those for more capital intensive projects.

No attempt is made to suggest exactly how capital might be raised. However, it is speculated that it might either come from the individuals on Eigg (each family would need to pay between about £600 and £1200 per year), or from a development body such as the Highlands and Islands Development Board. In the former case capital could well be raised by simple bank loans, suggesting a discount rate of about 8% before inflation, while in the latter case, since a public body is involved, a similar rate to that of H.M. Treasury (ibid), ie 5% p.a. suggests itself. This latter figure was chosen as applicable to Eigg.

There would be considerable social benefits associated with an improvement in Eigg's energy system, but these are difficult to quantify precisely. Therefore 'social' discount rates (see above) are not considered, and no attempt is made to modify the 5% discount rate chosen above to allow for such factors.

To attempt to specify a positive net present value (NPV) for investment in projects on Eigg is comparatively meaningless, especially if capital was raised by the islanders themselves. Since they would be paying for the energy themselves profits would return to them, and a positive NPV would simply mean higher unit energy costs. So this work uses zero NPVs for all supply equipment, implying that the investment exactly breaks even, there being neither profit nor loss in comparison with investing money in savings at the chosen discount rate.

Predicting the rate of energy inflation is not easy, as shown by the 40% cut in crude oil prices at the start 1986. Since one aim of this work is to make the island of Eigg self-sufficient in energy supplies, hence independent of imported fossil fuels, a zero rate of energy inflation is reasonable. The analysis below shows that no account need be taken of general inflation rate.

Both fuel and equipment costs (see chapter 6 and appendix 2) used in this work are representative of the years 1983/1984, which were chosen as reference years.

Unit costs

The net present value of an investment is given above as

$$NPV = [\sum_{k=1}^{n} S_k/(1+r)^k] - C_0 \qquad \text{cf (2.1.4)} \qquad (2.1.14)$$

With a non-zero general inflation rate i, and zero relative energy inflation e, the value r can be replaced by p where

$$p = r + i + ri \qquad \text{cf (2.1.8)} \qquad (2.1.15)$$

Since there is no capital investment after the initial investment, the net returns S_k are

$$S_k = R_k - (F_k + M_k) \qquad (2.1.16)$$

where R_k = Returns from 'selling' energy in year k,
F_k = Fuel cost in year k,
and M_k = Maintenance cost in year k.

('selling' refers to either selling energy to another consumer or cost to the producer of generating and using his own energy)

With a general inflation rate i p.a., fuel, maintenance and energy costs all increase by this rate, so

$$R_k = R_o(1 + i)^k \qquad (2.1.17)$$
$$F_k = F_o(1 + i)^k \qquad (2.1.18)$$
$$\& \; M_k = M_o(1 + i)^k \qquad (2.1.19)$$

Substituting these values and the effective rate p in eqn. 2.1.14 gives

$$NPV = [\sum_{k=1}^{n}(R_o - F_o - M_o)(1 + i)^k/(1 + p)^k] - C_o \qquad (2.1.20)$$

As mentioned above, in this work all NPVs should be zero, so

$$(R_o - F_o - M_o)\sum_{k=1}^{n} (1 + i)^k/((1 + i)(1 + r))^k = C_o \qquad (2.1.21)$$

It can be seen that the general inflation term (1 + i) cancels out*, leaving the yearly returns as

$$R_o = [C_o + (F_o + M_o)\sum_{k=1}^{n} 1/(1 + r)^k]/\sum_{k=1}^{n} 1/(1 + r)^k \qquad (2.1.22)$$

The term $\sum_{k=1}^{n} 1/(1 + r)^k$ can be reduced to

$$\sum_{k=1}^{n} 1/(1 + r)^k = [(1 + r)^n - 1]/[r(1 + r)^n] \qquad (2.1.23)$$

Therefore

$$R_o = r(1 + r)^n C_o/[(1 + r)^n - 1] + F_o + M_o \qquad (2.1.24)$$

If the yearly energy output from any energy supply device in year 1 is P, the unit cost of energy (Q, £/kWh) is

$$Q = R_o/P \qquad (2.1.25)$$

It is worth noting here that the Central Electricity Generating Board (U.K.) uses costs per rated power output (£/kW) as their comparative measure for large power stations (Jenkin 1982). The NPV is divided not by the annual energy output, but by the rated power output of the station. This method does not allow direct comparison between different types of energy sources, particularly, as in the case of renewables, when average outputs are often significantly below the rated values.

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* NOTE: This treatment of inflation is suitable for most applications. A fuller treatment, to allow for non-constant inflation and interest rates (such as during hyper-inflation) is given in Appendix 4.

Specific Examples

In some cases in the energy planning model for Eigg, energy demands are supplied from devices (for example gas cookers) where the only cost is assumed to be that of the fuel itself; there being little or no capital or maintenance costs. In these cases equation 2.1.24 reduces to

$$R_o = F_o \qquad (2.1.26)$$

The method is further illustrated by the example of a 3.5 kW diesel generator. The initial capital cost of the generator is £1700, its maintenance £25 p.a., its fuel cost 0.028 £/kWh, and its lifetime 15 years. The generator produces 12300 kWh/y at an average thermal efficiency of 18%, so it follows that the yearly fuel cost is

$$F_o = 0.028 \times 12300/0.18 = 1910 \text{ £/y} \qquad (2.1.27)$$

If the discount rate r is 0.05, substituting values in eqn. 2.1.24 gives

$$R_o = 0.05(1+0.05)^{15}1700/[(1+0.05)^{15}-1] + 25 + 1910 \qquad (2.1.28)$$
$$= 2100 \text{ £/y}$$

Dividing this by the yearly energy output gives a unit cost of

$$Q = 2100/12300 = 0.1706 \text{ £/kWh} \qquad (2.1.29)$$

Equation 2.1.24 can be applied to any component in an energy system individually. A renewable energy converter would have only capital and maintenance costs, and zero fuel costs. Central heating distribution systems would have only capital cost, with no fuel or maintenance cost (the fuel cost is accounted for by the device supplying the system), and the yearly energy from the system can be estimated knowing its rating. A similar procedure can be used for electricity grids and heat pumps. Section 4.1 describes this fully.

2.1.5 DISCUSSION

This section has presented the methods and equations necessary to determine the unit energy costs (£/kWh) of different energy sources. Section 4.1 will show how these unit costs are used as a basis for selection by the energy planning model.

The Net Present Value method was chosen as the most suitable method for calculating unit costs, since this allows for the fact that money can change value over time, owing to interest gained or value lost through inflation. It is only by accounting for this that a realistic assessment of energy costs can be made (assuming non-zero interest or inflation rates), and decisions be taken on which projects to adopt.

A brief discussion of interest and inflation rates used by other researchers was given (including speculation as to what rates should be, accounting for such effects as, for example employment, environmental pollution, storage of nuclear waste, etc.), and it was shown that rates between 0% and 30% have been used. High discount rates favour relatively low initial capital investment projects (typical of most fossil fuel projects), while low rates favour high initial investment projects (typical of renewable energy projects). It was concluded that care has to be taken by analysts to remain disinterested in the rates they choose, so as not to unfairly bias their 'favourite' project over other projects. For application of the method to the island of Eigg, an interest rate of 5% p.a. was chosen.

It was shown that for this project general inflation (price increases of all goods and services) need not be considered. However, the relative inflation of energy (increase in energy and fuel prices relative to other goods) is an important factor. Energy inflation rates used by other researchers have varied between 0% and 10% p.a.: a value of 0% p.a. was chosen for the study of Eigg.

Section 2.2 Thermodynamic Analysis of Energy Systems

2.2.1 INTRODUCTION

This section presents and discusses the methods and equations needed to develop the second type of energy systems' analysis investigated by this thesis, namely thermodynamic analysis. Section 4.2 shows how the equations presented here can be applied to practical energy systems, and the results of thermodynamic optimisation and economic optimisation (presented in the previous section and in section 4.1) will be compared and discussed in chapter 6.

The important property used in thermodynamic analysis is known as exergy; that is the amount of energy from a supply which is available as useful work. Exergy is used in this work to calculate "second law efficiency" of energy systems, the measure by which thermodynamic performance is assessed. Exergy is also used to calculate "energy quality" (related to the work potential of energy), which will be shown in section 4.2 to be a useful parameter in visualising thermodynamic performance. Exergy, second law efficiency and energy quality are all defined specifically in section 2.2.3, and equations for their formulation are given in section 2.2.5.

A brief literature review of the historical development of thermodynamics and exergy analysis is given. The analysis will show that exergy calculations differ from other methods, such as (changes in) Gibbs Free Energy, Helmholtz Free Energy or Availability, which have been used by other researchers, in that exergy can be applied to all energy systems, whereas the others relate to specific systems only.

This work differs from that of other researchers in that it also assesses exergy after, rather than before, the energy has undergone an initial primary transformation. This makes the analysis more closely related to practical, rather than theoretically ideal processes.

2.2.2 SYMBOLS AND UNITS

Symbol	Description	Units
B	Exergy	J
B_b	Exergy remaining after combustion	J
ΔB	Exergy loss	J
C_p	Specific heat at constant pressure	J/(kg K)
COP	Coefficient of performance	-
D	Steady-state availability function	J
E_e	Energy output of electrical sources	J
E_m	Energy output of mechanical sources	J
F	Helmholtz free energy	J
F'	Special case of Helmholtz free energy	J
G_f	Gibbs free energy	J
H	Enthalpy	J
ΔH	Heat of combustion	J/mol
P	Pressure	N/m^2
Q	Heat	J
S	Entropy	J/K
ΔS_{sa}	Entropy change of environment and system	J/K
ΔS_b	Entropy change from change of composition	J/K
ΔS_p	Entropy change from isobaric heating	J/K
T	Temperature	K
U	Internal energy	J
W	Work	J
Z	Height	m
c	Velocity	m/s
g	Acceleration due to gravity	m/s^2
m	Mass	kg
n	Number of moles	-
q	Energy quality	-
ϱ	Density	kg/m^3
η_1	First law energy efficiency	-
η_2	Second law exergy efficiency	-

Subscripts

c	Cold heat sink
carnot	From a Carnot engine
d	Demand
f	Flame
h	Hot heat source
i	Thermodynamically ideal
in	Into the system
max	Maximum
min	Minimum
o	Natural environment
out	Out of the system
r	Real device or system
rev	Reversible
s	End state
1	Initial state
2	Final state

2.2.3 DEFINITIONS

Second law efficiency

The definition of second law efficiency (η_2) used in this work is that given by, among others, Ford et al (1975), as

$$\eta_2 = \frac{\text{Useful heat and/or work transferred by a given device or system}}{\text{Maximum possible useful heat and/or work transferred for the same function by any ideal, unspecified device or system with the same inputs as the given device or system}} \qquad (2.2.1)$$

Although this can be applied without a knowledge of exergy (defined below), equation 2.2.1 can also be expressed as

$$\eta_2 = \frac{\text{Minimum exergy needed to perform a function by an ideal unspecified device or system}}{\text{Actual exergy used to perform the function by a given device or system}} \qquad (2.2.2)$$

First law efficiency (η_1) is usually defined as

$$\eta_1 = \frac{\text{Useful energy output of device or system}}{\text{Energy input to device or system}} \qquad (2.2.3)$$

It is easy to show that

$$\eta_2 = \eta_{1,r}/\eta_{1,i} \qquad (2.2.4)$$

where $\eta_{1,r}$ = first law efficiency of real device or system,

and $\eta_{1,i}$ = ideal first law efficiency for same process.

Exergy: Fundamental definition (later adapted)

Before giving the various relationships which are used to calculate exergy (sub-section 2.2.5), it is worth defining it in words. The term was first introduced by Rant (1956), and was effectively defined as:

> "Exergy is the maximum possible useful work which can be extracted from a source of energy as it changes from its initial state to the state in which it is in unrestricted equilibrium with the naturally-occurring environment".

Useful work means that work which is potentially available as shaft work (this also includes electrical potential, as this can theoretically be converted to shaft work with 100% efficiency), and excludes work done to displace the environment. Air flowing away from a wind turbine, or water from a hydro turbine, is pushing back the natural environment, and therefore does not contribute to useful work.

Unrestricted equilibrium is a theoretical state in which the system is not only in temperature and pressure equilibrium with its environment, but also in chemical, nuclear, gravitational, kinetic and electrical equilibrium. It is therefore impossible, from this state, to extract any further work. By naturally-occurring environment is meant temperature T_O (mean environmental temperature), pressure P_O (mean environmental pressure), height Z_O (ground or sea level), and with no remaining chemical or concentrational potential (ie fully diffused). The environment is assumed to always have constant pressure P_O and temperature T_O.

Exergy must be independent of device or process: the maximum work can only be calculated by considering ideal, reversible processes. It is also independent of rate, so to extract maximum work, especially when heat transfer is involved, infinitely long time and infinitely small temperature differences can be assumed.

Exergy: Practical definition (as used in this thesis)

The above fundamental definition includes some terms which are of little use in practical applications. For example it is difficult to envisage a device which could extract the work of diffusion. Similarly when dealing with hydro turbines, there is little point in talking about chemical equilibrium of the water. Therefore a more practical definition is required, excluding diffusion and nuclear terms (retaining chemical terms for combustible fuels), as follows:

> "Exergy is the maximum possible useful work which can be extracted from a source of energy as it changes from its initial state to the state in which it is in restricted equilibrium with the naturally-occurring environment"

Restricted equilibrium is defined as follows: for fuel sources it is the state in which complete combustion has taken place but kinetic energy (ie the speed of exhaust gases) is not considered. For heat sources it is the T_O, P_O state, and if the source is not fuel, chemical potential is not considered. For sources of kinetic or potential energy, restricted equilibrium is the state of minimum kinetic or potential energy (ie in which no more energy can reasonably be extracted, subject to there being sufficient energy to push back the environment).

There are two processes for which it is more practical to specify the device or type of process: combustible fuels and solar energy. These are discussed in section 2.2.5.

Energy quality

Energy quality is defined for both energy supplies and demands. These definitions are explained in more detail, with examples, later. For energy supplies the quality q is

$$q = \frac{\text{Exergy of supply}}{\text{Energy of supply}} \qquad (2.2.5)$$

For energy demands, the quality is defined as

$$q = \frac{\text{Exergy from amount of energy demand}}{\text{Energy demand}} \qquad (2.2.6)$$

Where the demand is for heat, the exergy content of the demand is shown in section 2.2.5 to be the work available from an ideal Carnot engine with a source temperature the same as the temperature of the demand.

Reversible processes

A reversible process is defined (Zemansky 1951) as "one that is performed in such a way that, at the conclusion of the process, both the system and the local surroundings may be restored to their initial state without producing any changes in the rest of the universe".

Wallace & Linning (1977) give equations for calculating the irreversibility of various real processes.

2.2.4 LITERATURE REVIEW

This review deals only with the theoretical background to the thermodynamical methods of analysis. The formulations for available energy or exergy are given in sub-section 2.2.5, and are not repeated here. A review of the application of the methods to practical energy systems, and also to exergy economics, is given in sub-section 4.2.3.

The study of energy availability, later called exergy, started in the 19th century with work by Carnot (1824, reprinted in Kestin 1976), Clausius (1865), Tait (1868), Maxwell (1871 & 1878) Gibbs (1931, from a paper presented in 1873) and Thomson (1879). Carnot's work led to the formulation of the Carnot cycle heat engine, an important 'standard' since, although it is not practical, is one of three heat engine cycles (the others being the Stirling cycle and the Ericsson cycle, both described in Rogers & Mayhew 1976) which extract maximum work from an energy source, and have what is known as the Carnot efficiency. Clausius was the first to introduce the concept of entropy (a measure of the 'order' of energy), and this led to analytical derivations for available energy and exergy.

Tait was the first to write about 'availability' to calculate the work potential of heat, and Maxwell was the first to introduce the term 'available energy' in his "Theory of Heat" published in 1871, although he credits Thomson (Lord Kelvin) with the original ideas. Maxwell wrote in 1878 (reprinted in 1890) in his review of Tait's work "Sir William Thomson, the last but not the least of the great founders (of classical thermodynamics; the other two being Rankine and Clausius) does not even consecrate a symbol to denote the entropy, but he was the first to clearly define the intrinsic energy of a body, and to him alone are due the ideas and the definitions of the available energy and the dissipation of energy". Thomson did not mention 'availability' or 'available energy' in his own work, but he did study reversibility and reversible heat engines, and also energy dissipation in a body as energy is redistributed throughout the body which initially had a non-uniform temperature distribution (Thomson 1853 and ibid).

Gibbs appears to have been the first to derive the equations needed to calculate the available energy (the shaft work available) from a given heat source, in 1873 (reprinted in 1931), but Keenan (1941) was the first to present Gibbs' work in an easier-to-understand and more practical form. However Maxwell (1875) in the fourth edition of his "Theory of Heat" also derived similar, but much more easily-understandable, relationships to those of Gibbs, although this work appears to have received little attention.

Development of thermodynamics continued throughout the 20th century, particularly in the German language (for example Stodola 1898, Planck 1927, Rant ibid, Baehr 1965 and a review of exergy literature by Gasparovic 1961). A good summary of this work, and of the various formulations of availability, is given by Haywood (1974a & 1974b), who also provided the background to the 19th century review above.

Rant was the first to use the term 'exergy'. He used a general definition which was that, since work can be transformed into other forms of energy, exergy is that part of energy which can be transformed into any other form of energy. Baehr (ibid) reviews other work on exergy, and includes the term anergy, which is that part of energy not capable of being transformed into other forms of energy.

A most useful reference, as far as this thesis is concerned, was that of Ford et al (ibid). This gives the definitions of second law efficiency used in this work, and analyses various energy systems (including the combustion of fuels described in the next section) from a thermodynamical point of view. Rotty & Van Artsdalen (1978) present a very similar paper to Ford et al, and although they mention energy quality, they do not define it. Sorensen (1981) does introduce equations for energy quality, but his choice of symbols does not make this an easily-read paper. Better references to energy quality are given in sub-section 4.2.3.

Classical thermodynamics considers ideal processes: those in which heat transfer can occur through infinitely small temperature differences, heat being supplied from or rejected to infinite sources or sinks, and over infinitely long time. Therefore the aim is to maximise energy outputs. Some researchers, though, have concentrated on more realistic analysis of energy systems, in which time and limited heat capacity of sources are considered. These aim more at maximising power outputs (energy/time); a more relevant concept for real systems.

Curzon & Ahlborn (1975) analyse a Carnot cycle whereby heat transfer is limited (by heat exchangers) to a finite rate. In this situation, first law efficiency for the cycle giving maximum power is

$$\eta_1 = 1 - (T_c/T_h)^{0.5} \qquad (2.2.7)$$

as opposed to the maximum energy criterion of Carnot, where

$$\eta_1 = 1 - (T_c/T_h) \qquad (2.2.8)$$

where T_h = temperature of hot source
and T_c = temperature of cold sink.

They apply this maximum power efficiency to various common energy systems (power stations, etc.), and show that the maximum power efficiency is closer to first law efficiency (energy in/energy out) of the systems under real conditions than to the Carnot efficiency.

Similar analysis is undertaken by Rubin et al (1981) and Andresen et al (1977). Ondrechen et al (1981) analyse systems for which the heat source is of finite capacity. Their analysis is beyond the scope of this review, but one important conclusion is that a cycle similar to the Otto or Brayton cycles can be derived which will give higher efficiency than the Carnot cycle when the source is not infinite, but changes temperature as energy is extracted.

2.2.5 SPECIFIC FORMULATIONS OF EXERGY AND ENERGY QUALITY

Before giving specific formulations for exergy, energy quality and second law efficiency, it is worth discussing briefly the second law of thermodynamics, summarising some important aspects of exergy and energy quality, presenting the Carnot cycle and defining maximum flame temperatures, as these are important in the formulations below.

The Second Law of Thermodynamics

This has been stated in many different forms (first considered by Carnot ibid), with several corollaries (covered, from an engineering viewpoint, by Wallace & Linning ibid). The Second Law is not directly theoretically provable (although the corollaries can be easily shown to be consistent). Planck (ibid) states it as "It is impossible to construct a system which will operate in a cycle, extract heat from a reservoir, and do an equivalent amount of work on the surroundings". Stated mathematically,

$$W_{out} < Q_{in} \qquad (2.2.9)$$

meaning that the work output from a system is always less than the heat input, and that some heat must always be rejected to a cold sink. This has become known as the Kelvin-Planck statement. If an engine could violate this statement, it would be a perpetual motion machine of the second kind (perpetual motion machines of the first kind are those which produce work without receiving energy from any source).

Aspects of Exergy and Energy Quality

Unlike energy, exergy is not a conserved quantity by definition, being conserved only in ideal (reversible) processes. If an energy transformation goes directly from an amount of energy at high temperature (high quality) to a similar amount at low temperature (low quality), as in the case of a boiler burning fuel at high temperature to produce low temperature space heat, even though there might be very small energy losses (from the flue), there are high exergy losses.

Losses of exergy can be shown to be directly related to increases in global entropy. Entropy increases correspond to degradation of energy and increased randomness of the universe. Only in 'reversible' processes is the total entropy of the universe held constant. Minimum energy exchange is required for a process if it is done reversibly, and maximum work output comes from reversible processes. It follows from this that maximum exergy (ie work) can only be extracted by reversible processes. Energy cannot be created or destroyed, only changed to other forms, but all real (hence irreversible) processes decrease the exergy extractable from a system, while keeping the total energy constant.

Most important in this type of analysis is the fact that an amount of energy of low quality can never supply the same amount of energy at higher quality (10 joules of hot water at 20°C cannot supply a demand for 10 joules at 60°C). If low quality energy has to supply high quality demands, there will always be large energy losses to the environment in the conversion process. On the other hand, high quality energy can supply a greater amount of lower quality energy (an input of 10 joules to a heat pump might typically give 30 joules of hot water at 60°C, the heat pump having up-graded energy from the surroundings). It is therefore most important, when designing energy systems from a thermodynamic point of view, to avoid low to high quality energy transformations, and to make maximum use of high quality sources.

Carnot Cycle

The Carnot cycle consists of four reversible processes: two isothermal (constant temperature) and two adiabatic (no external energy transfer). The cycle is shown on fig. 2.2.1 overleaf. For all processes to be reversible the heat source and sink must have infinite thermal capacity and constant temperatures, all processes must occur infinitely slowly, and if a closed system is used, the piston must be frictionless and it and its cylinder must be perfect insulators.

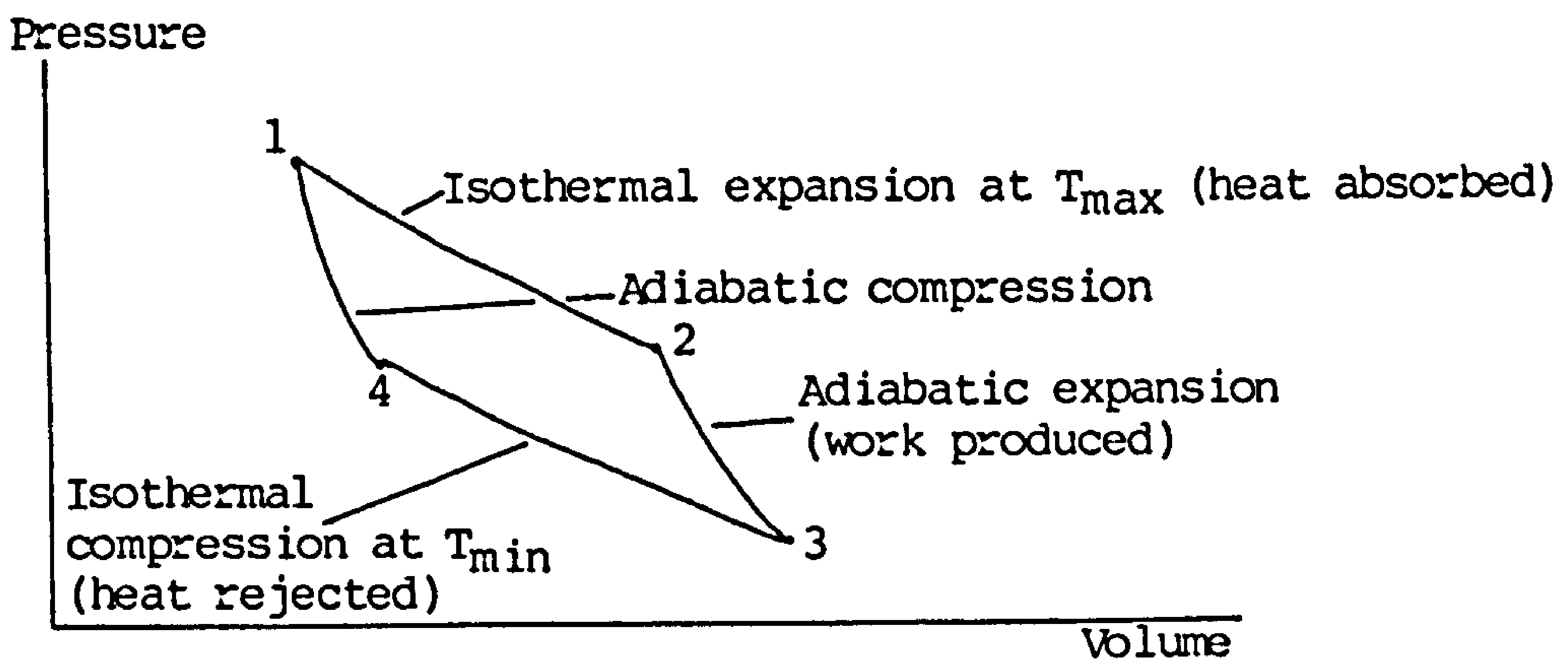

FIGURE 2.2.1 The Carnot cycle

It is easy to show (Zemansky ibid) that a Carnot engine has the maximum efficiency of work production, even though it is an impractical cycle. Its efficiency is independent of working fluid, and is

$$\eta_1 = 1 - T_{min}/T_{max} \qquad (2.2.10)$$

The Carnot cycle can also be reversed to act as a heat pump, in which case its coefficient of performance (COP), defined as heat out/work in, is given by

$$COP = \frac{T_{max}}{T_{max} - T_{min}} \qquad (2.2.11)$$

Maximum Flame Temperatures of Combustible Fuels

When calculating the exergy of a fuel after combustion, the concept of maximum adiabatic flame temperature is required. This is the temperature which would result from combusting a fuel at in air at STP, with all the fuel's energy going to heat and expand the combustion products. This implies an infinite, adiabatic store in which combustion takes place.

For all but the most chemically simple fuels, the theoretical calculation of flame temperature is difficult, especially if the fuel consists of several compounds. It is easier to use an empirical method, such as that of Rose & Cooper (1977), with fuel data from Johnson & Auth (1951) and Spiers (1932). For several common fuels of typical composition, the resulting flame temperatures (table 2.2.1) are:

Fuel	Net calorific value (MJ/kg)	Adiabatic flame temperature (K)
Butane	49.30	2280
Coal	28.95	2290
Diesel	43.16	2300
Kerosene	43.50	2270
Petrol	43.66	2260
Propane	50.00	2290
Wood	14.35	1940

Table 2.2.1 Adiabatic maximum flame temperatures and net calorific values of typical fuels

Specific Formulations for Calculating Exergy

Rather than defining a single relationship applicable to all systems (and hence often having many redundant terms), it is better to deal with each system needed for the study of Eigg individually. Two general systems, a non-cyclic closed system and a non-cyclic steady flow process are also considered, as is the exergy of energy demands.

Mechanical and electrical sources

Mechanical sources of energy which are already in the form of shaft work (or can be completely transformed to shaft work), have exergy

$$B = E_m \qquad (2.2.12)$$

where E_m = energy output of source.

Similarly, in this work, it is assumed that electrical energy sources can be completely transformed into shaft work, so

$$B = E_e \qquad (2.2.13)$$

Although, for example, diesel generators and petrol engines can be considered as electrical or mechanical sources, since they are powered by heat sources (diesel or petrol), they are considered separately under thermal sources.

Hydro and wind energy

The definition of exergy in this thesis excludes energy needed to displace the environment. Wind must move away from the turbine, and water must be able to move away from the water turbine. The losses associated with this moving away of wind or water do not enter the exergy term. The primary transformation for hydro and wind energy, after which exergy is calculated, is thus the extraction of kinetic energy by the turbine resulting in power at the turbine shaft.

Thermal energy sources

Thermal energy sources can be split into two categories: fuels (which give energy from combustion), and other heat sources (for example hot water). They can further be divided into steady-flow processes (diesel and petrol engines) or non-flow processes (Carnot engines, Stirling engines, etc.). The exergy of these sources are dealt with below, using the definition of exergy given in sub-section 2.2.3. Solar energy is treated separately in the energy quality section.

Combustion of fuels

More work could be obtained by electrochemical oxidation of a fuel in an ideal fuel cell than from combustion, but this is practical only for chemically simple fuels such as hydrogen. Combustion remains the practical method of energy extraction. Two methods are presented below, both giving the same value for the exergy after combustion.

Method 1

The fuel is combusted at its adiabatic flame temperature in an infinite, insulated container, with all the fuel's energy being used to heat and expand the combustion products. There is no initial heat extraction from the system. Subsequent processes, not considered here, extract work and heat. Figure 2.2.2 summarises the process.

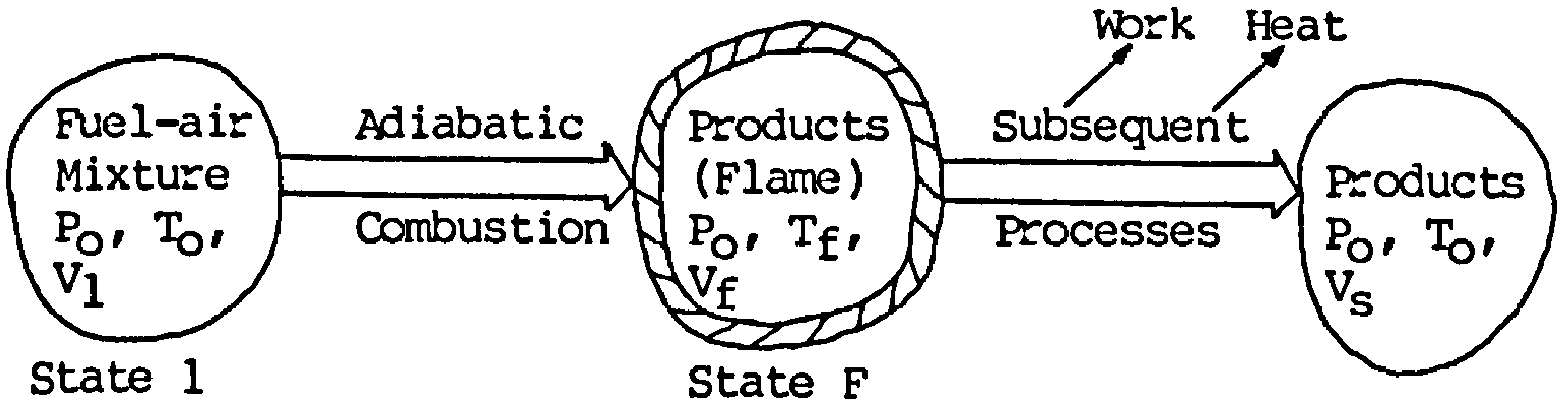

FIGURE 2.2.2 Fuel combustion

If the fuel was oxidised in a reversible fuel cell, its exergy (neglecting diffusion, which does not contribute to useful work) would be the change in Gibbs free energy (see below). This, for many fuels, is close to the heat of combustion $-\Delta H$ (Ford et al ibid). Combustion, however, is an irreversible process, so the exergy of the fuel after it is combusted is $-(\Delta H$ - exergy loss during combustion).

Using the ideal gas approximation, the temperature of state F can be calculated as

$$-\Delta H = nC_p(T_f - T_o) \qquad (2.2.14)$$

where n = number of moles of products
and C_p = the average specific heat of the products.

The loss of exergy ΔB is given by

$$\Delta B = -T_o \Delta S_{sa} \qquad (2.2.15)$$

where ΔS_{sa} = entropy change of the system and the environment.

But with no cross-boundary heat transfer the entropy of the environment does not change. The only changes are those of the system, these being

ΔS_b from change of composition
ΔS_p from isobaric (constant pressure) heating of the products

ΔS_p is far larger than ΔS_b, so the latter is ignored.

For an ideal gas undergoing isobaric heating,

$$\Delta S_p = nC_p \ln(T_f/T_o) \qquad (2.2.16)$$

Therefore

$$\Delta B = -T_o n C_p \ln(T_f/T_o) \qquad (2.2.17)$$

The exergy left after combustion, B_b, is given by

$$B_b = B + \Delta B = B - T_o n C_p \ln(T_f/T_o) \qquad (2.2.18)$$

Assuming that $B = -\Delta H$, and substituting for (nC_p) in eqn. 2.2.18 gives

$$B_b = -\Delta H[1 - (T_o \ln(T_f/T_o))/(T_f - T_o)] \qquad (2.2.19)$$

Method 2

In the analysis of combustion, it is not correct to use the Carnot relationship assuming T_h is the flame temperature. The flame is not an infinite heat source, but one whose temperature falls as heat is extracted. Combustion products must be removed from the system, and if they are removed at a temperature other than that of the environment, exergy is lost.

Referring back to fig. 2.2.1 (the Carnot cycle), for a finite source during process 1-2 the source falls from its initial temperature to T_2 (T_{max}). Heat rejection is still at T_o, the surroundings being an infinite heat sink.

The finite heat source, the flame (the hot reservoir at T_f), can drive a Carnot engine while the flame temperature falls from T_f to T_o. Thus for isobaric expansion of an ideal gas

$$W = nC_p\int_{T_f}^{T_o}(1 - T_o/T)dT \qquad (2.2.20)$$

which gives

$$W = nC_p(T_f - T_o) - nC_pT_o\ln(T_f/T_o) \qquad (2.2.21)$$

This can easily be shown to be the same as equation 2.2.19.

Other heat sources

If the source can be considered infinite (ie constant temperature T_h), the exergy is the work from a Carnot engine

$$B = Q_h(1 - T_o/T_h) \qquad (2.2.22)$$

where Q_h = energy extracted from the source at T_h.

More usually, though the source would be finite, so equation 2.2.21 applies, the integration being between T_h and T_o.

Non-cyclic open and closed system processes

The above treatment of combustion is a special case of a non-cyclic open system process, which itself is an expansion of a non-cyclic closed system process. These are covered by Wallace & Linning (ibid), but are briefly described here.

Non-cyclic closed system process

Figure 2.2.3 shows energy flows in a closed system, with only heat or work transferred across the system boundary, not mass.

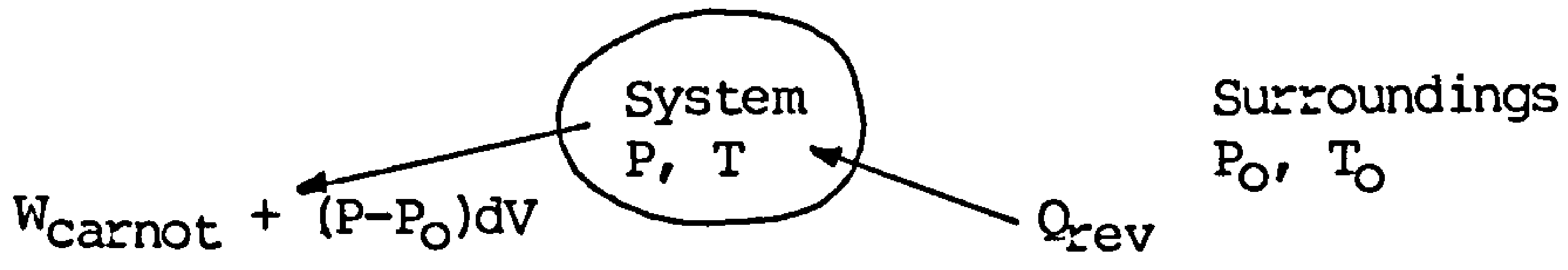

FIGURE 2.2.3 Non-cyclic closed system process

The exergy from the system of fig. 2.2.3 is

$$B = \int_1^0 dW = \int_1^0 -dU - \int_1^0 P_o dV + \int_1^0 T_o dS \qquad (2.2.23)$$

$$= (U_1 - T_oS_1 + P_oV_1) - (U_o - T_oS_o + P_oV_o) \qquad (2.2.24)$$

which is the 'availability' defined by Keenan (ibid). For a constant-volume process, equation 2.2.24 reduces to

$$B = (U_1 - T_oS_1) - (U_o - T_oS_o) \qquad (2.2.25)$$

which, if a function

$$F' = U - T_oS \qquad (2.2.26)$$

is defined as a special case of the Helmholtz free energy function $F = U - TS$, equation 2.2.25 becomes

$$B = F'_1 - F'_o \qquad (2.2.27)$$

Non-cyclic steady flow process

Steady flow processes have both energy and mass transfer across the system boundary. Figure 2.2.4 shows such a system.

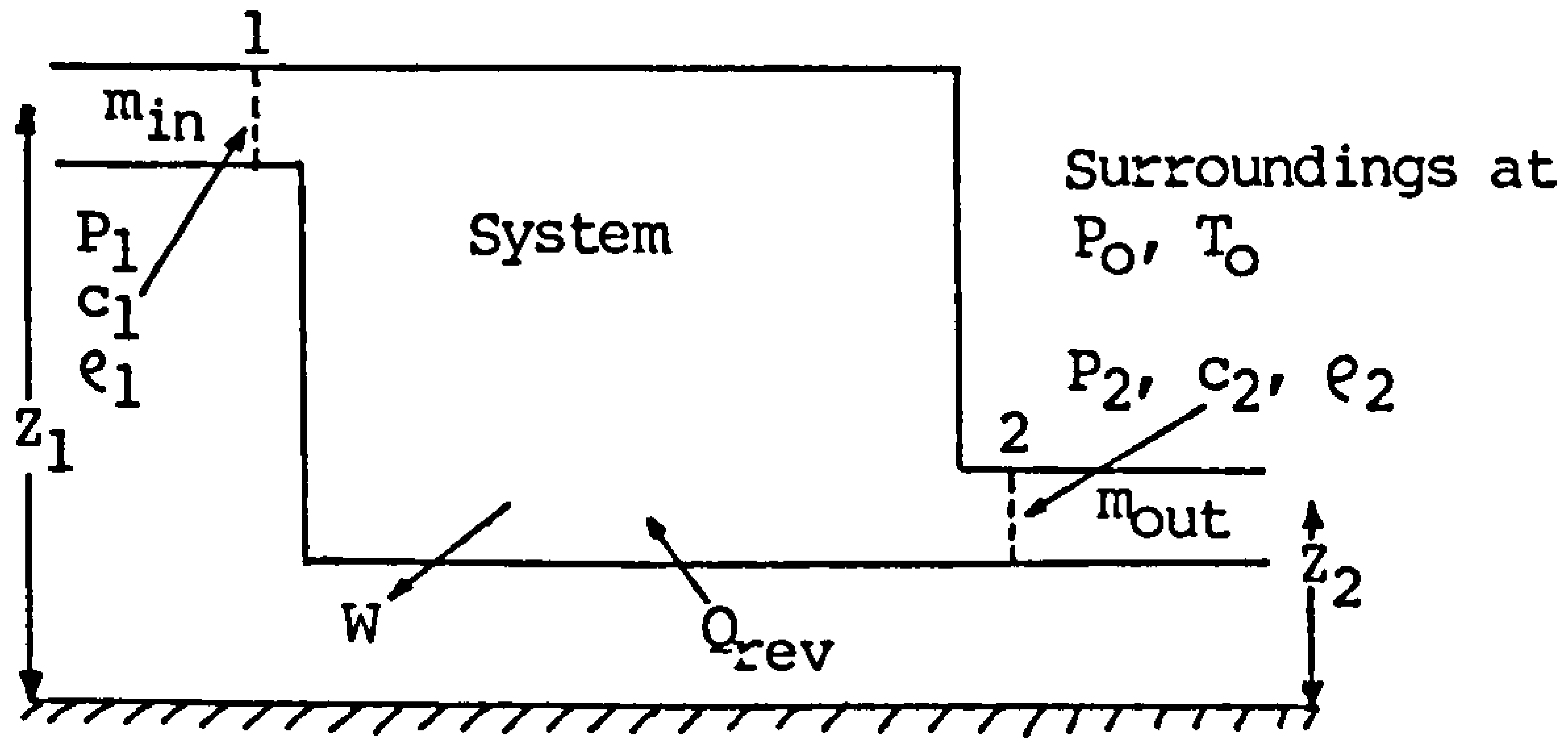

FIGURE 2.2.4 Non-cyclic steady flow process

Enthalpy is defined as $H = U + PV$, and since for a steady flow process $m_{in} = m_{out}$, it follows that

$$B = (H_2-H_1) - T_o(S_2-S_1) + m_{in}[(c_2^2-c_1^2)/2 + (Z_2-Z_1)g] \qquad (2.2.28)$$

The property $D = H - T_oS$ (2.2.29)

has been defined as the steady-state availability function, and is a special case of the Gibbs free energy, $G_f = H - TS$. So 2.2.28 becomes

$$B = D_2 - D_1 + m_{in}[(c_2^2 - c_1^2)/2 + (Z_2 - Z_1)g] \qquad (2.2.30)$$

or in cases where potential and kinetic terms can be ignored,

$$B = D_2 - D_1 \qquad (2.2.31)$$

Hence the exergy of a steady flow process with low potential and kinetic energy terms is a special case of the Gibbs free energy. Equation 2.2.31 gives the exergy from an ideal fuel cell.

Exergy of energy demands

In this work, energy demands relate to the desired end-effect, and so are independent of the means of supply or of the amount of energy input to a device to meet the demand. For example the demand for space heating is for heat at the desired air temperature of the room, not at the temperature of hot water in a radiator, or the temperature of an electric heating element, etc. This latter is consistent with the ideal assumption that heat transfer processes can take infinite time, and can be through infinitely small temperature differences.

If the demand is for shaft work (not the engine's fuel input, for transport), or electricity (for appliances, but not for cooking (by heat) or space or water heating), the exergy of the demand is simply the same as the energy level of the demand, ie

$$B = Q_d \qquad (2.2.32)$$

If the demand is for heat (cooking (by heat), space or water heating), the temperature of the demand remains constant. The exergy of the energy demand is therefore the work which could be extracted by a Carnot engine working between the temperature of the demand T_d, and the environmental temperature T_o, which is

$$B = (1 - (T_o/T_d))Q_d \qquad \text{cf } (2.2.22) \qquad (2.2.33)$$

Equations for Energy Quality

A knowledge of energy quality is not needed for the calculation of second law efficiency, so energy qualities in this work are chosen to reflect the most likely form of energy from a source, after its initial transformation. The likely form of energy from combustible fuels is heat at high temperature, for solar energy it is low temperature heat (see below), while the output of hydro and wind turbines is shaft power (or electricity). These qualities, when used to construct the exergy diagrams (see section 4.2), give much better insight into the resulting second law efficiency than if other quality values were used.

Energy supplies

For a supply of shaft work or electricity, 2.2.12 showed that the exergy is the same as the energy content of the supply. Therefore

$$q = B/E_m = 1.0 \qquad (2.2.34)$$

The definition of quality takes no account of the availability over time of the supply. Wind turbines, hydro turbines, and solar panels do not generally give out constant power. This is assumed to not affect the thermodynamic quality of the supply, so for example a wind turbine will always produce energy of quality 1.0 regardless of variations in energy output.

For energy from combustible fuels, equation 2.2.19 gave the exergy content of the fuel after combustion. The energy content of a fuel is considered to be the heat of combustion, so

$$q = -\Delta H[1 - (T_0 \ln(T_f/T_0))/(T_f - T_0)]/-\Delta H \qquad (2.2.35)$$

$$\text{or } q = 1 - (T_0 \ln(T_f/T_0))/(T_f - T_0) \qquad (2.2.36)$$

Applying this, as an example, to propane gas, for which the adiabatic flame temperature T_f is 2290 K, and the environmental temperature T_0 is 280 K (the yearly mean temperature on the island of Eigg, see section 5.1), the quality of propane after combustion is

$$q = 1 - (280\ln(2290/280))/(2290 - 280) = 0.707 = 70.7\% \quad (2.2.37)$$

If the energy supply is a heat source other than a combustible fuel, the quality is calculated from either equation 2.2.21 (for finite sources) or equation 2.2.22 (infinite sources).

Solar energy

Solar energy is one source for which it is difficult to define its quality. It is basically a thermal source, arriving at Earth's outer atmosphere with an equivalent temperature of about 6000 K. Its conversion to electricity (by photo-electric cell) changes its basic form and results in considerable energy losses; theoretical photo cells have efficiencies of only about 47% (Twidell & Weir 1986).

On the other hand, treating solar energy as a thermal source introduces the difficulty of which equivalent temperature to use. Twidell & Pinney (ibid) suggest 6000 K, inputting energy at this temperature to a Carnot engine. However this is limited by the difficulty of converting radiation from photon energy to heat at such a high temperature. Such a conversion would involve entropy creation, hence loss of exergy, leading either to lower energy output or lower quality. Photo-electric conversion implies changing the basic form of solar energy, so neither of these conversions is chosen as appropriate.

The other method of assessing the exergy of solar energy is by extracting heat from solar water or air heating panels, and this is chosen as the most appropriate transformation. Energy is output at 343 K (the average temperature of hot water demand on the island of Eigg), giving a quality of 0.184 (18.4%). This corresponds better to the performance of real systems than other, theoretical methods would.

The above value of quality can be compared with the analysis of O'Callaghan & Probert (1981). They apply an energy balance to an ideal collector surface, and use this to determine the optimum surface temperature, which can be taken to be the input temperature for a

Carnot engine. Using typical values for Eigg, a quality of 0.11 (11.0%) results with a first law (energy) efficiency of 50.5% (50% is used in this work). They also analyse a concentrating collector which, for conditions on Eigg, gives a quality of 35.8%.

The value of quality used in this work therefore falls between the two values above. However, the above analysis further highlights the problem of solar energy in that, even having chosen a direct radiation to heat transformation, the quality is device dependent. It is concluded that more work should be done to determine an appropriate reference for solar energy.

Energy demands

In this work there are four types of demand: space heating, hot water, cooking and electricity. Cooking is further divided into energy for boiling and that for frying (very little cooking on Eigg is done in ovens). The quality of energy demands is calculated in exactly the same way as for energy supplies. The exergy of electricity demand is the same as the energy level of the demand, so the quality is 1.0. For heat demands, quality is determined from equation 2.2.33 as

$$q_d = (1 - (T_o/T_d))Q_d/Q_d = 1 - (T_o/T_d) \qquad (2.2.38)$$

Table 2.2.2 shows the assumed temperatures of the heat energy demands (these all represent approximate mean temperatures for a year), and using the same environmental temperature as before ($T_o = 280$ K), gives the qualities of the energy demands. These will be used in the planning work described in section 4.2 and chapter 6.

Demand	Temperature (K)	Quality (%)
Space heat	293	4.4
Hot water	343	18.4
Cooking (boiling)	360	22.2
Cooking (frying)	490	42.9
Electricity	-	100.0
Transport	-	100.0

Table 2.2.2 Qualities of energy demands on the island of Eigg

2.2.6 EXAMPLES OF EXERGY ANALYSIS OF ENERGY SYSTEMS

The examples in this section show how second law efficiencies are obtained for various energy systems, and compare these with first law (energy) efficiencies, showing that the latter can give very misleading results.

The systems considered all use propane gas as input to: a conventional water heating boiler, a gas-driven electricity generator supplying direct-electric space heat, a gas driven generator supplying a commercially-available heat pump to give space heat, a gas driven generator supplying a thermodynamically-ideal heat pump, and finally an ideal fuel cell driving an ideal heat pump. The results are derived from Twidell & Pinney (ibid).

Gas driven water heating boiler

The boiler is a typical commercially-available model, with a first law efficiency (energy out/energy in) of 80%. The gas burns at its adiabatic flame temperature (2290 K), and supplies hot water at 80°C, which is used to give space heat to a room at 20°C. 10 GJ of fuel are input to the boiler.

The exergy input to the boiler is given by eqn. 2.2.19, but with the heat of combustion replaced by the energy content of the fuel. Thus

$$B = 10[1 - (280\ln(2290/280))/(2290 - 280) = 7.07 \text{ GJ} \qquad (2.2.39)$$

Since the demand is for heat energy at 20°C, using the criterion given above (disregarding the actual temperature of the energy supply), the exergy of the 'demand' (in this case output of the boiler, 10x0.8 = 8.0 GJ) at 20°C is

$$B_d = 8.0(1 - 280/293) = 0.35 \text{ GJ} \qquad (2.2.40)$$

where 280 K = environmental temperature.

So the second law efficiency (exergy out/exergy in) is

$$\eta_2 = 0.35/7.07 = 0.050 \text{ or } 5.0\% \qquad (2.2.41)$$

Gas driven electricity generator giving direct electric heat

The generator in this example is assumed to have a first law efficiency of 30%, and its input is again 10 GJ of gas. Its exergy, at the adiabatic flame temperature, is 7.07 GJ.

The generator's output of electricity (quality 1.0) is therefore 10x0.3 = 3.00 GJ. However, since this output is used to supply direct electric space heat (ie space heat at 20°C) the exergy of demand is

$$B_d = 3.0(1 - 280/293) = 0.13 \text{ GJ} \qquad (2.2.42)$$

Applying the second law efficiency to this system gives

$$\eta_2 = 0.13/7.07 = 0.018 \text{ or } 1.8\% \qquad (2.2.43)$$

Gas driven generator supplying heat pump

The generator is the same as that in the previous example. All its output is used to drive a commercially-available electric heat pump having a coefficient of performance (COP, defined as heat out/work in) of 3.0. The heat pump delivers heat at 70°C.

The 3.00 GJ electrical output provides 3.00x3.0 = 9.0 GJ of heat at 70°C. However, as before, the demand is for heat at 20°C, therefore the exergy of demand is

$$B_d = 9.0(1 - 280/293) = 0.40 \text{ GJ} \qquad (2.2.44)$$

and so the system efficiency becomes

$$\eta_2 = 0.40/7.07 = 0.056 \text{ or } 5.6\% \qquad (2.2.45)$$

The first law efficiency for this system is

$$\eta_1 = \text{Energy out/energy in} = 9.0/10.0 = 0.9 \text{ or } 90\% \qquad (2.2.46)$$

Gas driven generator driving an ideal heat pump

The same generator as above is assumed, but in this case it supplies a thermodynamically-ideal heat pump, based on the reverse Carnot cycle (fig. 2.2.1). There are no practical temperature limits, so the heat pump can supply energy at 20°C (the temperature demanded). The COP of such an ideal heat pump is given by equation 2.2.11 as

$$\text{COP} = T_h/(T_h - T_c) = 293/(293 - 280) = 22.5 \qquad (2.2.47)$$

so from the 3.0 GJ output by the generator, the heat pump produces 3.0x22.5 = 67.5 GJ, the exergy of which is

$B_d = 67.5(1 - 280/293) = 2.99$ GJ (2.2.48)

Therefore the second and first law efficiencies of this system are

$\eta_2 = 2.99/7.07 = 0.423$ or 42.3% (2.2.49)

$\eta_1 = 67.5/10.0 = 6.75$ or 675.0% (2.2.50)

Gas powered fuel cell driving ideal heat pump

To the level of approximation of this work (neglecting diffusion), exergy from an ideal fuel cell is $-\Delta H$. For methane $-\Delta H$ = 802.5 kJ/mol (this compares with the change in Gibbs free energy G_f = 809.2 kJ/mol, Ford et al (ibid)). So if 10 mol of methane are input, the exergy would be 10.0x802.5 = 8.02 MJ.

The COP of the heat pump is 22.5, calculated by equation 2.2.11 (note that this is a theoretically-ideal heat pump: practical ones would have much lower COP's), so its output is 22.5x8.02 = 180.45 MJ, and the exergy is

$B_d = 180.45(1 - 280/293) = 8.01$ MJ (2.2.51)

The second law efficiency is therefore

$\eta_2 = 8.01/8.02 = 0.999$ or 99.9% (2.2.52)

whereas the first law efficiency is

$\eta_1 = 180.45/10.0 = 22.5$ or 2250.0% (2.2.53)

2.2.7 DISCUSSION

Table 2.2.3 summarises the efficiencies (first and second law) for each of the five systems described in the previous sub-section.

System	First law efficiency (%)	Second law efficiency (%)
Gas boiler	80.0	5.0
Gas engine to direct heat	30.0	1.8
Gas engine to heat pump	90.0	5.6
Gas engine to ideal heat pump	675.0	42.3
Carnot engine to ideal heat pump	2250.0	99.9

Table 2.2.3 First and second law efficiencies of gas driven systems

Several general conclusions can be drawn from these results:

1) A process having a first law efficiency close to 100% is not necessarily optimum: first law values for ideal processes can be as high as 2250% from these examples. Second law efficiency can never exceed 100%, and for all real processes is less than this.

2) Processes involving energy transformations from relatively low quality (a combusted fuel) to higher quality (electricity) lead, in all real processes, to high energy losses to the environment.

3) Processes using an amount of heat of high quality to directly supply an equal amount of heat at low quality involve high exergy losses.

4) To get high second law efficiencies, the maximum potential of an energy supply must be used: for heat this is best done by heat pumps.

5) Only the second law efficiency, when applied to a single system, gives a true indication of the thermodynamic efficiency of that system. First law efficiency gives only comparative figures, and must be compared with the first law efficiency of an ideal process to properly judge system performance.

Interestingly, the conversion chemical combustion energy-electricity-heat via a heat pump, often claimed to be effective, is in fact little better than a conventional gas boiler, mainly owing to the high energy losses in the electricity production. Also the conversion chemical energy-electricity-direct heat, often proposed as good by Electricity Boards, is very poor from both first and second law viewpoints (the gas engine efficiency is similar to that of power stations). Yet this latter shows up the difference between cost and energy quality, in that direct electric heating is relatively cheap for mainland Britain, despite its poor efficiency.

Exergy values in this work have been calculated after an initial transformation process, these transformations chosen to represent the intrinsic quality of each energy supply. The transformations are: a) combustion for fuels, b) kinetic energy to shaft power or electricity by means of a turbine for hydro and wind energy, and c) radiation to low temperature heat for solar energy. Although further work should be done to define a more appropriate quality for solar energy, this method gives realistic and appropriate values for second law efficiency.

CONCLUSIONS

Two completely different methods of analysing energy systems have been presented in this chapter. Economic analysis can be used to evaluate systems purely on the basis of cost, thermodynamic analysis evaluates systems purely on the basis of how well the thermodynamic potential of energy supplies are used, entirely independent of cost.

Section 2.1 showed net present value analysis to be a suitable method for economic analysis, accounting for all costs (initial investment, maintenance and fuel) over the lifetime of the energy conversion equipment. The method allows unit energy costs (£/kWh) to be calculated for different energy supplies (renewable and non-renewable): these can be used to find the cheapest supply to use.

Section 2.2 developed the methods required for thermodynamic analysis, and showed the parameter 'second law efficiency' to be a better measure of thermodynamic performance than the more commonly used 'first law (energy) efficiency'. The parameters exergy and energy quality were defined and formulated; exergy being used to calculate second law efficiency, energy quality (relating to thermodynamic potential) giving a useful insight into thermodynamic performance.

Economic analysis of energy systems is investigated by this thesis as it is the most common and well-accepted method of assessing projects. The economic analysis of this chapter allows the development of an energy planning model for small communities (see section 4.1), which can be used to make recommendations to improve energy supplies. Thermodynamic analysis represents a different, and novel way of studying energy systems, overcoming some of the limitations of economic analysis outlined in section 1.3. One of the aims of this work is to compare and contrast the two methods of analysis (see chapter 6). The ways in which the thermodynamic equations of this chapter can be applied to practical energy systems are shown in section 4.2.

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CHAPTER 3 THE ISLAND OF EIGG

The island of Eigg off the Scottish coast (56° 53'N, 6° 9'W), was chosen as an example of a small community on which the energy planning strategy proposed in this thesis could be tested.

The island has a resident population of 64, with 27 permanently occupied dwellings. Activities vary between small scale farming and management of the island to craft work and tourism related activities.

A total energy census was undertaken of the island during 1983 to determine the current energy situation. Detailed energy audits for every property and energy-consuming activity were obtained by personal visits.

The methodology and results of the energy census are discussed, as is the usefulness of such a census for general energy planning work. A brief history (including past energy supplies) and description of Eigg is also given.

3.1 INTRODUCTION

The overall aim of this thesis is to develop a complete energy planning strategy which can be applied to all aspects of the domestic energy requirements of small, rural communities throughout the world. In order to test the planning strategy, it was important to find a small community, and the island of Eigg, off the west coast of Scotland, was chosen as being suitable.

There were several reasons for choosing the island of Eigg as a suitable example community:

1) An island forms a 'clearly bounded' system, which is easier to study. Since nearly all fuel has to be imported from the mainland, and with no mains electricity or gas supply, external fuel suppliers can be used as an independent check on energy usage figures from the islanders themselves.

2) With only 64 permanent residents (in 1983), in 27 households, it was possible to plan to survey all households and energy-consuming activities on the island.

3) The island depends almost entirely on imported fossil fuels from the mainland, which are consequently expensive; forming a major part of a householder's annual expenditure. Therefore any plans to reduce energy costs, or increase efficiency, should be welcomed.

4) Eigg has a good potential supply, relatively untapped, of renewable energies: namely hydro power, wind power, solar power and biofuels (wood). These, it is hoped, could be used to improve the island's energy self-sufficiency.

5) Since fuel prices on the island are high, the chances of suggested changes being economically viable are higher than they might be elsewhere.

6) With less than half the households having access to electricity supplies, there are good possibilities for improving living standards (with regard to comfort and energy usage) of the islanders.

7) Eigg is similar, in some respects, to many small, remote communities, in the developed and the Third world. Therefore developing the planning strategy with regard to Eigg makes it suitable for many other communities.

Much of the text of this chapter is reproduced from a published paper (Twidell & Pinney 1984), but this chapter gives more details of the survey method and results, as well as more general information about the island.

3.2 THE ISLAND OF EIGG

The description of Eigg, including its history, is taken mostly from four references: Banks (1977), Redfern (1966), Sutherland (1947) and MacEwen (1981).

General Description

The island of Eigg is one of four islands (the others being Rhum, Canna and Muck) which comprise the Small Isles Parish of the Inner Hebrides on the west coast of Scotland (56° 53'N, 6° 9'W). Its nearest point on the mainland is Arisaig (8 km east), from where a ferry runs during the summer months. The regular ferry (four times per week) runs from the port of Mallaig, 18 km north east.

The island is 9 km from top to bottom, and 6 km at its widest point (see map, figure 3.1 overleaf). The coastal level extends west to Grulin (the now deserted crofting settlement on the west coast), and north east to the once fertile fields of Kildonan. The island is dominated by An Sgurr, a spectacular hill rising to 390 m, while on the east a gentle slope rises to the Beinne Bhuidhe range, about 300 m high. Between these two areas of high ground comes Eigg's 'saddle', an area of moorland rising to about 200 m. 70% of the population live in the north-west, in Cleadale and Cuagach, on 15 crofting divisions, which have traditional rights of land occupancy. This area, around the most attractive Laig Bay, is ringed by high, steep cliffs.

The total area of Eigg is 3000 ha, of which (a) 400 ha are potential arable land, (b) 900 ha are rough grazing, (c) 100 ha are woodland (50 ha recently planted and 50 ha established woodland) and (d) 1600 ha are low productivity or inaccessible land. Farming is mostly for sheep sold on the mainland. The Eigg estate runs about 2000 sheep on the island. In addition there are about 20 cows, a few pigs, some poultry and a few goats. Hardly any local food is sold on the island, and there is no dairy or bakery.

FIGURE 3.1 Position and Detail of the Island of Eigg

Eigg has its own primary school, which had 6 pupils in 1983, but secondary pupils must travel to the mainland. The island has a doctor, with a well equipped surgery, who also looks after the other islands in the Small Isles parish. There is one grocery shop cum post office, and two craft shops. At the harbour is a tea room serving snacks and meals. Although there are two churches, there is no resident clergyman.

Houses on the island vary from the large and impressive Lodge, the island home of Eigg's owner Mr. Keith Schellenberg, to typical highland crofts: single-storey buildings with thick stone walls. The permanently occupied dwellings include 10 single-storey houses, 14 of two or more storeys, and three caravans.

The island's vegetation is varied, although much of the central highland is covered with heather, mosses and short scrub growing on a peat base. Much of the once-productive grassland of Kildonan and Cleadale is now spoilt by encroaching bracken. Well-established woodlands occur mostly around the harbour, and various plantations have been made in the past 100 years. The varied flora and fauna of the island (more than 80 species of birds nest on Eigg, and seals, dolphins and even killer whales can be seen offshore), and its geology, make Eigg a popular holiday area. Two bird species many people come to see are golden eagles (which nest on Eigg), and sea eagles (from the nearby island of Rhum). So there is a large influx of holiday makers and students during the summer, with about 6500 visitor-days per year.

In 1983 there were 27 households, totalling 64 people. This compares with a peak population of 550 in 1841, but like other Scottish islands and highland regions, its population has declined as the economics of island agriculture have declined and prospects appeared better in the cities and more prosperous southern Britain. By 1984 Eigg's population had dropped to 53.

A famous feature of Eigg is its 'singing sands', one of only three similar sites in the world. These are found in a small cove north of Laig Bay, and are made up of uniformly-sized quartz grains. The sands are supposed to 'sing', when they are dry, but in fact they 'squeak', owing to friction between the sand grains and to the minute air pockets around them.

The occupations of the islanders are quite varied. Salaried people include the doctor, the teacher, the factor (estate manager) and estate employees. Part-time jobs include those of the postman, the school 'bus' driver, and the boatman. Most people gain income from several sources, including farming, craft work, public services, pensions and state assistance. Interestingly Sutherland (ibid), writing in 1939, says that "the only necessities of life that a crofter needs to buy are tea, sugar, salt, meal, clothes, and boots". While this might have been true when agriculture was better established on the island, it belied the often difficult and uncertain life of island living. Nowadays many more commodities, including most food, clothing and fuel, have to be imported from the mainland.

The island had a cable telephone connection to the mainland in the past, but this has been replaced by a VHF radio link. It is interesting to note that, apart from the ferry, the telephone exchange and installation is the largest single fuel user on the island.

Climate

The climate of Eigg is much influenced by the Gulf stream, giving warm winters and cool summers, allowing sub-tropical plants such as cabbage palms and eucalyptus trees to grow in the grounds of the Lodge. Average temperatures (but see section 5.1) are 14°C in July, and 5°C in January. Rainfall averages about 1500 mm/y, but this can vary between 35 mm and 310 mm in individual months. The prevailing wind direction is south west, and Eigg is almost unobstructed to wind from the Atlantic. Anti-cyclones over Scandinavia, however, can produce significant periods of Easterly wind. Although no wind records are made on the island, average wind speed from the island of Tiree, 50 km south west (56^{o} 30'N, 6^{0} 53'W), is 9 m/s at 24 m above sea level, 16 m above ground level. However, the rugged topography of Eigg gives more gusty wind than on the flat Tiree. Frosts and snowfall on Eigg are comparatively rare.

History

Eigg may first have been inhabited around 3000 B.C. by mesolithic people who were known to have lived in caves near Oban on the mainland. The island has changed ownership many times, the longest period being under the Scottish clan the Clanranalds, who owned Eigg from 1386 for the next 440 years. A famous incident, perhaps legendary, is the Eigg cave massacre of 1577, when all but one of the 396 residents were killed by the rival Macleod clan.

From about 1590 to 1750, the population of Eigg increased from 300 to 500. At this time, it was economical for people to bring grain from other islands, and the mainland, to be ground by the mill at Kildonnan. This mill survived until the beginning of this century. The population reached its peak of 550 in 1841, but a potato famine in the late 1840s and a decline in the kelp trade led to a rapid slump to about 280 by 1871. A brief revival then occurred until 1881, mostly because of increased wool trade and commercial potato growing.

The island changed hands several times between 1827 and 1925, and was quite prosperous. It was bought by Sir Walter Runciman in 1925, who built the present Lodge (burnt down twice before) and laid out the sub-tropical gardens. Despite the improvements under the Runcimans, the population continued to decline (mainly for economic reasons) from 190 at the end of World War 1 to about 70 in 1966.

Eigg changed hands three more times until 1975, when it was bought by the current owner, Keith Schellenberg. He has attempted to reverse the loss of farm land by improving drainage, and had hoped to increase cattle exports to 200 per year, this latter plan not having materialised as yet. The increasing price of transport to the mainland makes agriculture on the island difficult, and fields left untended are soon taken over by encroaching bracken.

The future of the island remains uncertain, and it is beyond the scope of this thesis to speculate on it. Various people have suggested increased self-sufficiency as the key, but balanced against this is the desire to keep Eigg unspoilt (ie uncultivated) to make it attractive to tourists. The survival of the school is important, and improved energy supplies, both in terms of availability and cost, may help stabilise the population.

Energy Supplies

Historical energy supplies were wood, peat and heather. Peat was dug until about 1940, when the most accessible bogs were worked out. Much of the remaining peat has now been over-planted with trees. Hydro power has been established for a long time. The water mill, already mentioned, was first built in about 1780. In 1930 a 4 kW d.c. hydro plant (Set A on fig. 3.1) was installed, supplying the Lodge, the public hall, and one house. A second hydro turbine (Set B on fig. 3.1) was installed in Laig burn in 1982. This is a 4.5 kW a.c. set supplying Laig Farm, and fitted with electronic control to a dump heating load (this has been replaced with a dump to the central heating system).

Coal became an important supply about 100 years ago, and in the last 50 years petroleum-based fuel imports have also increased, with bottled gas (propane and butane), diesel fuel, petrol and kerosene, all being imported. This usually comes once a year, in 40 gallon barrels or 15kg and 47kg gas cylinders, imported mostly by the Eigg estate office.

Since 1981 three small wind turbines have been installed, which are used to charge batteries for lighting. They are all about 500 W capacity d.c. machines; one is home made, the others commercial machines (see White & Pinney 1984). The output of these is, however, insignificant compared with total island use.

Although the energy survey did not cover the financial situation on Eigg (other than that relating directly to energy), it is estimated that energy costs are more than 50% of a typical householder's annual expenditure.

Transport

There are 22 mechanical vehicles on the island, including five tractors, several Land Rovers, cars and motor cycles. A few bicycles are used, and in 1984 the University of Strathclyde lent an electrically assisted tricycle to a family on the island (see Appendix 3). This has had reasonable success, but the comparatively poor quality roads, steep hills, and some mechanical problems, have limited its use. However, the interest shown in the tricycle indicates that there would be a demand for other vehicles of a similar, but improved type.

There is only one tarmac road, leading north from the harbour to Cleadale, about 6 km long. Most journeys on the island are therefore short, and speeds low. Nonetheless, considerable energy savings could be made in fuel consumption.

The public ferry service makes four journeys per week, doing a round trip to Eigg, Rhum, Canna and Skye from Mallaig. The ferry cannot put in at the shallow harbour, but must be met by a small motor launch. This makes shipments of large or heavy goods difficult, and transport of livestock involves hiring a boat from the mainland. In addition there is a motor launch which runs from Arisaig to Eigg in the summer. Finally there was one commercially operating lobster fishing boat based on the island during 1983, one small dinghy and a launch run by the Eigg estate. The energy study did not include externally based boats, although approximate fuel consumptions were recorded.

3.3 THE ENERGY CENSUS: METHODOLOGY AND RESULTS

Methodology

The type of survey undertaken is a census, with all houses, rather than a proportion of them, being investigated.

Prior to visiting Eigg, a survey questionnaire was developed, based on that used, and on experience gained, by other researchers: Barbour & Twidell (ibid) and Good et al (ibid). The questionnaire was to be completed by the interviewer, during personal visits to each house on the island. This was tested on two mainland houses, and a few modifications were made as a result of these. A preliminary visit to Eigg was arranged, in May 1983, in which 5 permanent residences, and one occupied holiday home, were visited.

As a result of this visit, major modifications were made to the questionnaire, to make it far less time-consuming. One hour was found to be the maximum time for which interviewee's interest could be held: this had not shown up during the initial tests, as interviewees, knowing them to be tests only, had been more patient. Much information, such as type and rating of appliances, age of equipment, etc., was found to be unnecessary. Making sketch plans of each house was also found to be time-consuming: reasonable house layouts could usually be obtained by photographing the outside of the houses. The modified questionnaire (although still containing some superfluous questions) is shown in Appendix 1. With this questionnaire the remaining houses (with the exception of three, because of their owners' absence) were interviewed during another visit in June.

Interviewing techniques were based on recommendations from Atkinson (1967) and Casley & Lury (1981). Particular care was taken to avoid suggesting answers to interviewees, but various methods were found useful to prompt answers. Within 24 hours of each interview a summary sheet (figure 3.2) was completed in detail for each household or facility. Errors could be detected by this process, and occasionally it was necessary to return to interviewees to check inconsistencies. All interviews were carried out by one interviewer (A.A.P).

The accuracy of energy data was tested using two principles: (a) nodal point accounting, and (b) forward and reverse information.

(a) Energy usage was investigated at three 'nodes': the householders themselves, the Eigg estate records, and records from external suppliers. The latter two, however, proved difficult to monitor, and gave only partial information. Table 3.1 summarises data obtained from these three nodes.

(b) In the interview, questions were asked about energy supplies (eg How many bottles of gas do you buy per year?); this is called forward information. Later in the interview end-use information was asked for (eg How often do you use the gas cooker?), this being called reverse information. Total consumption from reverse information could be calculated from assumed appliance ratings (table 3.2). On the energy flow diagram (fig. 3.2) arrows indicate the direction of information, and the average of both directions (where applicable) was carried forward to later calculations.

Fuel	Survey data		Estate Records or Bulk Orders
Propane	28550 + 3920 (tea room)*	= 32470	33290
Butane	91090 + 10680 (hol. homes)*	= 101770	73640
Paraffin	4010	= 4010	- ‡
Coal	309260	= 309260	359680
Wood	140230 - 46310 (collected free)	= 93920	58700
Kerosene	128710	= 128710	101720
Diesel	407810 - 61203 (bought elsewhere)	= 346580	220720†
Petrol	64650	= 64650	12260†
Phurnacite	47580	= 47580	- ‡
Candles	370	= 370	- ‡
Hydro power	3490	= 3490	-

Notes: * = Figures from estate records.
† = Figures represent fuel ordered for April 1983-April 1984.
‡ = No records exist for these fuels.

Table 3.1 Island energy supplies (April 1982-April 83), from survey data and estate records of bulk orders. Units kWh/y

Appliance		Typical input rating (kW)	Efficiency or COP	Contribution to space heat
Open fire		5	0.30[§]	0.30
Open fire with back boiler		5	0.60[§]	*
Closed stove		5	0.65[§]	0.65
Closed stove with back boiler		11	0.70[§]	*
Range with openable fire		5	0.50[§]	†
Closed range		2-7	0.72[§]	†
	Rings	2[¶]		
Gas cooker	Oven	3[¶]	0.60	0.40
	Grill	3[¶]		
Gas water heater		7	0.75	0.00
Gas room heater		1-3	1.00	1.00
Gas lights		0.5	0.01	1.00
Candles		0.15	0.01	1.00
Paraffin lamps		0.5	0.01	1.00
Unlagged hot water piping		-	0.95	0.05
Unlagged hot water tank		-	0.86	0.14
Lagged piping and tanks		-	1.00	0.00
Hot water radiators		1	1.00	1.00
Gas fridge		0.5	0.23 COP	1.00-1.23
Electric fridges and freezers		0.5	0.90 COP	1.00-1.90
Electric immersion heaters		3	1.00	0.00
Electric space heaters		1-3	1.00	1.00
Incandescent electric lights		0.6	0.05	1.00
Fluorescent lights		0.4	0.15	1.00
Other electric appliances		‡	0.20	1.00
Transport and agriculture		-	0.25	0.00

Notes: * = Dependent on amount of input used to heat water.
† = Range input is split into: water heating, from end use, assuming water heated from $10^{\circ}C$ to $60^{\circ}C$ and accounting for pipe and tank losses, cooking the same as for gas cooker, where house has both, otherwise estimated from cooking times, space heat being the remainder.
‡ = Electrical appliance ratings taken from Norgard (1979) and Leach et al (1979).
§ = Values from Solid Fuel Advisory Service (1976) or Glynwed Appliances Ltd (personal communication, 1983). Cooking on range taken to be 60% efficient, 40% going to space heat.
¶ = Gas cookers running for less than 10 minutes do so at rated output, for longer periods at 1/6 rated output.

Table 3.2 Average appliance ratings and efficiencies

Nodal point accounting is particularly powerful for islands, where there are only a few facilities for trading and transporting fuels. Transactions also tend to be in relatively large, easily remembered, unit quantities. However the former depends heavily on the participation of suppliers.

No instruments were used or measurements made during the study, so few energy transformations could be directly enumerated and standard manufacturers' information (table 3.2) was used whenever needed. It was important that the interviewer (i) was an experienced scientist making reasonable judgements, and (ii) that he became closely involved with the interviewees. A 'distant' approach would not have obtained the same levels of information.

Example of one household supply

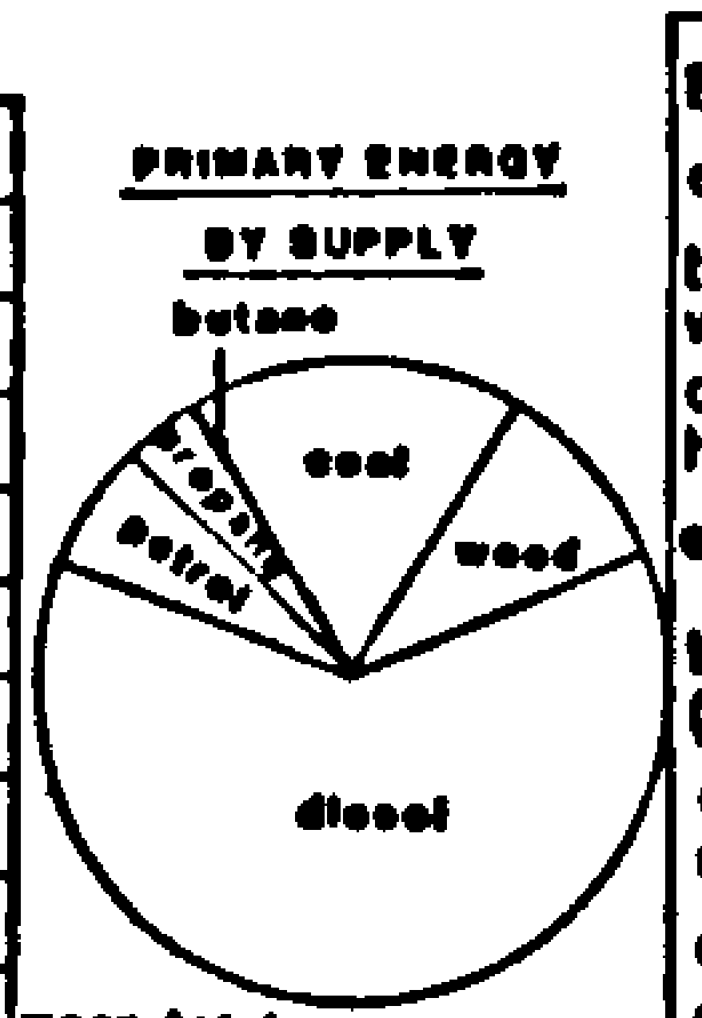
After each interview, a detailed flow chart was produced. An example is given on figure 3.2. Most units are kWh/y, as this was considered more practical, especially when showing results to interviewees. Bracketed data represent those obtained by difference, and an unwarranted number of figures are used to avoid intermediate rounding errors.

1) Propane. Forward information was that four 47kg cylinders were used per year (2610 kWh/y). Reverse information from questions on cooker usage and lighting gave cooking 1800 kWh/y, 80% and lighting 440 kWh/y, 20%. Average usage from forward and reverse information is therefore 2430 kWh/y. This is divided between cooking and lighting in the percentages above (80% and 20%), and taken to supply appliances having the efficiencies of table 3.2. Consequently energy goes to cooking and lighting (solid lines) and free gains (dashed lines) to space heat.

2) Wood. An estimated 11000 kWh/y of wood fuel was determined by forward information. Reverse information was that a nominal 11 kW output wood stove burned for 370 h/y at its rated output, indicating a consumption of 4020 kWh/y. An unknown amount of wood was burned with coal in the range, so by difference 7270 kWh/y were used in the range.

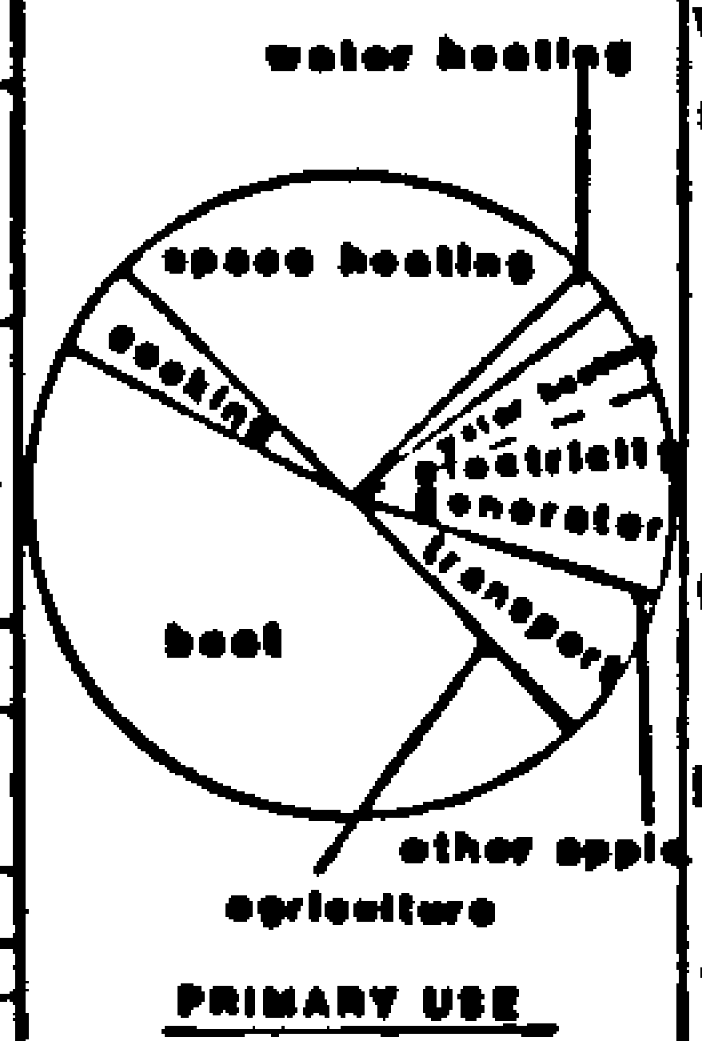
PRIMARY ENERGY BY SUPPLY

Fuel	kWhy⁻¹	kWhy⁻¹	
propane	2610	2240	
butane	410		
paraffin			
coal	19760		
wood	11290		
kerosene			
diesel	61230	61230[3]	
petrol	7090		
others			mean total
total	102390	102020	102210



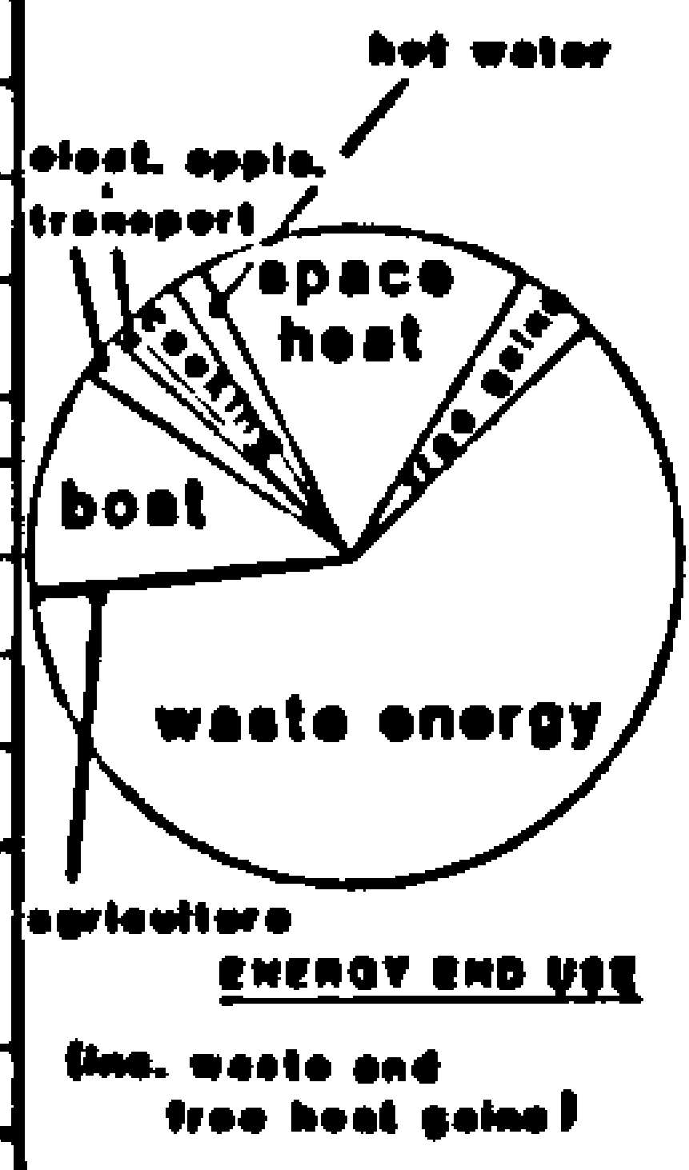
PRIMARY USE

Energy used for :	kWhy⁻¹
cooking	4450
total domestic water heating	9000
of which : water heated by electric immersion	4700
total space heating (exc. free gains)	26400
of which :electric space heating	
diesel for generator	13590
gas appliances (incl. lights but not heaters)	480
transport	7090
agriculture	950
boat	46690
domestic total (exc. electric space and water heating)	47480
total (exc. electric space and water heating)	102210



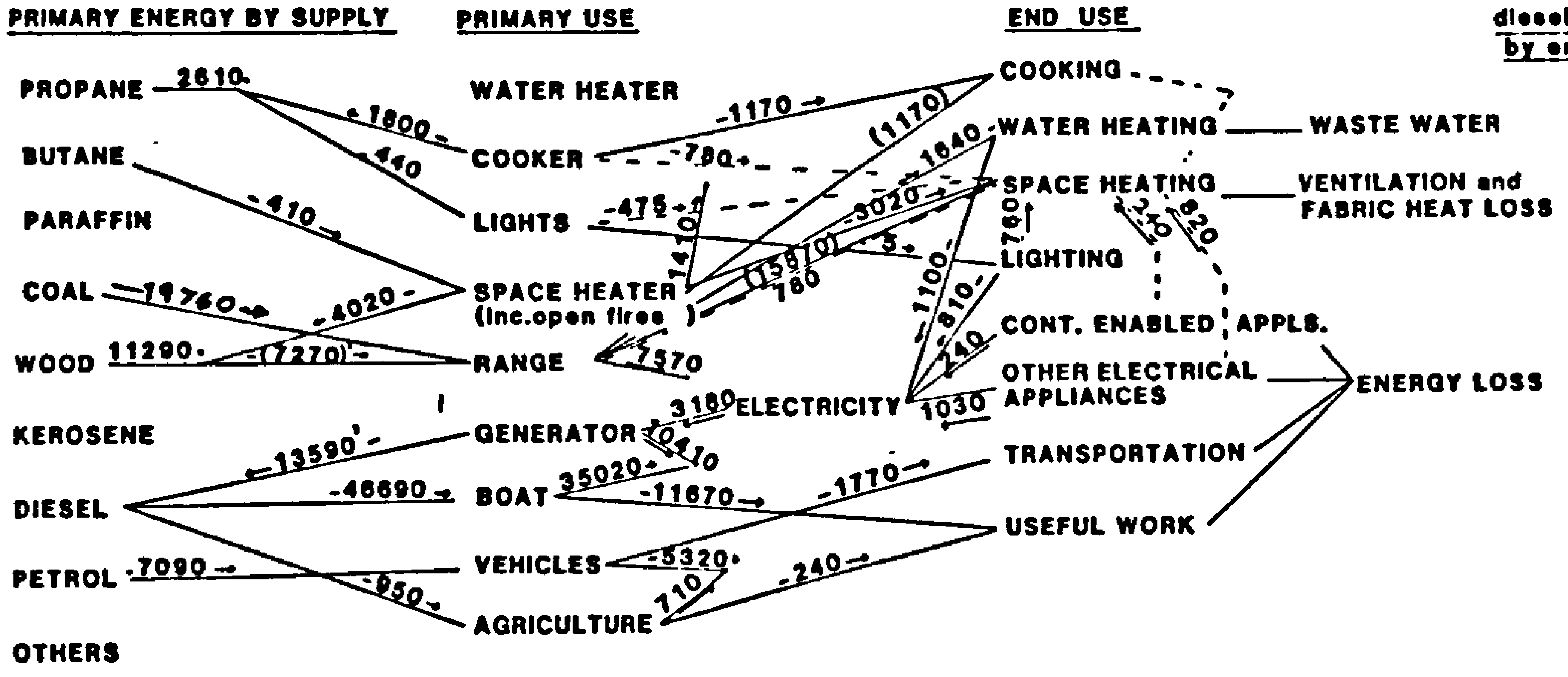
ENERGY END USE

energy end use	effy.%	kWhy⁻¹
cooking	50.3	2240
water heating	30.3	2740
space heating	71.9	18990
elec. appls. lights	1.6	50
cont. enabled	21.1	220[1]
others	4.7	210
gas appliances	1.0	5
transport	25.0	1770
agriculture	25.0	240
boat	25.0	11670
domestic total used(exc. trans. agri. boat	%	24455
useful ' total	37.3	38135
free heat gains	3.6	3635
waste energy	59.1	60440
total	100.0	102210



FUEL COST

fuel	gross cost (similar for all users) £/kWh	cost per useful kWh £/kWh
propane	0.038	0.038
butane	0.044	0.044
paraffin		
coal	0.014	0.019
wood	0.009	0.013
kerosene		
diesel for generator	0.021[3]	0.120[1,2,3]
other diesel	0.121[3]	0.084
petrol	0.040[3]	0.160
others		



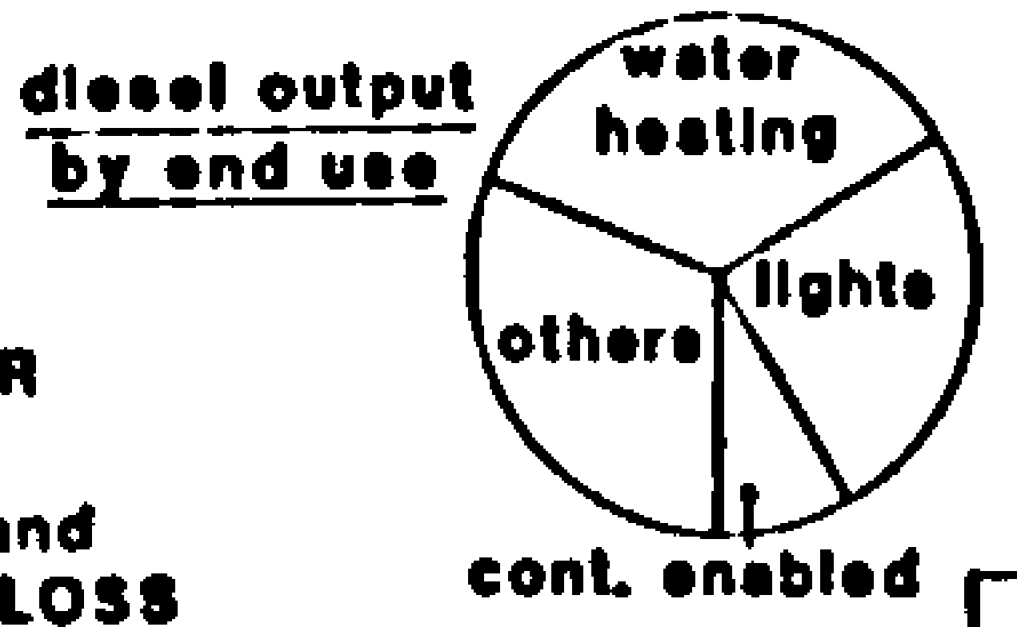
KEY : ——— inefficiency loss

- - - - - - free heat gain

direction of arrows indicates direction of information
bracketed information obtained by difference

1) see code 5 notes
2) see general notes
3) see code 5 notes

DIESEL GENERATOR DETAILS



Generator type	Rating	Calculated efficiency
Lister startomatic (starts at load of 400w) shared with code no.3	7kW	23.4%

TRANSPORT

Vehicle type	fuel used per year(kWhy⁻¹)	Miles per gallon
Volvo estate 2000 cm³	7090	17

Insulation Details

general standard of insulation	: poor, but some windows sealed
draughts froom doors and windows	: some
hot water tank insulation	: sprayed polystyrene foam
hot water pipe insulation	: fibreglass roll
comfort level	: ● ● ●

PERMANENT RESIDENTS: MALE.1..FEMALE.1..CHILDREN..4.

CODE NUMBER..5..

FIGURE 3.2 Example of Household Energy Summary Sheet: Eigg 1982/1983

3) Cooking and water heating range. An input of 19760 kWh/y of coal, from forward information, was supplemented by 7270 kWh/y of wood, by difference, giving a total input of 27030 kWh/y. Hot water and cooking, by reverse information, required 1640 kWh/y and 1950 kWh/y respectively. From the quoted efficiency, flue losses were 7570 kWh/y, leaving 15870 kWh/y for space heating.

4) Other supplies. Diesel fuel usage came from forward information for the boat (46690 kWh/y) and agriculture (a tractor, 950 kWh/y). That used for the diesel generator was obtained by difference. However, this particular generator also supplied another house, so the usage for each house was obtained by dividing total diesel usage (by difference) in the ratio of yearly electrical appliance usage (reverse information).

5) Primary use. This table on fig. 3.2 divides energy usage by its intended end use. For example, to obtain 1640 kWh/y of hot water from the range (at the manufacturer's efficiency of 72%) required 2280 kWh/y of primary energy input. Similarly, 4700 kWh/y of diesel fuel were needed for water heating via the electric immersion heater. So the total primary energy used for water heating was 6980 kWh/y.

6) End use. This table derives information from assumed appliance efficiencies. End use refers to energy in its desired end form (for example light from a light bulb), but energy can also become useful free gains to space heat, which is often welcome on Eigg for comfort or drying. Subsequent processes involving the useful energy are not considered. The wasted energy is that lost to the environment at intermediate transformations.

7) Fuel cost. The questionnaire included questions on fuel costs, some of which are shown on fig. 3.2, in gross cost (£/kWh supply), and useful cost (£/kWh end-use) knowing the intervening efficiencies. Table 3.3 summarises gross costs for the island, and compares them with similar costs on the mainland.

Fuel type	U.K. mainland	Eigg island	Notes
Natural gas	0.011	-	National grid
Propane	0.035	0.038	Cylinders
Butane	0.040	0.044	Cylinders
Paraffin*	0.020	0.043	For lighting
Kerosene*	0.019	0.024	Fuel oil
Coal	0.012	0.014	
Phurnacite	0.019	0.021	For ranges
Wood	†	0.009	Local supply
Candles	†	0.610	
Petrol	0.040	0.042	
Diesel	0.021	0.028	For generators
Electricity	0.050	0.240	Incl. maintenance

Notes: * = Distinction between kerosene and paraffin indicates different prices.
† = Prices not given owing to large variations by types and location.

Table 3.3 Eigg island and U.K. mainland average fuel costs in 1983-84. Units £/kWh

8) Diesel generators. Any future energy supply system for Eigg will almost certainly include electricity, so attention was paid to diesel generator operation. Generator efficiencies were obtained by dividing reverse information of electricity consumption by forward information on fuel usage. Efficiencies were nearly always below manufacturer's recommendations because (a) generators are often underloaded, (b) machines run intermittently, and (c) most machines are old.

9) Transport. An attempt was made to gain more detailed information on journeys and fuel usage than the questionnaire alone gave. Some islanders were encouraged to keep records of their journeys and fuel use, and were provided with log books for this purpose. However, no records were kept in detail and the study was abandoned.

During the interviewing visit three householders were absent, so a postal questionnaire was developed for them, which is also shown in Appendix 1. This is much simpler than the first version, yet still obtained almost the same level of information. Two replies were received from the three questionnaires sent out. It is suggested that this simplified version might be more applicable for further studies.

One household could not be interviewed, for personal reasons. However a visit to the house allowed an estimate to be made of energy consumption, based on personal experience and Estate records. The same was done for the house not covered by the postal questionnaire.

Results

The individual house results, and those from the post office, school, telephone exchange, surgery and church were summed to give total island energy usage for the year April 1982-April 1983. Figures 3.3 to 3.5 and table 3.4 show the overall energy supplies and usage for the island during this year. The demand for space heating is by far the largest single demand (47% of primary supply), followed by diesel generator fuel (18%), local transport (14%), cooking (8%) and the one commercial fishing boat (4%). Agricultural machines (excluding transport for agricultural activities) use only 1.6% of primary supply.

The pie charts shown on figures 3.4 and 3.5 split fuel supply, primary energy usage and end usage into categories, and the relative percentage of each fuel and type of end-use can easily be seen. Figure 3.4 includes waste energy in all diagrams, whereas figure 3.5 excludes waste from the primary and end-use charts. The reduced areas of these therefore represent waste energy. Wasted energy (that lost to the environment without any gain to the user) makes up 49% of total energy supply. The greatest losses are from the 15 diesel generators (total nominal capacity 104 kVA). These are on average only 17 (+/-3)% efficient in producing electricity. Although not fully utilised during the year of the survey, the two hydro turbines managed to produce 9% of the island's total electricity. Other large losses are from vehicles, and flue losses from ranges, stoves and open fires. Vehicles have an average fuel consumption of 30 litres/100 km: on the mainland 10 litres/100 km would be expected from similar vehicles.

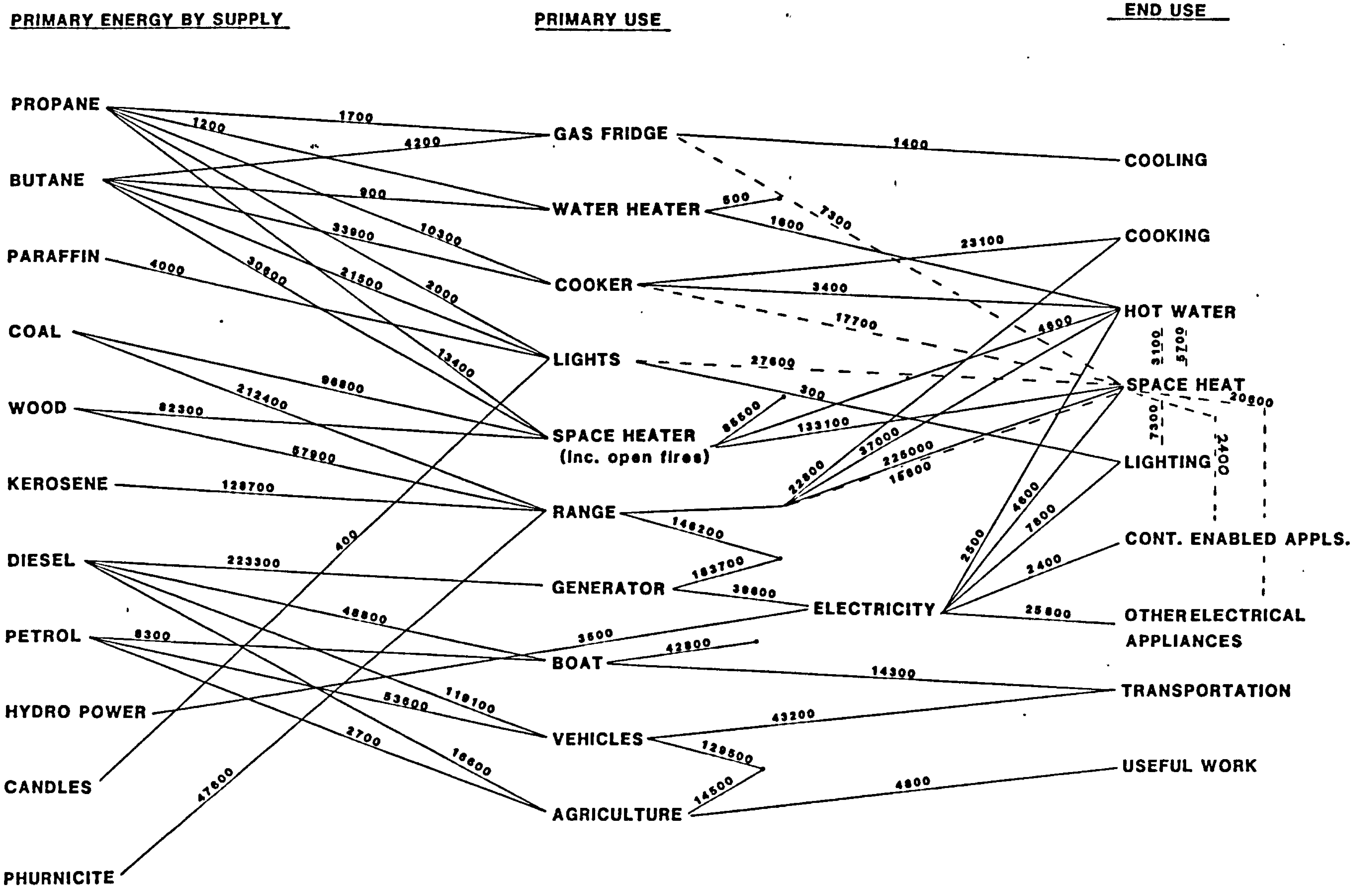


FIGURE 3.3 Island Total Annual Energy Flow Diagram (excluding holiday homes) Units: kWh/y

PRIMARY ENERGY BY SUPPLY

	Forward Information	Reverse Information
PROPANE	29000	28100
BUTANE	92400	89800
COAL	309300	
WOOD	140200	
PHURNACITE	47600	
KEROSENE[1]	128700	
PARAFFIN[1]	4000	
DIESEL	404000	411700
PETROL	64500	64800
HYDRO POWER		3500
TOTAL	1223200	1227700
MEAN TOTAL	1225400	

PRIMARY USE

COOKING	98000
WATER HEATING	73100
SPACE HEATING	582000
DIESEL FOR GENERATORS[2]	122000
HYDRO POWER	3500
GAS APPLIANCES[3]	33400
DOMESTIC TOTAL	912000
TRANSPORT	172700
AGRICULTURE	19300
BOATS	57100
DIESEL FOR TELEPHONE EXCHANGE	64300
TOTAL	1225400

END USE

		Efficiency/%	
COOKING		47	45900
HOT WATER		55	40400
SPACE HEAT		63	368300
ELEC. APPLS.	LIGHTS	1	500
	CONT. ENABLED	18	2200
	OTHERS	4	5200
GAS APPLIANCES[3]		5	1600
DOMESTIC TOTAL			464100
TRANSPORT		25	43200
AGRICULTURE		25	4800
BOATS		25	14300
USEFUL TOTAL		43	526400
FREE HEAT GAINS		8	96200
WASTE ENERGY		49	602800
TOTAL			1225400

NOTES: 1) The same fuel sold at different prices
2) Excludes fuel used for electric space and water heating
3) Includes paraffin lamps and gas fridges

Table 3.4 Total Yearly Energy Use on the Island of Eigg Units: kWh/y

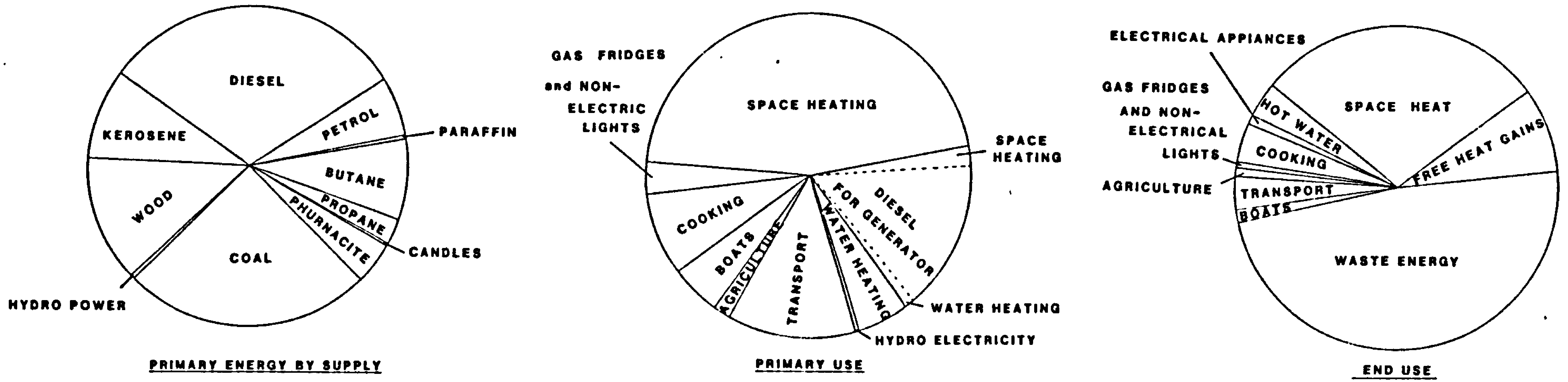


FIGURE 3.4 Island Total Energy Use Including Waste (excluding holiday homes), 1982/83

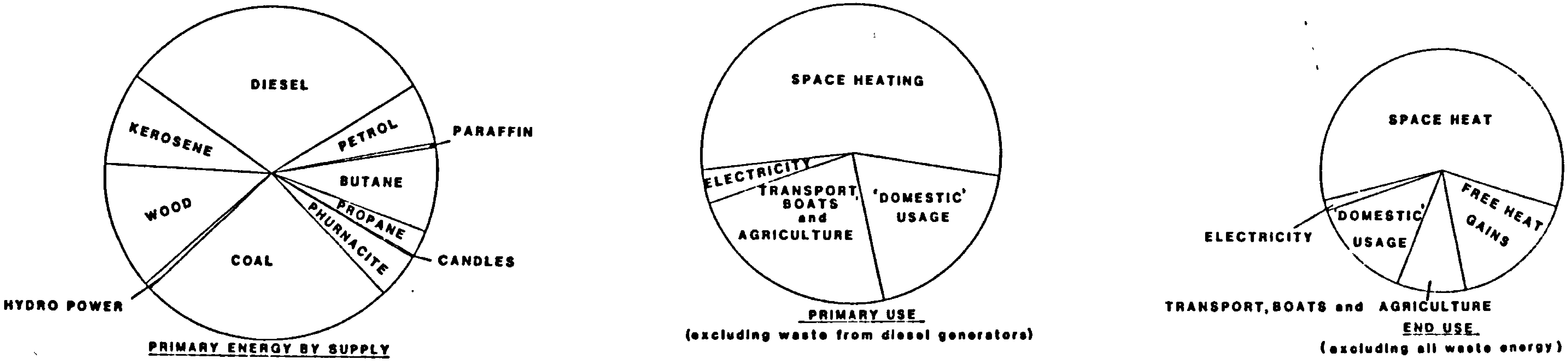


FIGURE 3.5 Island Total Energy Use as in Fig 3.4 but Net of Waste. Reduced Diameters Represent Waste Energy

Table 3.3 shows fuel and prices on Eigg compared with those on the mainland. Prices on Eigg are about 20% higher on average than the mainland. The average electricity cost to householders is 0.160 £/kWh (excluding labour costs of the operator) compared with typical mainland values of 0.05 £/kWh. However, average electricity costs on the island including the telephone exchange, is 0.24 £/kWh. The telephone exchange is the single largest fuel user on the island, being of standard unit size with considerable overcapacity. Its fuel consumption was 64000 kWh/y, with an average of 490 W continuous per line.

The results from a statistically-average house on Eigg are shown on table 3.5. Island averages and standard deviations are shown, from which it can be seen that there are large differences between houses.

The per capita energy supply on Eigg is 19000 kWh/y (2.2 kW continuous average). Table 3.6 compares this with other islands, some other rural communities and with the U.K. and U.S.A. mainland averages. The table excludes the primary fuel used to generate electricity, so electricity use can be compared irrespective of method of generation. It can be seen that islands have a much higher per capita energy consumption than mainland Britain. For the island of Coll, the per capita use is higher than the U.S.A, the largest energy using country in the world. These higher values are, to a large extent, accounted for by lower efficiencies of energy transformations and insulation standards. It is equally interesting to compare per capita energy use in developing countries with those of the U.K. and U.S.A. For example, in Tanzania, the usage is only 5% of that in the U.K. This highlights the importance of assessing energy demands carefully if the energy planning model developed in this thesis is to be applied to other areas of the world.

PRIMARY ENERGY BY SUPPLY

	Usage	Standard Deviation	Standard Error of the Mean
PROPANE	570	1080	± 210
BUTANE	3030	3110	± 620
COAL	11260	8810	± 1760
WOOD	5280	7770	± 1550
PHURNACITE	1900	6970	± 1390
KEROSENE	4150	8730	± 1750
PARAFFIN	160	490	± 100
DIESEL	9710	17190	± 3440
PETROL	2590	3910	± 780
HYDRO POWER	140	600	± 120
TOTAL	38790	26050	± 5210

PRIMARY USE

	Usage	Standard Deviation	Standard Error of the Mean
COOKING	3540	2420	± 480
TOTAL DOMESTIC HOT WATER	2630	1750	± 350
of which: WATER HEATED BY ELECTRIC IMMERSION	1200	1010	± 200
TOTAL SPACE HEAT (Exc. free gains)	20120	11010	± 2200
of which: ELECTRIC SPACE HEATING	850	2190	± 440
GENERATOR FUEL	5210	7350	± 1470
HYDRO	140	600	± 120
GAS APPLIANCES[1] (Inc. lights but not heaters)	1210	1040	± 210
TRANSPORT	4030	7270	± 1450
AGRICULTURE	770	2190	± 440
BOATS	2280	9400	± 1880
'DOMESTIC' TOTAL[2]	31710	16550	± 3310
TOTAL	38790	26050	± 5210

NOTES: 1) Includes paraffin lamps and gas fridges
2) Excludes electric space and water heating, transport, agriculture and boats

Table 3.5 A Statistically-Average Household on the Island of Eigg Units: kWh/y

Details	Eigg island	North Ronaldsay island	Coll island	U.K. mainland[2]	Collins community Canada[3]	U.S.A. mainland[4]	Peipan China[5]	Kilombera Tanzania[5]	Arango Mexico[5]	Mangaon India[5]
Population	64	120	100	5×10^7	100	2×10^8	1000	100	420	1000
Gas	1870	810	1560	3200	1080	6040			490	
Coal	4830	5670	10000	2360	-	~0	880[6]			
Wood	2190		1100	~0	11930	630	5860[7]	640	4180[8]	290
Kerosene/paraffin	2070	4080	920	780[9]		13350[9]			210	
Diesel and/or heating oil	2880[1]	1890[1]	3030[1]		2930				2090	
Petrol	1010	2750	3690	3830	1200					
Electricity[1]	670	500	3280	1650	930	2010			5680	
Crop residue and dung										880
Animal labour							1460		2090	2200
Other			2030 peat		50 naptha					
TOTAL	15520[1]	15700[1]	25620[1]	11820	18120	22030	8200	640	14740	3370

NOTES: 1)Diesel fuel excludes electricity generation. Data for electricity are for electrical power generated, not the primary fuel or supply for generation.
2)Ref. Leach (ibid).
3)Ref. Canadian Min. of Energy (1982).
4)Ref. Scientific American (1979)
5)Ref. Makhijani (1975).
6)Coal, oil and electricity included together.
7)Includes dung and crop residues.
8)Includes crop residues.
9)All domestic liquid fuels.

Table 3.6 Primary Domestic and Local Transport Energy Use for Three Scottish Islands and other Comparative Regions

(Excludes industrial energy use) Units: kWh/y per capita

3.4 CONCLUSIONS

One problem with the type of energy survey presented in this chapter is that it does not indicate the 'true' demand for energy. Fuel prices on Eigg are high, comfort levels relatively low, energy efficiency and insulation levels often low, and many householders would use considerably more energy (their 'true' demand) if it were cheaper and more available. Considerable modification has to be made to the energy demands found by the survey to make them more representative of this true demand (sections 5.3 and 5.4 discuss this further). Although Eigg has a higher per capita energy consumption than the U.K. mainland, it uses energy far less efficiently, giving lower comfort levels for the amount of energy used. It is therefore concluded that the survey on Eigg, as far as its usefulness for the energy planning strategy is concerned, was too detailed, and attempted to obtain too much information.

A simpler method was the postal questionnaire shown in appendix 1. A detailed energy survey would be justified for communities where comfort levels (with regard to energy usage) are already satisfactory, and therefore are unlikely to change with cheaper, more available supplies. But it is not worth using it in communities where it will not find the true energy demand. It is more useful to develop methods to determine energy demands other than by survey, and this is done in sections 5.3 and 5.4. The one advantage of the personal survey was the insight it gave into likely levels of demand given cheaper energy, and to gain a closer contact with the community.

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CHAPTER 4 ECONOMIC AND THERMODYNAMIC ASSESSMENT OF ENERGY SYSTEMS FOR SMALL COMMUNITIES

This chapter presents the two methods of analysing energy systems for small, rural communities which are used in this thesis: namely economic analysis, and thermodynamic analysis.

Section 4.1 describes in detail the computer-based economic assessment model, which uses the economic theory developed in section 2.1. An example is given of running the model for a small community.

Section 4.2 describes and discusses the methodology of thermodynamic optimisation and assessment of the same energy systems analysed by the economic model. Using the concepts second law efficiency, exergy and energy quality developed in section 2.2, a diagramatical method for exergy analysis is presented.

The literature review of section 4.2 investigates various other methods of thermodynamic assessment, particularly exergy economics, and shows how these differ from the type of analysis used in this work. The review of section 4.1 describes three other models for economic assessment of energy systems, comparing them with the model developed in this thesis.

Section 4.1 Methodology for Economic Assessment of Energy Supply Systems for Small Communities

4.1.1 INTRODUCTION AND MODEL OVERVIEW

Before installing any energy supply equipment, a careful economic analysis should be carried out to determine whether such an installation would be cost-effective. This is particularly important when there are several possible ways of supplying the energy demand, in which case the best way must be chosen.

This section describes an economic and technical feasibility study model for analysing domestic energy supplies to small communities of up to about 30 houses. The model currently includes those energy supplies most likely to be found in remote rural communities or small islands, both renewable and non-renewable. Its modular construction allows easy modification to study other equipment.

The model outputs are cost per year of running the system, and performance data for all equipment in the simulation. The results are in a form which suggest improvements to system design after each run of the simulation: those supplies which, on the basis of cost, were seldom required can be excluded from further simulations; those which were over- or under-rated can be changed accordingly.

The model is split into four main programs (with a fifth optional), and four smaller programs which generate input data for the main programs, if required. Figure 4.1.1 shows a flow chart for using all the programs, and these are summarised here:

COSTCALCS: This program calculates the cost per kilowatt-hour of energy from all primary energy supply equipment in the community: hydro-electric turbines, wind turbines, solar panels, diesel generators, cooking ranges, heating stoves and gas water heaters.

HOUSECOSTS: The principle aim of this program is to calculate the cost per kilowatt-hour of energy in its final form (space heat,

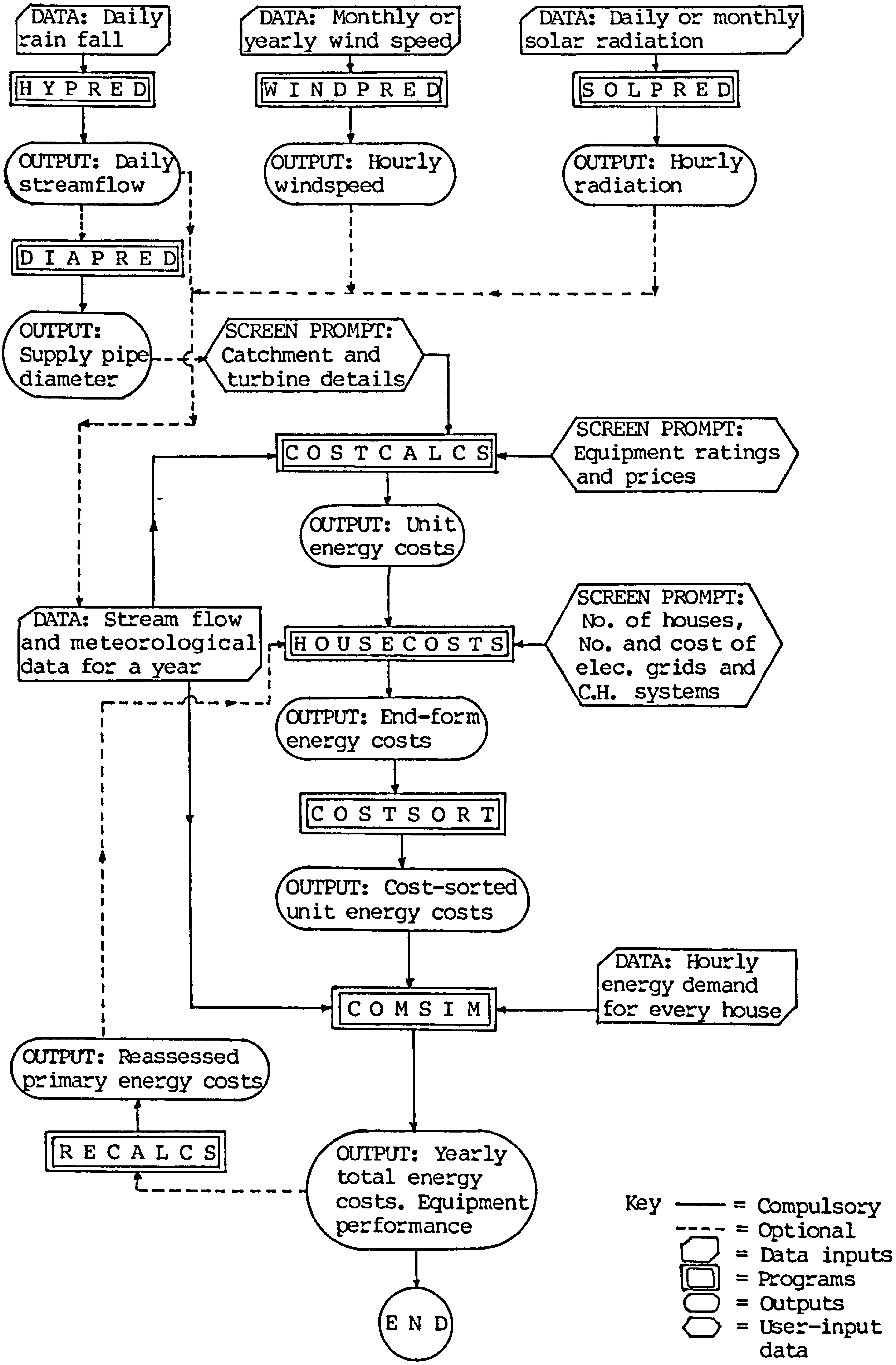


FIGURE 4.1.1 Programs available and data requirements for the economic and technical feasibility model

cooking, hot water or electricity) for each house, from all equipment supplying the house.

COSTSORT: This program sorts the final-form energy unit costs for each house (from HOUSECOSTS) into the order ready to be used by COMSIM.

COMSIM: This is the actual community simulation program. On an hourly basis (for a whole year), the program reads energy demand data for electricity, water heating, cooking and space heating, for each house or house heating zone, from files. It then attempts to satisfy the demands with the available supplies, using supplies in the order taken from COSTSORT. The order is such that renewable energies are used to replace the most expensive non-renewables first.

RECALCS: The cost per kilowatt-hour figures obtained by COSTCALCS and HOUSECOSTS depend implicitly on the amount of energy from each piece of equipment used during a simulation. Assumptions about usage are made in COSTCALCS and HOUSECOSTS, but if these prove to be inaccurate after studying the simulation results, RECALCS modifies the relevant unit costs prior to re-running the simulation. The use of this program is optional.

The four other optional programs, used to generate input data for the main programs are:

1) HYPRED: Uses the hydrological model described in section 5.2 to predict daily streamflows from catchments suitable for hydro power.

2) DIACALC: Calculates the optimum supply pipe diameter for hydro turbines using the method of section 5.2.

3) WINDPRED: Simulates daily wind speeds (to calculate wind energy availability) from annual mean or mean monthly wind speeds, using the first method described in section 5.1.

4) SOLPRED: Simulates hourly solar radiation (used to calculate available solar energy) from daily total radiation.

4.1.2 SYMBOLS AND UNITS

Symbol	Description	Units
A	Solar panel surface area	m^2
C_a	Annual cost	£/y
C_p	Specific heat	J/(kg k)
C_u	Unit energy cost	£/kWh
COP	Coefficient of performance	-
D	Energy demand	kW
E_a	Annual energy transmitted by grid	kWh/y
H_s	Static head	m
I	Equipment capital cost	£
L	Pipe length	m
M	Annual maintenance cost	£/y
N	Equipment lifetime	y
P_a	Power output used per year	kWh/y
P_i	Power input to central heating	kW
P_t	Hourly potential power output	kW
P_y	Yearly potential power output	kWh/y
Q	Streamflow	m^3/s
Q_f	Yearly fuel cost	£/y
R	Remaining potential power output	kW
a	Constant	$m^3s^{1.75}$
b	Constant	-
d	Pipe diameter	m
f	Power usage factor	-
g	Gravitational acceleration	m/s^2
h	House or list number	-
hf	Friction head loss	m
m	Mass of water	kg
r	Discount or interest rate	y^{-1}
ρ	Water density	kg/m^3
η	Efficiency	-
Φ	Global solar radiation	W/m^2

Suffices and superscripts

c	Central heating system
e	Energy supply equipment
g	Electricity grid
h	Heat pump
m	Number of non-renewable energy sources
p	Number of renewable sources
s	List number
t	Time (hour)
N	Non-renewable energy sources
R	Renewable energy source

The units used by the model are kW, kWh, kWh/y and £/kWh. It was felt that these were easier to understand than more usual SI units. All equations are modified to allow for these units.

4.1.3 LITERATURE REVIEW

Much work has been done on energy planning, with different levels of complexity and detail. The criteria also vary, and planning covers many topics including: economic studies, substitution of non-renewable fuels by renewables, and thermodynamics (see section 4.2). Since this thesis studies small communities, only references dealing with this level are covered. Similarly, only models studying a range of energy supplies, rather than a single type of supply, are covered.

It is highly likely that many other models exist (for example the model SOSIE, developed in France (Matarasso & Valette 1984) is known to exist, but the reference does not allow more than its basic aims to be understood), but these, developed by under- or post-graduates, university departments or consultancy companies, are often not properly referenced and so are not found by usual methods of literature search.

SIENA

SIENA was developed by the University of Milan (Castelli 1984), and is now the model adopted by the Food and Agriculture Organisation project "Development of Integrated Farm Energy Systems".

The model studies energy requirements for farms, covering what are called 'stationary user-points'. These are electricity and heat (at two temperature levels) demands for such processes as: crop drying, milking, space heat for animal rearing, feed processing, and farm-based light industry. SIENA studies both renewable and non-renewable energy sources, including import to, and export from the farm of electricity. Three model operation modes exist: (1) maximisation of Internal Rate of Return (section 2.1), (2) maximisation of use of renewable energy, or (3) maximisation of renewable energy usage for a preset IRR.

Energy demands for the farm's user points are determined by detailed energy survey (Pellizzi & Castelli 1984) as monthly mean and the maximum daily and minimum daily level, for each month of the simulation year. These are converted to daily mean levels using a random number process. A similar procedure is used to obtain solar radiation, streamflow and biomass potential, but SIENA uses the first method of section 5.1.4 of this thesis to determine daily wind speed.

Details of each piece of energy supply equipment used in the simulation must be input, and these include: minimum and maximum plant size and step change to be studied (for example 10kW to 20kW, with step size 2kW for a wind turbine), unit power costs at rated output (£/kW not £/kWh) of energy equipment (but unit energy costs for imported electricity of combustible fuels in £/kWh or £/kg respectively) and money interest and energy inflation rate (section 2.1).

A simulation of SIENA uses a daily time step, attempting to meet the energy demand on each day by the renewable supplies, and if this is not possible, using non-renewable sources. Renewable energies are used in a preset order, based on their versatility, but irrespective of unit cost. Thus solar panels (only able to produce heat) would be used before a hydro turbine (which can produce heat or electricity). A simulation considers all combinations of equipment sizes specified, by changing each rating one step at a time. A result-set is determined for each combination, showing the percentage of heat and electricity covered by the renewables, total plant cost, cost savings compared with using all conventional energy, internal rate of return, payback time and net present value (see section 2.1).

SIENA has some advantages over the model proposed in this thesis: it needs less accurate data, monthly averages as opposed to hourly values, and it can be run on a micro computer, making it possible to run it 'on site'. However, it also has some disadvantages:

1) In assessing system cost, SIENA takes no account of total output from any piece of equipment. The yearly cost (£/y) is used, rather than unit cost multiplied by output (£/kWh x kWh/y). This fails

to show that large investments might be made in a piece of equipment for fairly little energy production. It is also impossible, using this strategy, to know which demands renewable sources should supply in preference (substituting for the most expensive non-renewables) to give maximum cost savings. Finally, without knowing unit energy costs, it is impossible to compare renewable energy supplies with imported energy. While this is unimportant if the aim is to maximise renewable energy usage, it would be important if the aim is to minimise system costs.

2) There is no correlation between the various stochastically predicted meteorological parameters, or between these parameters and energy demands. For example a run of sunny days (predicted by the model) might also correspond to a high demand for crop drying, whereas the opposite is usually the case.

3) Chapter 6 of this thesis shows that there are considerable differences between using a daily simulation time step and an hourly step, particularly for wind and solar power. The use of the longer time step of one day by SIENA might lead to errors.

4) Using equipment in order of 'versatility', rather than cost, can give sub-optimal results. For example, if large investment is made in a hydro turbine producing cheap energy, to use more expensive energy supplies in preference does not make the best use of the investment.

5) SIENA does not easily allow the use of several conventional energy sources, usually studying only one heat production plant, and one source of electricity (other than imported electricity). While this is not important for a single farm, it would be unrealistic for larger communities in which several different sources might be used.

For these reasons the SIENA method was not used in this thesis.

SIKKE

The SIKKE model was developed by the Riso National Laboratory in Denmark (Nielsen 1986). It aims to study several alternative energy sources (used in combination) to supply domestic energy to small villages (less than 200 inhabitants).

Its data inputs for energy demands are obtained either from standard (hourly) time series, scaled accordingly, which are available in Denmark, or from recorded values. Like SIENA, these data are combined to give total electricity and heat demands for the whole community. Meteorological data are similarly obtained from standard time series for the 'reference' year in Denmark (available from the Danish Building Research Institute).

The model can study nine renewable and non-renewable energy sources, including heat storage. Devices are used in the order specified by the user, including which are used for base load, and which for peak load. After a yearly simulation, the model shows the output of each device used to supply heat or electricity, the capacity factor (useful output/total potential output), the yearly cost of the system, and its net present value for different money interest rates. It is unclear exactly how these latter values are obtained, but most likely they are determined by a similar process as in SIENA, namely using the yearly cost of each device.

Using an hourly time step, and standard demand data, this model overcomes two of the disadvantages of SIENA, while the use of a user-specified order of preference for energy sources is better than a pre-determined order, assuming the correct order of preference can be chosen by the user. A more detailed description of the model's strategy would be needed before closer comparison could be made between SIKKE, SIENA and the model of this thesis, but its brief description implies that it overcomes some of the problems of SIENA.

MERDA

The MERDA model differs from the others, which use linear programming methods and economic optimisation, in that it is a system dynamics model. Cause-effect relationships are represented by differential equations, solvable by numerical analysis. The model is used to study improvements in agriculture and energy supplies (often inter-related) for small rural villages in the Third World, with the emphasis on self-reliant development, and uses a system dynamics approach because no single criterion for optimisation for such villages could be found. The success of improvements could be judged by: adequate nutritional standard, adequate health, enhanced money income, greater self-sufficiency in energy, and greater attraction of living in the rural environment.

MERDA was developed at the University of Strathclyde (IFIAS 1981). A simple example of its method is shown by figure 4.1.2. Differential equations for each link are determined, allowing the effect on all other parameters of a change in one or more individual parameters to be calculated. Note that figure 11 contains not only energy balances but also population and money balances. Any of these can be optimised by the model.

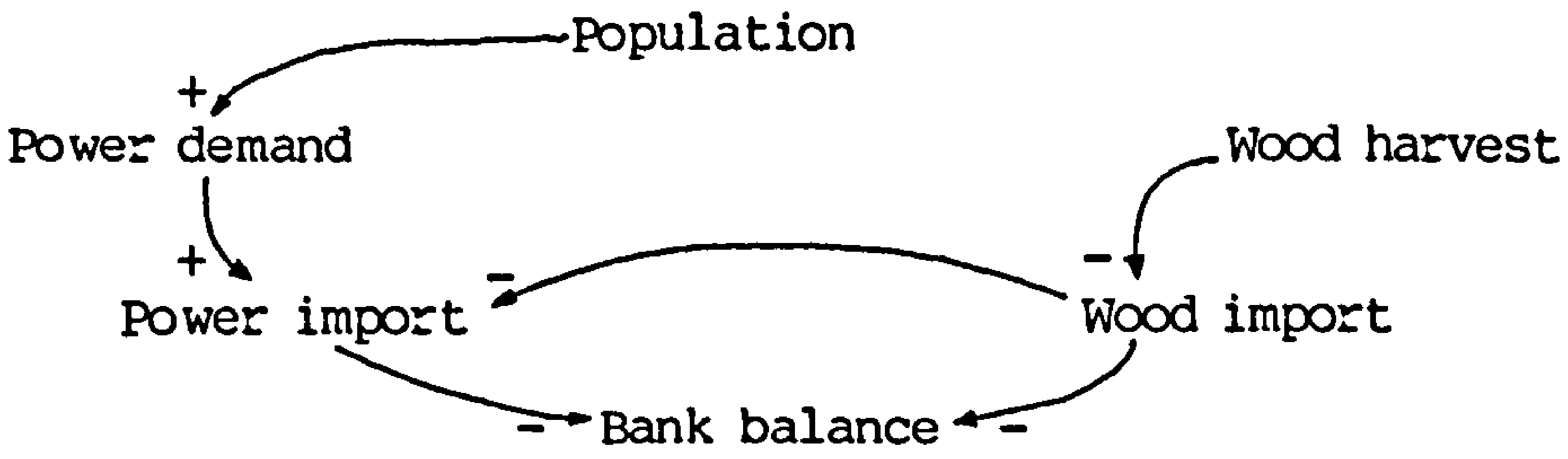


FIGURE 4.1.2 Causal loop diagram of MERDA model

The economic planning model of this thesis does not determine any other effects than reduction of cost (or maximisation of renewable energy usage) for a given energy demand level. Therefore there is only one parameter to optimise, and the type of analysis used by MERDA would be unnecessarily complicated. However, MERDA is reviewed to show other ways in which energy systems can be optimised.

4.1.4 DESCRIPTION OF THE MODEL

The source code for the four main models is contained in a separate volume of the thesis, available from the author.

4.1.4a Data requirements and computer needs

Data requirements can be split into two types: those input by the user while running each of the programs, and those held in computer files and read automatically by the programs. Data for the four optional programs are described in Chapter 5.

User-Input Data

For COSTCALCS, the user is asked, in turn, for details on the following energy supply equipment: hydro turbines, wind turbines, solar air or water heating panels, diesel generators, coal, wood or kerosene fired cooking ranges, coal or wood fired heating stoves and gas water heaters. The user need not specify all types of equipment; and he need only input data for one of each different device (different fuel cost, output or efficiency). HOUSECOSTS later asks which type of device a house uses. For all types of equipment: capital cost, annual maintenance costs, equipment lifetime, rated power output (for all equipment other than wind turbines) and fuel cost (if applicable) are asked for. In addition, for all equipment other than wind turbines and solar panels, the user is asked for average device efficiency.

The capital cost is that related only to the plant or device itself. Electrical connection or distribution system costs are not included, but the figures should include things such as: transport of the equipment to the site, installation costs and related civil engineering costs (dams and pipework for hydro turbines, foundations for wind turbines, sheds for diesel generators, etc.).

When specifying hydro turbines, data are required for: catchment number (relating to a file containing streamflow figures for that catchment), static head of the river, supply pipe length and supply pipe diameter. If wind turbines are specified, the user is given the option of selecting from eleven commercially available machines, for which performance data are held in a file. He may also chose other machines, in which case he is asked for their performance: cut-in and cut-out wind speeds, and power output at 4, 6, 8, 10, 12, 14 and 16m/s wind speeds. When specifying solar water or air heating panels, the total panel area must be input.

For HOUSECOSTS, the user must input the following data:

1) The number of houses in the community (up to 30).

2) The number of types of electrically driven heat pumps: their output rating, COP, capital cost and lifetime.

3) The number of electricity grids in the community. The capital cost and lifetime of each grid is required, and which machines supply each grid. A generator can only supply one grid.

4) The number of houses on each grid.

For each house on each grid in turn, the user is then asked for:

1) The number of space heating zones in the house, and their type (kitchen, living room, bedroom or general room). He is asked if the house has a central heating (CH) system. If it does, the system capital cost, rating and lifetime must be input, and which zones it supplies.

2) If the house has electrically-driven heat pumps. Note that: a) The heat pump must supply the CH system if a house has one, and must therefore be an air-to-water machine. b) Only one heat pump can be specified for a house having a CH system. c) The heat pump can only give domestic hot water if the house has a CH system. If the house does not have a CH system, it can have one air-to-air heat pump in each zone, if required. Heat pumps are assumed to be driven by all the electricity generators supplying the house.

3) Whether the house has any of the solar panels specified in COSTCALCS. If it has air heating panels, they must have their own air distribution system. Capital cost and lifetime of the hot air system will be asked for, and which zones are supplied by it. Solar water heaters will automatically supply the CH system if a house has one; if not the panels can only give domestic hot water, not space heat.

4) Whether the house has any of the cooking ranges, heating stoves or gas water heaters specified in COSTCALCS, in which zone they are and if they supply the CH system, if the house has one. A house can only have one range of each type, and only one stove of each type per zone. Gas water heaters automatically supply the CH system if it exists.

If the number of houses on all grids is less than the number of houses in the community, or if no grids are specified, the user is asked whether each house has electricity from non grid connected machines. A similar set of questions to those above follow, except that if a house has no electricity supply, it cannot have heat pumps.

The only data required by COSTSORT are: the unit costs of butane gas, propane gas, coal and wood fuel (in cost per kilowatt-hour of the primary fuel), if each house has a butane or propane gas cooker, and if each zone in the house has a coal of wood fired open fire.

COMSIM, finally, requires only the level of electricity demand for each house. The level can be: 1) 60 W average daily demand; 2) 160 W daily average; 3) 280 W daily average; 4) 560 W average; 5) 820 W average; or 6) No electricity demand.

Data on Computer Files

The following information applies to the model run with an hourly simulation time step: mean daily or mean weekly data can be used if the model is run with these time steps. All files should contain hourly data for the whole year, but COMSIM can repeat data which are the same each day or week.

Energy demand data are required in the following files:

1) Five files containing electricity demand (kW) for the five levels of demand mentioned above. This demand should not include electricity used for cooking, hot water or space heating.

2) A file containing hot water demand for each house.

3) A file containing cooking demands for each house.

4) Four files containing space heat demands for each of the four types of zone mentioned above (see chapter 5.3).

To assess renewable energy potential, COSTSORT and COMSIM both require hourly values of wind speed (m/s) and total solar radiation (W/m^2) for the year simulated. Files are also required containing hourly streamflows (m^3/s) for each catchment producing hydro power.

Performance data for the 11 wind turbines that can be selected is the final requirement. This contains cut-in and cut-out wind speeds, and power outputs at 4m/s to 16m/s wind speed for each turbine.

Each program in the sequence requires the output files from the previous program. It would be difficult to construct the necessary files other than by running the programs.

COMPUTER NEEDS

All programs were developed on a DEC mainframe VAX/VMS 11/785 single-processor computer. Using the VAX meant that programs could be developed without disk space or running time limitations. Future work should lead to versions of the model suitable for use on micro computers. The language used throughout is VAX 11 PASCAL (only slightly different from standard PASCAL), which is an easy language to learn. Its structured nature allows easy program development and de-bugging.

Table 4.1.1 shows the disk space used by the four main programs (source and executable files) and the data files (including data files generated by the programs). The size depends on: the number of houses, the time-step and length of the energy demand files and the number of energy supply devices. The values here are for the 27 houses on Eigg.

File	Disk Space	File	Disk Space
COSTCALCS	32.3	Cooking demand	18.4
HOUSECOSTS	78.3	Space heat demand 4x158.2 =	632.8
COSTSORT	104.5	Catchment streamflow 5x6.1 =	30.5
COMSIM	93.7	Wind turbine performance	1.5
		Meteorological data	385.5
Elec. demand 5x6.1 =	30.5	Intermediate files	549.9
Hot water demand	1.5	Results files	30.2
			1989.6

Table 4.1.1 Disk space requirements for program and data files (kbytes)

The running time of the programs depends a) on the number of houses in the community, and b) the number of different supply devices being considered. A typical run of COSTCALCS, HOUSECOSTS and COSTSORT for the island of Eigg (27 houses) takes about one hour for data input, and negligible computer time. A run of COMSIM, using an hourly time step, needs about 1.5 hours of central processor unit (CPU) time, while a similar run using a daily time step takes about 5 minutes CPU time.

4.1.4b The program COSTCALCS with example run

This program calculates the unit costs of energy from each of the types of energy supply equipment in a simulation. This is the cost of energy as output by the equipment, and does not include distribution costs. The method used to calculate unit costs is a net present value technique described fully in section 2.1, and is only summarised here. The annual cost of an energy supply device is:

$$C_{a,e} = [Ir(1+r)^n/((1+r)^n - 1)] + M + Q_f \qquad \text{cf } (1.1.24) \qquad (4.1.1)$$

The potential yearly output (P_y) from a device comes from:

$$P_y = \sum_{t=1}^{8760} P_t \qquad (4.1.2)$$

where P_t = hourly power output at time t,
8760 = number of hours in the year.

For specific devices eqn. 4.1.2 has the following forms:

1) For hydro turbines the equations of section 5.2 are used. Thus the total potential power throughout the year is given by

$$P_y = \sum_{t=1}^{8760} \varrho g \eta Q_t [H_s - (aQ_t^{1.75} L/D^{4.75})] \qquad (4.1.3)$$

where Q_t = streamflow at time t,
and a = constant, value 8.04×10^{-4} $m^3 s^{1.75}$.

If the streamflow exceeds the value for rated output, the turbines' output is set at its rated value.

2) For wind turbines hourly power output is from interpolation of the turbine performance characteristics knowing the hourly wind speed.

3) For solar panels, the yearly potential power comes from

$$P_y = \sum_{t=1}^{8760} \eta A \Phi_t \qquad (4.1.4)$$

where η = collector efficiency,
A = panel area,
Φ_t = global radiation at time t.

The values of , from Duffie & Beckman (1980), are 50% for water heating panels and 40% for air heating panels.

4) For all ranges, heating stoves, diesel generators and gas water heaters, the potential power output is simply the hourly rated power output multiplied by the number of hours per year.

The cost per unit output depends on the amount of energy from each device used in a year (seldom the same as the potential output). So actual output is estimated as a proportion of the potential by:

$$P_a = P_y f \qquad (4.1.5)$$

where P_a = power output used by the consumer,
and f = proportion of potential power used.

The factor f has the initial values shown below, but can be modified.

Device	Usage factor	Device	Usage factor
Hydro turbines	0.80-1.00	Ranges	0.70-1.00
Wind turbines	0.80-1.00	Heating stoves	0.70-1.00
Solar panels	1.00	Gas water heaters	0.08
Diesel generators	0.40	Heat pumps	0.25

Table 4.1.2 Usage factors for energy supply equipment

Finally the cost per unit output is calculated by:

$$C_{u,e} = C_{a,e}/P_{a,e} \qquad (4.1.6)$$

Table 4.1.3 shows an example run of COSTCALCS. The program itself only prints the unit costs (although it retains the ratings, efficiencies and annual energy outputs in files to be used by other programs). Other data are shown for information only.

Energy supply device	Type	Unit cost (£/kWh)	Capital cost (£)	Fuel cost (£/kWh)	Rating (kW)	Eff. (%)	Life (y)
Hydro turbines	1	0.0065	10000	-	11.0	90	40
	2	0.0088	8500	-	8.0	90	40
	3	0.0127	5500	-	3.0	90	40
Wind turbines	1	0.0491	59000	-	60.0	-	25
	2	0.0466	22000	-	22.0	-	25
Water solar panels	1	0.0503	800	-	2.5m^2	50	20
Diesel generators	1	0.1700	1700	0.028	3.5	18	15
	2	0.1740	1100	0.028	1.9	18	15
Wood fired ranges	1	0.0181	1900	0.009	2.5	70	30
	2	0.0209	1700	0.009	1.5	70	30
	3	0.0190	1700	0.009	2.0	70	30
Wood fired stoves	1	0.0265	600	0.009	1.5	55	40
	2	0.0254	900	0.009	2.5	55	40

Table 4.1.3 Output from run of COSTCALCS

4.1.4c The program HOUSECOSTS with example run

This program uses unit cost data from COSTCALCS to calculate, for each house in the community, the unit costs of energy in its final form, which is either: electricity, hot water, cooking or space heat.

The user-input data needed are described in sub-section 4.1.4a. So only the methods of calculation, and the conditions relating to supplies are presented here. Figure 4.1.3 shows a flow chart for the program. The letters A, B and C show routes through the program.

Central Heating Systems

The advantages of specifying a central heating (CH) system are that a) it acts as a partial heat store, smoothing out short-term fluctuations in energy supply, b) it allows solar water panels, ranges, heating stoves and gas water heaters to supply space heating to several or all of the zones in a house.

The annual cost, $C_{a,c}$, of the CH system is calculated by eqn. 4.1.1 (maintenance and fuel costs being zero). The system rating is known, and it is assumed that the CH runs at its rated power for 25% of the year (f=0.25). The unit cost of the system, $C_{u,c}$, from eqn 4.1.6 is

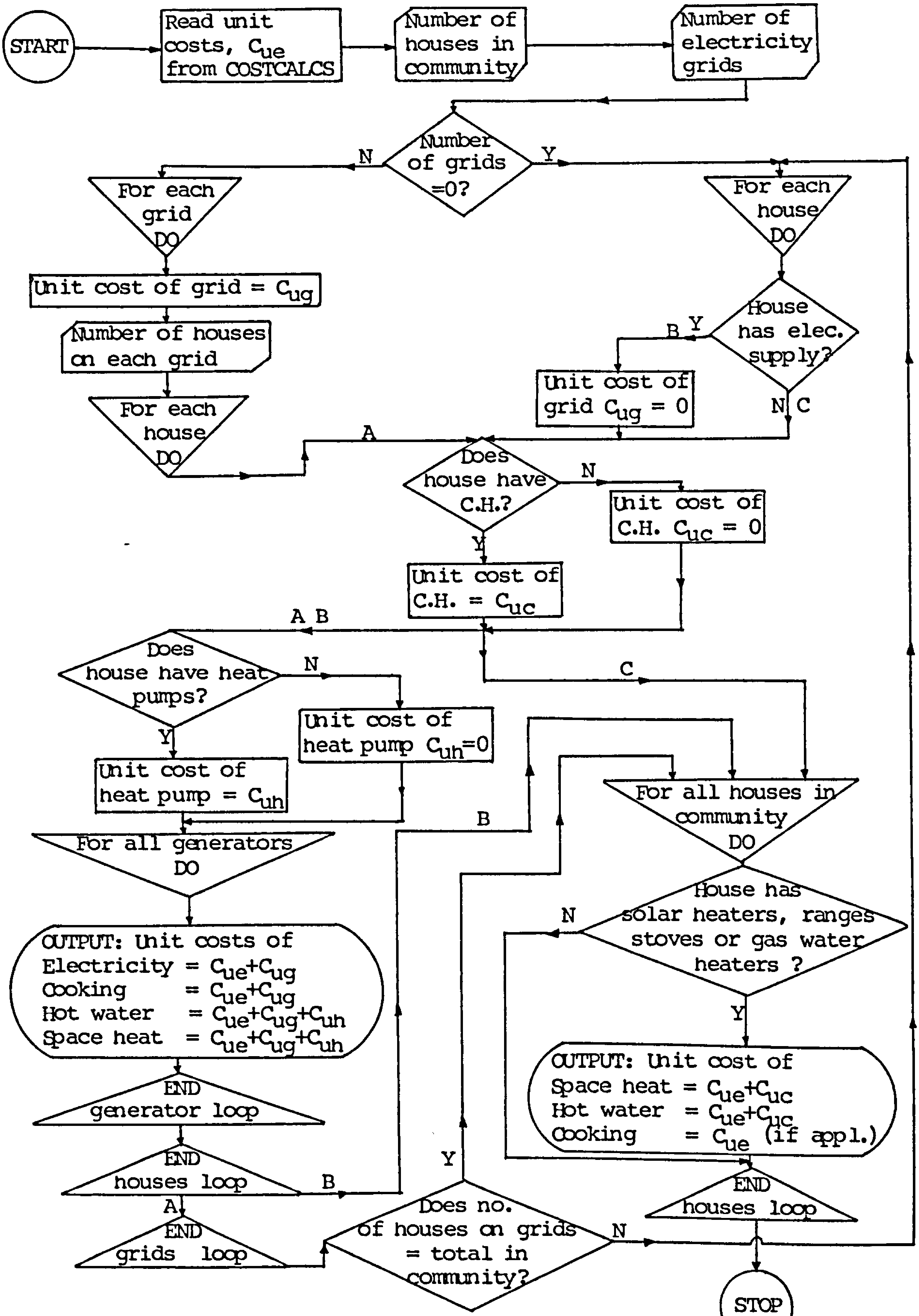
$$C_{u,c} = C_{a,c}/P_{a,c} \qquad (4.1.7)$$

The unit costs of a direct hot water system are small compared with those of a CH system, so no cost is assigned to a direct system.

Electricity Grids

An electricity grid is defined as any two or more houses sharing one or more electricity generators through a common electrical connection. Each hydro turbine can only supply one grid, but there can be one of each type of wind turbine per grid, and several of each type of diesel (up to a maximum total of 10). A house not on a grid can have one hydro turbine, one wind turbine and/or one diesel generator.

The likely average power transmitted by the grid is calculated using the yearly machine output figures from COSTCALCS. The user inputs



Key: As figure 4.1.1

∇ = Start of loop

Δ = End of loop

FIGURE 4.1.3 Simplified flow chart of the program HOUSECOSTS the grids' capital cost (including any switch gear, transformers, synchronisation equipment, etc.) and lifetime. If the yearly cost of the grid is $C_{a,g}$ (eqn. 4.1.1) and the yearly energy transmitted by the grid is E_a, the grid's unit cost is

$$C_{u,g} = C_{a,g}/E_a \qquad (4.1.8)$$

This unit cost is added to the unit energy costs from each generator on the grid to give the cost per unit of electricity delivered to the house. Unit costs of electric appliances are small compared with the costs of electricity supply, so are not considered.

Final-form Unit Energy Costs

For electricity generators, if the house has a CH system the unit cost of the system is added to the delivered electricity unit cost to give a final cost of hot water and space heat from the CH system. Each generator can supply electric appliances, hot water (which must come via the CH system if one exists), electric cooking and space heat (which can be both direct, in which case its cost is the same as for electric appliances, and from the CH system). If no CH system is specified, $C_{u,c}$ is zero, as is the grid cost if the house is not grid connected. So final-form end costs from each device are:

1) Electrical appliances $= C_{u,e} + C_{u,g}$ (4.1.9)
2) Hot water $= C_{u,e} + C_{u,g} + C_{u,c}$ (4.1.10)
3) Cooking $= C_{u,e} + C_{u,g}$ (4.1.11)
4) Space heating (direct) $= C_{u,e} + C_{u,g}$ (4.1.12)
(via CH) $= C_{u,e} + C_{u,g} + C_{u,c}$ (4.1.13)

For ranges and heating stoves similar equations are used, but the range or stove can only give direct space heat to the zone it is in. If there is a CH system, ranges and stoves can only give domestic hot water via the system. If no CH is specified, they have the option to give direct hot water. Thus the unit costs of final-form energy are:

1) Cooking (ranges only) $= C_{u,e}$ (4.1.14)
2) Space heat (direct to zone) $= C_{u,e}$ (4.1.15)
(via CH) $= C_{u,e} + C_{u,c}$ (4.1.16)
3) Hot water (via CH) $= C_{u,e} + C_{u,c}$ (4.1.17)
(direct) $= C_{u,e}$ (4.1.18)

Gas water heaters can only give space heat if a CH system has been specified, and if it has the heater must supply its hot water via the system. If a CH system is not specified, the heater can only give direct hot water. For the former case, hot water and space heating costs come from eqn. 4.1.16, while eqn. 4.1.18 is used in the latter.

Solar air panels can only supply space heat, and they must have their own air distribution system. Thus eqn. 4.1.16 is used, but $C_{u,c}$ relates to the cost of the air distribution system.

Heat Pumps

Two types of electrically driven heat pumps (HP) can be studied: air-to-air (for space heat to a single zone) or air-to-water which must supply a CH system, giving hot water and space heat to all zones the CH supplies. Heat pumps for domestic hot water only are not studied.

After inputing capital cost, life time, COP and output rating of each type of HP in the simulation, their unit costs come from eqn 4.1.1. The user is asked if a house has a HP, and if so which type.

If there is no CH, the generator cost $C_u = C_{u,e} + C_{u,g}$, else $C_u = C_{u,e} + C_{u,g} + C_{u,c}$. The unit cost of the HP is $C_{u,h}$. Because the heat pump increases the effective energy output from the generator, C_u must be decreased accordingly. So unit costs from the heat pump are:

$$\text{Hot water (via CH)} = C_{u,h} + (C_{u,e} + C_{u,g} + C_{u,c})/\text{COP} \qquad (4.1.19)$$
$$\text{Space heat (via CH)} = C_{u,h} + (C_{u,e} + C_{u,g} + C_{u,c})/\text{COP} \qquad (4.1.20)$$

$$\text{Space heat (direct)} = C_{u,h} + (C_{u,e} + C_{u,g})/\text{COP} \qquad (4.1.21)$$

If the generator cost is high, as with diesels, unit costs from the HP will be less than direct heating. But if the cost is low, for example for hydro turbines, the HP output cost may be higher than direct heating because its unit cost is greater than the generation and distribution costs divided by the COP (see examples below).

Tables 4.1.4 and 4.1.5 show outputs from a run of HOUSECOSTS. Table 4.1.4 gives details of a house on electricity grid one, with a CH sytem and an air-to-water HP with unit cost 0.0282 £/kWh output. Table 4.1.5 gives details for a house which has an air-to-air HP (unit cost 0.0225 £/kWh) in zone 2, and one (unit cost 0.0375 £/kWh) in zone 3.

```
Hydro turbines 1 and 2, wind turbine 1,
1 diesel type 1 and 2 diesels type 2: are on grid 1.
Hydro turbine 2, 1 diesel type 1: are on grid 2

House 1 is on grid 1 and is supplied by:

Hydro turbine 1 with prices:
  Elec. appliances  = 0.0069      Elec. cooking      = 0.0069
  Hot water from CH = 0.0257      Space heat from CH = 0.0257

Hydro turbine 2 with prices:
  Elec. appliances  = 0.0091      Elec. cooking      = 0.0091
  Hot water from CH = 0.0279      Space heat from CH = 0.0279

Wind turbine type 1 with prices:
  Elec. appliances  = 0.0445      Elec. cooking      = 0.0445
  Hot water from CH = 0.0632      Space heat from CH = 0.0632

Diesel generator type 1 with prices:
  Elec. appliances  = 0.1708      Elec. cooking      = 0.1708
  Hot water from CH = 0.1896      Space heat from CH = 0.1896

Diesel generator type 2 with prices:
  Elec. appliances  = 0.1747      Elec. cooking      = 0.1747
  Hot water from CH = 0.1935      Space heat from CH = 0.1935

House 1 is also supplied by

A wood fired range type 1 giving:
  Cooking           = 0.0181      Direct space heat  = 0.0181
  Hot water from CH = 0.0369      Space heat from CH = 0.0369
  Range is in zone 1

A wood fired stove type 2 giving:
  Direct space heat = 0.0265      Space heat from CH = 0.0453
  Hot water from CH = 0.0453
  Stove is in zone 2

House 1 water solar panel type 1 giving:
  Hot water from CH = 0.0690      Space heat from CH = 0.0690

CH system supplies zones 3 and 4.
  Zone 1 is type 2                Zone 2 is type 4
  Zone 3 is type 1                Zone 4 is type 3

Hydro turbine      1 drives HP supplying CH = 0.0504
Hydro turbine      2 drives HP supplying CH = 0.0515
Wind turbine type 1 drives HP supplying CH = 0.0692
Diesel gen.  type 1 drives HP supplying CH = 0.1324
Diesel gen.  type 2 drives HP supplying CH = 0.1343
```

Table 4.1.4 Example results from HOUSECOSTS showing data passed to COSTSORT. Units £/kWh

```
House 6 is not on a grid and is supplied by:

Hydro turbine      3 with prices:
  Elec. appliances  = 0.0127          Elec. cooking      = 0.0127
  Direct hat water  = 0.0127          Direct space heat = 0.0127

Wind turbine type 2 with prices:
  Elec. appliances  = 0.0467          Elec. cooking      = 0.0467
  Direct hat water  = 0.0467          Direct space heat = 0.0467

Diesel gen.  type 2 with prices:
  Elec. appliances  = 0.1743          Elec. cooking      = 0.1743
  Direct hot water  = 0.1743          Direct space heat = 0.1743

House 6 is also supplied by:

A wood fired range type 2 giving:
  Cooking           = 0.0209          Direct space heat = 0.0209
  Direct hot water  = 0.0209
  Range is in zone 1

  Zone 1 is type 2                   Zone 2 is type 4
  Zone 3 is type 4

Hydro turbine      3 gives dir. heat from HP in zone 2 = 0.0280
Wind turbine type 2 gives dir. heat from HP in zone 2 = 0.0412
Diesel gen.  type 2 gives dir. heat from HP in zone 2 = 0.0923

Hydro turbine      3 gives dir. heat from HP in zone 3 = 0.0444
Wind turbine type 2 gives dir. heat from HP in zone 3 = 0.0609
Diesel gen.  type 2 gives dir. heat from HP in zone 3 = 0.1247
```

Table 4.1.5 Example results from HOUSECOSTS showing data passed to COSTSORT. Units £/kWh

4.1.4d The program COSTSORT with example run

This is the largest and most complex of the programs making up the model. It determines the order in which energy supplies are used when running COMSIM, but keeps specific data about each piece of equipment as this is also used by COMSIM. The program asks whether each house has propane or butane gas cooking, and whether each zone in each house has a coal or wood fired open fire. It then carries out a sorting procedure summarised on figure 4.1.4 overleaf, and described below.

The sorting procedure puts the most expensive non-renewables first into a data file, so that they can be substituted first by renewables. The sorting procedure takes the following seven steps:

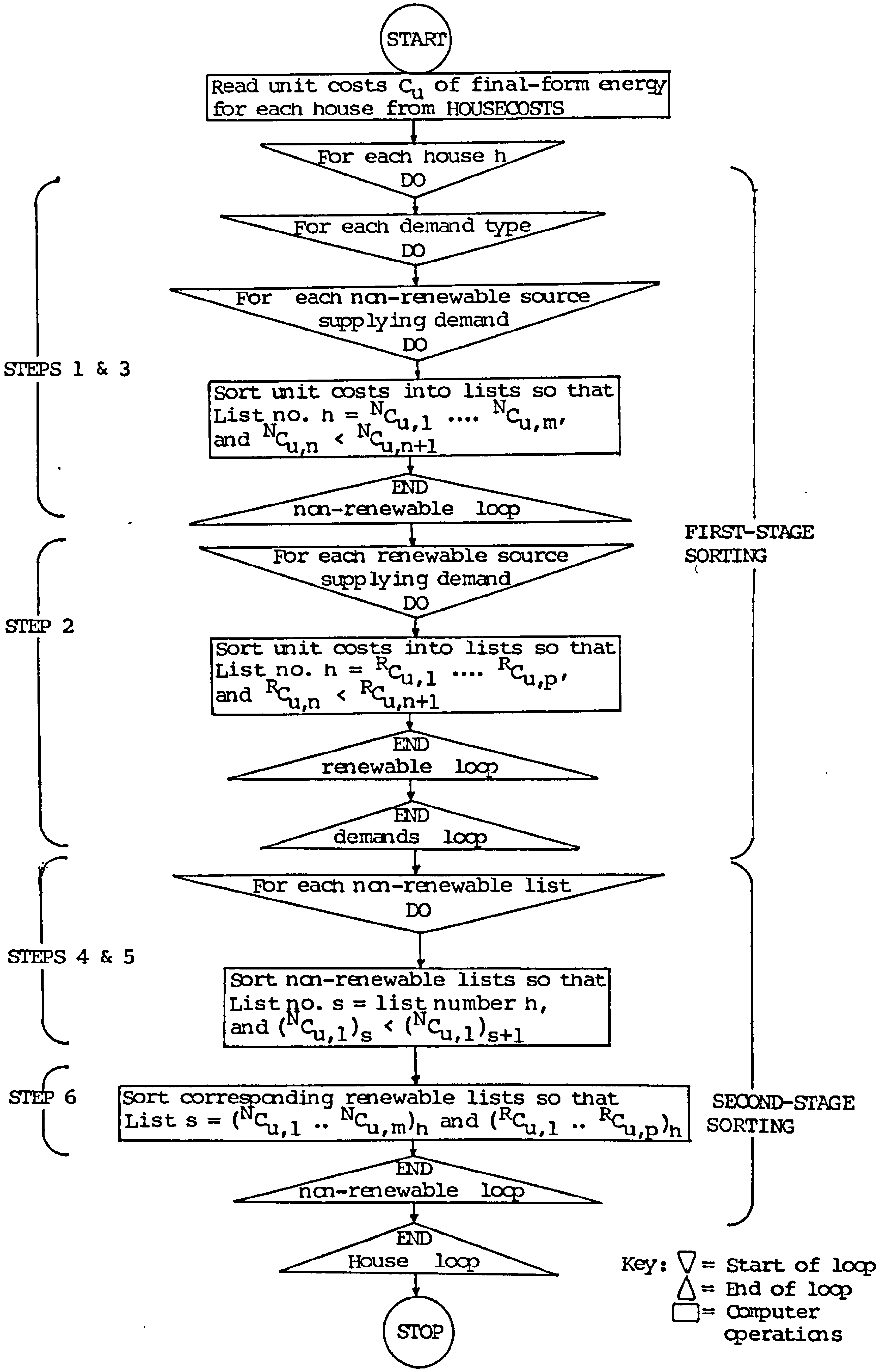


FIGURE 4.1.4 Simplified sorting routine of the program COSTSORT

STEP 1: For each house, all the non-renewable energy equipment supplying electricity, hot water and cooking demands is sorted, with the cheapest first. Thus the first-stage sorted results, for house 1 described above, are shown on table 4.1.6:

Demand	House	Cost (£/kWh)	Machine	Type	Rating (kW)	CH/Dir.	Zone
Elec. App.	1	0.1708	Diesel	1	3.5	-	-
	1	0.1747	Diesel	2*	1.9	-	-
Hot Water	1	0.1324	Dies HP	1.01†	2.0	CH	-
	1	0.1343	Dies HP	2.01†	2.0	CH	-
	1	0.1896	Diesel	1	3.5	CH	-
	1	0.1935	Diesel	2	1.9	CH	
Cooking	1	0.0380	Prop Gas	-	- ‡	-	-
	1	0.1708	Diesel	1	3.5	-	-
	1	0.1747	Diesel	2	1.9	-	-

Notes: *-Although there are two diesels of type 2 supplying house 1, only one is listed here.
†-Numbers after decimal point is HP type; rating is HP rating, but diesel rating is also recorded.
‡-Gas cookers and open fires do not have output ratings.

Table 4.1.6 Example of first-stage sorted non-renewable sources

STEP 2: The corresponding renewable energy sources which supply the same demands as those on table 4.1.6 are put into the same order. Thus the sorted renewable energy supplies for house 1 are (table 4.1.7):

Demand	House	Cost (£/kWh)	Machine	Type	Rating (kW)	CH/Dir.	Zone
Elec. App.	1	0.0069	Hydro	1	11.0	-	-
	1	0.0091	Hydro	1	8.0	-	-
	1	0.0445	Wind	1	62.0	-	-
Hot water	1	0.0257	Hydro	1	11.0	CH	-
	1	0.0279	Hydro	2	8.0	CH	-
	1	0.0369	W. Range	1	2.5	CH	1
	1	0.0453	W. Stove	2	1.5	CH	2
	1	0.0504	Hydro HP	1.01	2.0	CH	-
	1	0.0515	Hydro HP	2.01	2.0	CH	-
	1	0.0632	Wind	1	62.0	CH	-
	1	0.0690	Wat S.P.	1	4.1m^2	CH	-
	1	0.0692	Wind HP	1.01	2.0	CH	-
Cooking	1	0.0069	Hydro	1	11.0	-	-
	1	0.0091	Hydro	2	8.0	-	-
	1	0.0181	W. Range	1	2.5	-	1
	1	0.0445	Wind	1	62.0	-	-

Notes as for table 4.1.6

Table 4.1.7 Example of first-stage sorted renewable sources

STEP 3: A similar first-stage sorting process as in steps 1 and 2 is done for space heating, but data for this include the zone to which energy is supplied. For example a range supplies direct space heat to the zone it is in, but might also supply several other zones via the CH. Electricity generators always give direct space heat to all zones in a house, but they must also supply the CH system if there is one.

An example of first-stage sorting of space heating for house 1 (table 4.1.4) is shown on table 4.1.8, but showing only zones 1 and 3.

Space heating:

House	Cost (£/kWh)	Machine	Type	Rating (kW)	CH/Dir.	Zone Supplied
Non-Renewable Supplies						
1	0.1708	Diesel	1	3.5	Dir	1
1	0.1747	Diesel	2*	1.9	Dir	1
1	0.0467	Coal F.	-	- ‡	Dir	3
1	0.1324	Dies HP	1.01†	2.0	CH	3
1	0.1343	Dies HP	2.01†	2.0	CH	3
1	0.1708	Diesel	1	3.5	Dir	3
1	0.1747	Diesel	2	1.9	Dir	3
1	0.1896	Diesel	1	3.5	CH	3
1	0.1935	Diesel	2	1.9	CH	3
Renewable Supplies						
1	0.0069	Hydro	1	11.0	Dir	1
1	0.0091	Hydro	2	8.0	Dir	1
1	0.0181	W. Range	1	2.5	Dir	1
1	0.0445	Wind	1	62.0	Dir	1
1	0.0069	Hydro	1	11.0	Dir	3
1	0.0091	Hydro	2	8.0	Dir	3
1	0.0257	Hydro	1	11.0	CH	3
1	0.0279	Hydro	2	8.0	CH	3
1	0.0369	W. Range	1	2.5	CH	3 §
1	0.0445	Wind	1	62.0	Dir	3
1	0.0453	W. Stove	2	2.0	CH	3 §
1	0.0504	Hydro HP	1.01†	2.0	CH	3
1	0.0515	Hydro HP	2.01†	2.0	CH	3
1	0.0632	Wind	1	62.0	CH	3
1	0.0690	Wat S.P.	1	$4.1m^2$	CH	3
1	0.0692	Wind HP	1.01†	2.0	CH	3

Notes: As for table 4.1.6

§ -Program remembers which zone the stove or range is in.

Table 4.1.8 First-stage sorting of space heating supplies

If, during first-stage sorting, there is no renewable source for a particular demand, the computer prints, for example

No renewable source available for cooking for house 4

and places a zero unit cost in the appropriate space in the file. Renewable sources without non-renewable backup are sorted later.

STEP 4: Once all first-stage sorting is complete, secondary sorting starts. The lists are sorted by comparing the first value (the cheapest supply) from each list, and placing these in decreasing cost order. Taking values from tables 4.1.6 and 4.1.8, and those for house 6 from table 4.1.5, the sorted first values are in the order of table 4.1.9.

Array Index No.	House	Cost (£/kWh)	Machine	Type	Rating (kW)	CH/Dir.	Zone	Demand
1	6	0.1743*	Diesel	2	1.9	-	-	Elec.
2	6	0.1743*	Diesel	2	1.9	Dir	-	Hot W.
3	6	0.1743*	Diesel	2	1.9	Dir	1	Spa H.
4	6	0.1743*	Diesel	2	1.9	Dir	3	Spa H.
5	1	0.1708	Diesel	1	3.5	-	-	Elec.
6	1	0.1708	Diesel	1	3.5	Dir	1	Spa H.
7	1	0.1324	Dies HP	1.01	2.0	CH	-	Hot W.
8	1	0.0467	Coal F.	-	-	Dir	3	Spa H.
9	6	0.0467	Coal F.	-	-	Dir	2	Spa H.
10	6	0.0440	But. Gas	-	-	-	-	Cook.
11	1	0.0380	Prop Gas	-	-	-	-	Cook.

Notes: *-When several demand types have the same cost, they are placed in the order: electric appliances, cooking, hot water and space heat. See text below for explanation.

Table 4.1.9 Example of second-phase sorting for two houses

STEP 5: Having sorted the first values in each list, all other values in the list are put into a three dimensional array containing unit costs in order, demand type supplied by the equipment, and all equipment data needed by COMSIM. Using, for example, index nos. 7, 8, 9 and 10 from table 4.1.9, the array has the form shown on table 4.1.10.

Array Index				
7	0.1324 House 1 Dies HP Eqt. data Hot water	0.1343 House 1 Dies HP Eqt. data Hot water	0.1896 House 1 Diesel Eqt. data Hot water	0.1935 House 1 Diesel Eqt. data Hot water
8	0.0467 House 1 zn. 3 Coal fire Eqt. data Space heat	0.1324 House 1 zn. 3 Dies HP Eqt. data Space heat	0.1343 House 1 zn. 3 Dies HP Eqt. data Space heat	...... House 1 zn. 3 ...... Eqt. data Space heat
9	0.0467 House 6 zn. 2 Coal fire Eqt. data Space heat	0.0923 House 6 zn. 2 Dies HP Eqt. data Space heat	0.1743 House 6 zn. 2 Diesel Eqt. data Space heat	
10	0.0440 House 6 But. gas Eqt. data Cooking	0.1743 House 6 Diesel Eqt. data Cooking		

Table 4.1.10 Second-stage sorting of non-renewables. Units £/kWh

STEP 6: The lists of renewable energy sources corresponding to each index number are written to an array in the same order as their equivalent non-renewables. Taking index numbers 7 to 10 from table 4.1.10, the corresponding renewable supplies would be as table 4.1.11.

This sorting of renewables ensures that when COMSIM attempts to use the renewables in their sorted order, they will automatically substitute for the most expensive non-renewables.

STEP 7: A final sorting procedure is carried out before the arrays are written to external files. If there are any renewable sources without non-renewable back-up, they are not sorted by the above steps. They are now sorted into increasing cost order for the first values of each list (the cheapest first: the opposite order to above). The reason is that without non-renewable back-up, the cheapest way of using the renewables is for them to supply those demands which they do most cheaply.

Array Index				
7	0.0257 House 1 Hydro Eqt. data Hot water	0.0279 House 1 Hydro Eqt. data Hot water	0.0369 House 1 W. range Eqt. data Hot water	...... House 1 ...... Eqt. data Hot water
8	0.0069 House 1 zn. 3 Hydro Eqt. data Space heat	0.0091 House 1 zn. 3 Hydro Eqt. data Space heat	0.0257 House 1 zn. 3 Hydro CH Eqt. data Space heat	...... House 1 zn.3 ...... Eqt. data Space heat
9	0.0127 House 6 zn. 2 Hydro Eqt. data Space heat	0.0280 House 6 zn. 2 Hydro HP Eqt. data Space heat	0.0412 House 6 zn. 2 Wind HP Eqt. data Space heat	0.0467 House 6 zn. 2 Wind Eqt. data Space heat
10	0.0137 House 6 Hydro Eqt. data Cooking	0.0211 House 6 W. range Eqt. data Cooking	0.0467 House 6 Wind Eqt. data Cooking	

Table 4.1.11 Second-stage sorting of renewables. Units £/kWh

Note that each list contains details of unit costs, details of equipment, details of which house (or which zone in a house) is being supplied and which demand the equipment is supplying (electricity, hot water, cooking or space heat). The equipment data (referred to on tables 4.1.10 and 4.1.11) are the same as those shown on table 4.1.9: namely equipment type, rating, whether energy is via central heating or direct, zone in which equipment is situated (if applicable) and zone supplied by equipment (for space heat only). Therefore COMSIM receives all the information it requires from reading the lists.

As mentioned in the notes for table 4.1.9, when several types of demand have the same price, they are sorted in the order: electricity, cooking, hot water and space heat. There are generally fewer devices which can supply electricity than there are to provide hot water and space heat, and generators can put surplus energy into hot water tanks or central heating systems. This order of sorting prevents generators from being unable to meet electricity demands because of having put too much of their output into hot water tanks or central heating systems.

The method of sorting in COSTSORT puts all energy sources into an order which, when they are used in this order by COMSIM, will automatically make the most economic use of the sources. It will also give the greatest cost savings, by always using the cheapest supplies, to substitute for the most expensive ones, first.

4.1.4e The program COMSIM with example run

COMSIM is the program which runs the community simulation. For each time step (in this case each hour) the following steps take place:

1) The lists of energy supplies sorted by COSTSORT are read and used one by one in the order of index number in which they were written (the most expensive non-renewable, with its renewable, list first).

2) The program obtains from these arrays the house or zone, and type of demand the supplies are used for.

3) The demand level for the hour is obtained from files.

4) The cheapest renewable supply in each list is 'called' first, and its potential output assessed. If this supply has been called before, either by being in a previous list, or by occurring earlier in the same list, its potential is the remaining potential from the supply after attempting to meet a previous demand. If it has not been called, its output becomes its maximum potential for that hour.

5) The program attempts to cover the demand using the first renewable. If the supply covers the demand, the demand becomes zero and the remaining potential from the particular source becomes its initial potential minus the demand it has supplied.

6) If the supply does not cover the demand, the demand is reduced by however much it can cover, and the potential from the particular supply becomes zero.

7) The next cheapest renewable in the list is called, and steps 4 to 6 repeated until all renewables have been called.

8) Each non-renewable supply in the corresponding list is called, using the cheapest first, and steps 4 to 6 are repeated until all non-renewables have been called.

9) Having called all supplies, if the demand is not zero a shortfall is recorded, having the level of the remaining demand.

10) The next list is read, and steps 2 to 10 repeated.

11) The performance of each supply in the list is recorded. This is: the proportion of the total demand on a supply for that hour which the supply meets, the output from the supply used, and the potential output from the supply for that hour.

12) Once all lists have been read and analysed, the program moves to the next hour and repeats all steps until the end of the simulation.

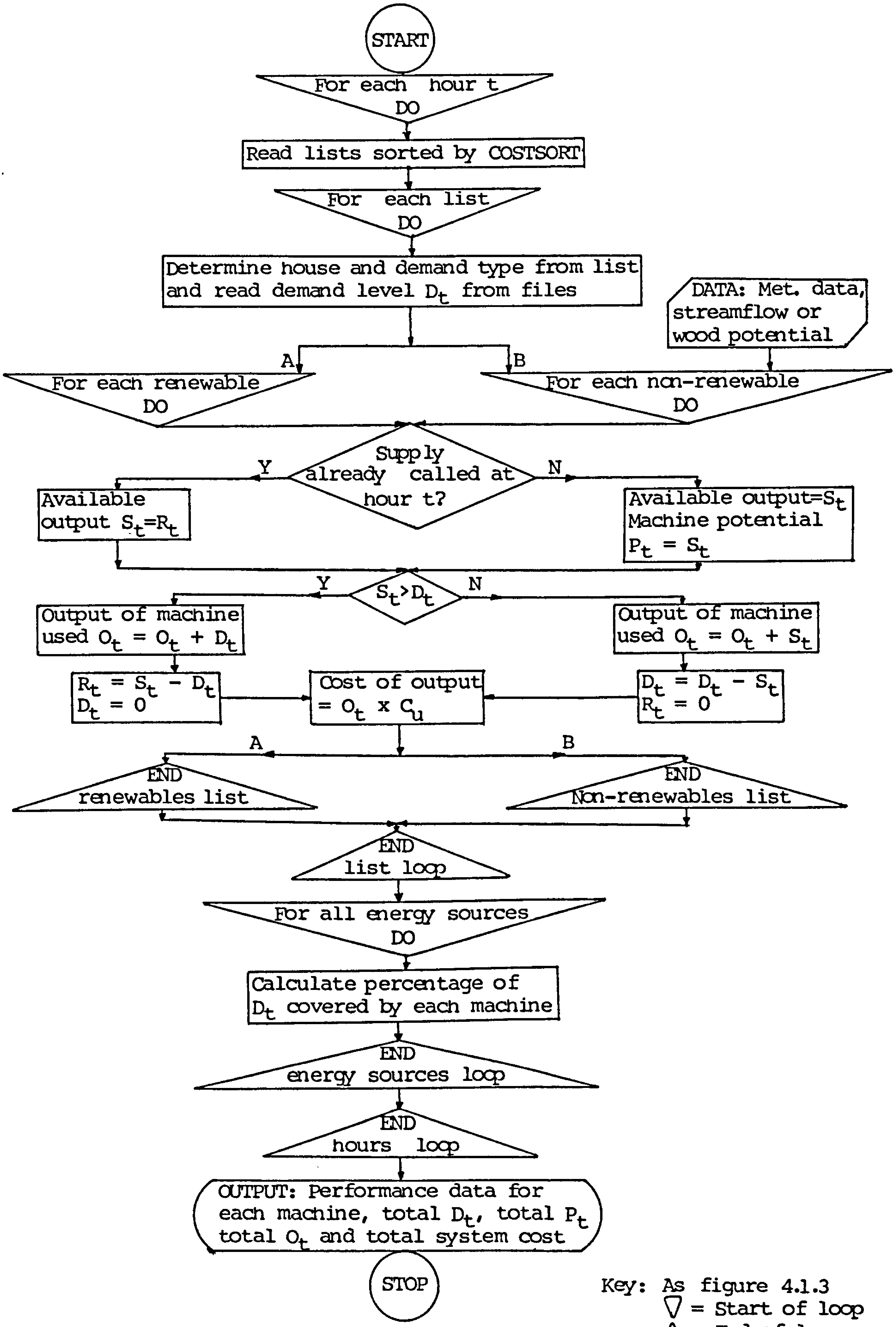
These steps are summarised in the flow chart for COMSIM shown on figure 4.1.5 overleaf, and more details are given below.

STEP 1: The ordered lists from COSTSORTS are read at the start of the program into internal files. The lists contain all information needed to determine: whether equipment is used by an individual house or whether it is on a grid; if there is more than one diesel generator on a grid, which one is being used at any one time; and which zone the ranges or heating stoves are in (this is important to determine which source is supplying the central heating (CH) system in another zone).

STEPS 2 and 3: As each list is dealt with in the order determined by COSTSORT, the program reads which house (or zone) is being supplied by the equipment, and reads the corresponding energy demand D_t from files.

STEP 4: Each energy source in the renewable part of the list is considered in turn, starting with the cheapest. A supply can be 'called' several times during each hour: an electricity generator on a grid would be called by each house on the grid, and for each of the four types of energy demand, and a range or stove might be called by several lists to supply hot water, space heating or cooking. A supply can be called more than once from the same list, for example a generator could be called to supply direct space heat, then again for space heat from a CH system, and finally space heat from a heat pump.

If a supply has been called before, its output potential P_t would have been reduced by however much energy it has already supplied. If it has not previously been called, its output is its maximum



Key: As figure 4.1.3
▽ = Start of loop
△ = End of loop

FIGURE 4.1.5 Simplified flowchart for the program COMSIM potential output for that hour depending on: the relevant hourly meteorological parameter (read from a file for each hour) for wind and solar power, the hourly value of streamflow for hydro turbines, or the total annual wood potential (set by the user as a limit within the program) for wood ranges, stoves or open fires. All equipment (except open fires and gas cookers) is limited by its maximum rated output. The program retains the hourly potential for use in step 11, and it also sums the potential throughout the simulation for use at the end.

STEPS 5 and 6: The program compares the potential supply with the demand, and calculates either the remaining potential, R_t, or the remaining demand, D_t using the following algorithm:

If $P_V >= D_t$, then $R_t = P_t - D_t$ and $D_t = 0$ (4.1.22)
If $P_t < D_t$, then $R_t = 0$ and $D_t = D_t - P_t$ (4.1.23)

The value R_t becomes P_t for the supply, and the modified value of D_t becomes the new D_t, for all subsequent calls during this hour.

The program records: how much energy from the supply is used during the hour, the demand on the supply (summed for each time it is called) and sums the total energy output from the supply during the year. Energy output from a supply may be slightly more than the demand, as surplus energy can be put into hot water storage in CH systems.

STEP 7: The next renewable supply in the list is called, and steps 4, 5 and 6 repeated until all renewables in the list have been called. All renewables, and all non-renewables (see step 8), in a list are always called regardless of the level of demand, even if the demand is zero.

Step 8: A similar procedure to steps 4 to 7 is carried out for all non-renewables in the corresponding list. The initial output potential from all non-renewables is their output rating, as no limitations on fuel supplies are assumed. If there is more than one diesel generator of the same type (and hence the same unit cost) on a grid, they are each called in succession after the first of the type has been called.

STEP 9: If all potential supplies for a particular demand have been called, and the demand is not zero, an energy shortfall is recorded. The amount of the shortfall, and the number of hours when shortfalls arose, are calculated for each type of demand throughout the year. Shortfalls cannot be carried forward to subsequent hours (although hot water and space heat can be taken from storage). Once a shortfall is recorded for the hour, it is set to zero and does not affect the demand in the next hour.

STEP 10: Steps 2 to 9 are repeated for each list in the arrays written by COSTSORT (until the program has attempted to satisfy all demands for all houses for the current hour). The renewable sources without non-renewable back-up are studied once the other lists have been finished, and steps 2 to 7, and step 9 are repeated for these renewables.

STEP 11: Once all lists have been considered, the computer has in its memory: the total energy demand (also including surpluses put into hot water storage) on each piece of equipment in the simulation (this can be from several houses or zones, and for more than one type of demand: a diesel generator on a grid may supply electricity, cooking and hot water to several houses, and space heat to many zones in those houses), the maximum output potential of the equipment for that hour, and the total output used in meeting, or attempting to meet, the demand.

A routine then takes place to determine what percentage of the total demand each piece of equipment met during the hour. This is split into five categories:

1) Demand exceeded potential supply by 60% - 100%,
2) Demand exceeded potential supply by 20% - 60%,
3) Demand equalled potential supply to -20% - +20%,
4) Potential supply exceeded demand by 20% - 60%,
5) Potential supply exceeded demand by 60% - 100%.

One unit (for one hour) is placed into the appropriate category for each hour of the simulation. In the same way as for energy shortfalls, energy surpluses cannot be carried forward to the next hour. Once a surplus is recorded, its value is set to zero, and does not effect the potential output during the next hour.

STEP 12: All steps are repeated for the next hour, and so on until the end of the simulation. At the end of each hour the program resets the boolean value "equipment called?" to false so that the maximum hourly potential output is obtained the first time the equipment is called during the next hour. Energy shortfalls or surpluses are set to zero, and the hourly demand on, or output from, all supplies are also set to zero, prior to being recalculated for the next hour.

Central heating systems

COMSIM deals with CH systems by controlling their water temperature, between the limits 60°C and 80°C. Energy cannot be drawn out of the system if the temperature is below 60°C, and energy cannot be stored if it exceeds 80°C.

If P_t is the energy supplied to the system during hour t, D_t is the demand for space heat or hot water from the system, and T_{t-1} the water temperature at the start of hour t, the temperature at time t is:

$$T_t = T_{t-1} + ((P_t - D_t)/mC_p) \tag{4.1.24}$$

where m = mass of water in system

The following conditions apply:

$$\text{If } T_t > 80, \quad \begin{aligned} R_t &= P_t - D_t - (mC_p(80 - T_{t-1})) \\ D_t &= 0 \\ P_i &= P_t - R_t \\ \text{and } T_t &= 80 \end{aligned} \tag{4.1.25}$$

$$\text{If } 60 < T_t <= 80, \quad \begin{aligned} R_t &= 0 \\ D_t &= 0 \\ \text{and } P_i &= P_t \end{aligned} \tag{4.1.26}$$

$$\text{If } T_t < 60 \text{ and } T_{t-1} > 60, \quad \begin{aligned} D_t &= D_t - P_t - (mC_p(T_{t-1} - 60)) \\ R_t &= 0 \\ \text{and } P_i &= P_t \end{aligned} \tag{4.1.27}$$

$$\text{If } T_t < 60 \text{ and } T_{t-1} <= 60,\ R_t = 0 \text{ and } P_i = P_t \qquad (4.1.28)$$

P_i is the input from the supply to the store. Therefore the initial demand on the supply is $D_t + P_i$. The value R_t becomes the value P_t for successive calls of the supply. If the CH system is called more than once, the value T_i becomes T_{t-1} in the above equations. The modified value of D_t is carried forward to the next supply in the list.

Results

An example run of COMSIM is presented below, showing the various outputs at the end of a yearly simulation. It shows how results can be used to improve the system, but no optimisation is attempted. The simulation was for six houses, but equipment results are only shown for houses 1 and 6 described above. Table 4.1.12 shows results for house 6.

```
               Demand exceeded supply by:  Supply exceeded demand by:
Unit:hours     60/100%    20/60%     +20/-20%     20/60%     60/100%
Unit:kWh/y      Total energy used         Potential

Hydro 3           0          769        2406          3782       1803
                     17410                  26280

Wind turbine 150             2          2121            19       6468
type 2                 460                   7480

Diesel            0            0           0             0       8760
type 2                   0                  16640

Wood fired        0          171         109           174       8306
range                  610                  13140

Butane gas        0            0          41             0       8719
cooking                 30                   UNSPECIFIED

Coal open fire 0               0         118             0       8642
in zone 2               40                   UNSPECIFIED

Demand on HP in zone 2 = 0 kWh/y, potential from HP = 21900 kWh/y
Demand on HP in zone 3 = 0 kWh/y, potential from HP = 13140 kWh/y

Total hours all possible supplies for house 6 failed to meet:
Electricity demand    = 0,   energy shortfall = 0 kWh/y
Hot water demand      = 0,   energy shortfall = 0 kWh/y
Cooking demand        = 0,   energy shortfall = 0 kWh/y
Space heating demand = 0,    energy shortfall = 0 kWh/y
```

Table 4.1.12 Performance results of equipment supplying house 6

Table 4.1.13 shows results for the equipment supplying house 1 (the electricity generators also supplied house 2).

	Demand exceeded supply by:			Supply exceeded demand by:			
Unit:hours	60/100%	20/60%	+20/-20%	20/60%	60/100%		
Unit:kWh/y						Total energy used	Potential
Hydro 1:	270	622	2200	3814	1854	53900	85120
Wind turbine 1 on grid 1	72	0	2193	15	6480	300	20310
Diesel type 1 no. 1 on grid 1	0	0	1	2	8757	15	30660
Diesel type 2 no. 1 on grid 1	0	0	0	0	8760	0	16640
Diesel type-2 no. 2 on grid 1	0	0	0	0	8760	0	16640
Water solar panels	0	0	4288	0	4472	0	1220
Wood fired range	1	54	42	100	8563	510	21900
Propane gas cooking	0	0	14	0	8746	20	UNSPECIFIED
Wood stove in zone 2	0	0	0	0	8760	40	21900
Coal open fire in zone 3	0	0	0	0	8760	0	UNSPECIFIED

Demand on heat pump = 0 kWh/y, Potential from HP = 17520 kWh/y
CH system was called on: 8760 hours, Demand on CH = 2990 kWh/y

Total hours all possible supplies to house 1 failed to meet:
Electrical demand = 0 hours, energy shortfall = 0 kWh/y
Hot water demand = 0 hours, energy shortfall = 0 kWh/y
Cooking demand = 0 hours, energy shortfall = 0 kWh/y
Space heating demand = 0 hours, energy shortfall = 0 kWh/y

Table 4.1.13 Performance results of equipment supplying house 1

The results from tables 4.1.12 and 4.1.13 show that most of the equipment is over-rated. The following changes could be made:

1) Remove the type 1 diesel and one of the type 2 diesels from grid 1, and de-rate the remaining diesel to about 0.8 kW.

2) Remove solar water heating panels from the simulation.

3) De-rate the ranges in houses 1 and 6 to about 1.5 kW and 1.0 kW.

4) Possibly remove gas cooking from house 1 and house 6.

5) Remove the wood stove and coal fire from zones 2 and 3 of house 1, and the coal fire from zone 2 of house 6.

6) Remove diesel supplying house 6 from simulation.

COMSIM finally prints the total yearly system costs for all equipment in the simulation. These are shown on table 4.1.14.

Hydro turbines	= 620	Diesel generators	= 650
Wind turbines	= 910	Coal fired ranges	= 0
Air solar panels	= 0	Kerosene fired ranges	= 0
Water solar panels	= 0	Coal fired stoves	= 0
Wood fired ranges	= 810	Coal fired open fires	= 0
Wood fired stoves	= 340	Propane gas cooking	= 100
Wood fired open fires	= 260	Butane gas cooking	= 0
Hydro-driven heat pumps	= 0	Dies.-driven heat pumps	= 0
Wind-driven heat pumps	= 0		

Total System Cost = 3780 £/y

Table 4.1.14 Total energy costs for a year. Units: £/y

The results of table 4.1.14 suggest the following improvements:

1) Attempt to substitute hydro and wind power for diesel generators (possibly by connecting turbines on grid 1 to grid 2).

2) Replace propane cooking with cheaper wood burning ranges.

3) Replace coal open fires by CH systems or wood burning stoves.

To have stoves or fires in every zone in a house may be impractical because of the time needed to light and tend them. Therefore a better, although slightly more expensive, option could be to give each house a CH system, and this might also improve the cost-effectiveness of the heat pumps.

An advantage of this model is that equipment which is never used does not affect the system cost. Therefore it is possible to include as many supplies as required, simply leaving out those with no demand from subsequent simulations. Note also that there would be little point in running RECALCS at the end of the above simulation, as the ratings are so far from being correct. RECALCS would only be run once correct ratings and types of equipment were better established.

4.1.5 DISCUSSION

The model always makes the most economical use of the energy supplies available in a simulation, subject to one of the two possible model strategies. However, there are some limitations to this methodology when applied to practical systems:

a) No lower limits are set on the outputs of non-renewable sources. Diesel generators, in particular, run very inefficiently below about 80% of their ouput rating. The model could be modified to give lower limits on outputs, but studying simulation results can be used as a reasonable check on output levels.

b) No limits are set for minimum running time for any supply. Coal and wood fires, once lit, would probably burn all day or all evening; they would not be repeatedly lit and extinguished as the demand changed. The model could be modified to set minimum run times for various supplies.

c) No priority of energy use is given among houses sharing a common energy supply (houses on an electricity grid). However, it has been found both on Lundy island and Fair Isle (both of which have a wind turbine with diesel backup supplying a grid to several houses) that consumers are careful not to overload their systems, and limit their demands to the available supply (Infield & Puddy 1984 and Sinclair et al 1984). Therefore this limitation is not considered too important.

The choice of an hourly time step in this work was chosen as a compromise between accuracy and practicality in terms of computing time. Inaccuracies occur particularly when averaging wind and solar power over an hour, as the output from these can vary considerably on a much shorter (less than 5 minute) basis. Similarly using electricity demands averaged over an hour cuts out most of the short-term demand fluctuations (such as boiling a kettle) which renewable supplies, in particular, might find difficult to cover. The capability of a chosen system could be tested over short periods, given sufficient data, by running the model for a few days using a short time step, since it is easy to change the time step and simulation time in the model. Chapter 6 shows considerable differences between an hourly time step and the daily and weekly steps tested in the model, so the compromise of the hourly step is considered to give reasonably accurate results, bearing in mind that short-term demand fluctuations would most probably be met by the diesel generators.

Although the sensitivity of the model to changes in data inputs (small fluctuations in fuel costs, equipment costs or ratings) could be tested, this would be time-consuming with a model of this complexity. Unless the variations are sufficient to change the order of supplies determined by COSTSORT, there would be no effect on equipment usage and performance, and the effects on overall system cost would probably be small. It is, however, important to test the performance of the system if renewable energy supplies are limited, and this was done when the model was applied to the island of Eigg (see Chapter 6).

The model is not in itself an optimisation model, as it does not improve the system during a simulation. It is in fact a study model, assessing the performance of any system, but giving results which suggest optimisations. The user must then make optimisations by modifying the system, and re-running the model to assess the new system's performance.

Despite the above limitations, the model presented here is considered to have advantages over other models of a similar type (see sub-section 4.1.3) both in terms of its accuracy and in terms of its methodology. Therefore it is concluded that the model is suitable for assessing energy supply systems for small communities, and would give results accurate enough to determine which equipment to install.

Section 4.2 Thermodynamic Analysis and Optimisation of Energy Supply Systems for Small Communities.

4.2.1 INTRODUCTION

A full introduction and discussion of the underlying principles and objectives of thermodynamic analysis are given in section 2.2, so are only summarised briefly here. The aim of this type of analysis is to determine how effectively the potential of an energy supply is being used to supply an energy demand. The potential of an energy supply can be calculated as its exergy, which is its potential to produce work. By defining second law (exergy efficiency) as exergy of demand divided by exergy of supply, a measure of how effectively the supply is being used can be determined.

This section presents a diagramatical method for studying second law efficiency. Energy quality (defined in section 2.2) is plotted against energy quantity, so the area represents exergy. These diagrams give good insight into values for second law efficiency. They show how both high quality renewable energies (hydro and wind energy), and low quality renewable energy (solar energy) can be used to replace thermodynamically inefficient energy transformations.

The energy qualities in this work are chosen to represent the basic form of the energy supply: combustible fuels are sources of high temperature heat, wind and hydro power are sources of shaft power and solar energy is a source of low temperature heat.

Exergy analysis is beginning to become established as a method of system comparison. Other researchers have used different techniques: exergy economics, resource allocation, entropy management and net energy analysis. A review of this work is presented, and its methods compared with those of this section.

Several examples of exergy analysis are taken from a paper summarising the analysis method, written by Twidell and Pinney (1985).

4.2.2 SYMBOLS AND UNITS

Symbol	Description	Units
B	Exergy	J
C	Unit cost	£/J
C_y	Yearly total cost	£/y
D	Yearly energy demand	J/y
E	Yearly energy production	J/y
F	'Free energy'	J
P	Energy rate	J/y
Q	Heat energy	J
R	Energy service	-
ΔS	Entropy change	J/K
T	Temperature	K
dt	Time increment	-
f_d	Demand factor	-
f_e	Environmental quality factor	-
q	Energy quality	-
η	Efficiency	-

Subscripts

B	Exergy
a	Actual yearly supply or demand
c	Component
cap	Capital
d	Demand
e	Energy
fu	Fuel
h	Hot source
i	Initial
in	Input
loss	Lost
m	Mechanical
o	Atmospheric or dead state
out	Output
q	Heat
r	Maximum or rated level
s	Supply
w	'Transformation': other than heat or mechanical

4.2.3 LITERATURE REVIEW

The theoretical background to thermodynamic analysis is presented fully in section 2.2. This review covers only the application of such analysis to practical energy systems.

Thermodynamic analysis falls broadly into four categories: 1) exergy efficiency analysis, 2) exergy economics, 3) resource allocation and entropy management and 4) net energy analysis. This review attempts to place different research work into its nearest appropriate category. Since this thesis covers the first two methods, these are reviewed in more detail. A good review of much of the current work on exergy is given by the American Chemical Society (1980).

Exergy efficiency analysis

One of the most thorough coverages of this type of analysis is that of Ahern's (1980) book "The Exergy Method of Energy System's Analysis". Although this concentrates mainly on engineering power cycles, it gives a good introduction to the fundamentals of energy, the physical basis for exergy, and a brief history of exergy development.

The book presents a useful method for analysing energy production cycles, such as steam turbines. This calculates exergy losses by determining entropy change, using the basic equation

$$B_{loss} = T_0 \Delta S_c \qquad (4.2.1)$$

which is particularly easy to apply to systems for which tabulated entropy values are available. The equation used by Ahern to calculate overall system efficiency is the same as the definition of second law efficiency in this work.

A useful and easily read paper applying exergy analysis to an electricity generating steam turbine plant is that of Gaggioli & Wepfer (1983). This shows that components often considered highly efficient, for example boilers (energy efficiency 90%), are only 50% efficient in exergy terms. This paper differs in its method from that of this thesis, in that it assesses the exergy of energy supplies before they undergo any transformation; this thesis assesses exergy after a primary conversion (see section 2.2.5). The paper concludes that much work currently done on energy conservation might instead concentrate on exergy conservation, as this is where large potential savings exist.

Gaggioli & Wepfer (ibid) is one of several refences which use exergy flow diagrams for an entire country, of a type first introduced by Cook (1971). Reistad (1980) shows exergy flows in the USA in 1970, and calculates that the second law efficiency for the USA is about 10%, as opposed to its energy efficiency of 50%. He concludes that such diagrams highlight where research efforts should be concentrated to improve exergy efficiency. Wall (1980) constructs such an exergy diagram for Sweden in 1975, but extends it to include production of some of Sweden's main industries. An example of this type of exergy flow diagram, for the island of Eigg, is given in the next section.

A detailed exergy analysis of heating systems is given by Borel (1976). This otherwise thorough paper is spoilt by assuming (as do several other authors) that the exergy of a heat source can be calculated by the Carnot equation

$$B = Q[(T_h - T_o)/T_h] \quad (4.2.2)$$

Section 2.2.5 shows this to be true only for infinite sources.

Few references deal with renewable energy sources, or energy quality, in other than superficial fashion. Wall (ibid) investigates their contribution to the Swedish energy system, but gives a "quality" (undefined) to solar energy of 90%. The Watt Committee on Energy (1979) also ascribe energy qualities of a sort to various energy sources, but they do not show how they determine the values.

One reference dealing in detail with renewable energy sources and their quality is Twidell & Pinney (ibid). This uses the same definitions as section 2.2, but with a different quality for solar energy. The paper develops the concept of energy quality further, by defining "service" and other factors for renewable energy supplies (described below). Over a period of, for example, one year, the environmental quality factor, f_e, is defined as

$$f_e = E_a/E_r \quad (4.2.3)$$

where E_a = actual energy produced in the year
and E_r = potential energy produced if device ran continuously at its rated output.

A good hydro turbine might have $f_e = 1.0$, but wind and solar supplies typically have values $f_e < 0.3$ (solar energy at best could never exceed 0.5). Similarly the demand factor, f_d, is

$$f_d = D_a/D_r \qquad (4.2.4)$$

Since energy quality is defined as $q = B/E$, it follows that

$$B_s = q_s f_e E_r \qquad (4.2.5)$$

$$\& \; B_d = q_d f_d E_d \qquad (4.2.6)$$

(subscripts s and d referring to supply and demand)

In an ideal system, with no exergy loss, $B_s = B_d$, so

$$q_s f_e E_r = q_d f_d E_d \qquad (4.2.7)$$

$$\text{or } q_d = q_s f_e E_r / f_d E_d \qquad (4.2.8)$$

Finally service, R, is defined as

$$R = q_s f_e f_d \qquad (4.2.9)$$

and the success of any system is assessed by comparing R with q_d.

These ideas are still in an early stage of development, and more work is needed before their usefulness can be determined. They could be extended to cover non-renewable supplies, but care is still required in the definition of the fundamental quality of renewable energy supplies.

Exergy economics

The main objective of exergy economics is to determine the cost of commercial and other products by basing costs on exergy rather than energy. This gives a rational basis for product pricing and evaluation of operating decisions. One of the first, and most frequently cited authors on this subject is Georgescu-Roegen (1971). His work is summarised (Georgescu-Roegen 1975) by a paper in which he states the principle that all actions, of man or nature, must involve an increase in global entropy; implying that all processes, including economic activity, lead eventually to exhaustion of resources. He further dispels the myths, long held by economists, that (a) the price mechanism can always overcome resource shortages, or (b) technologists or engineers will always find replacements for depleted resources or increase indefinitely the productivity of any kind of energy.

Much of his paper deals with limits to economic 'growth' (referring mainly to consumption). He gives eight suggestions for limiting growth, one of which is to avoid all inefficient uses of energy, until the direct use of solar power or controlled nuclear fusion are achieved.

Practical examples of exergy economics are given by Gaggioli & Wepfer (1980). Their equation for unit exergy costs is

$$C_B = (P_{in}C_{fu} + C_{cap})/P_{out} \qquad (4.2.10)$$

where C_{fu} = unit fuel cost,
P_{in} = energy input to device,
C_{cap} = capital cost
and P_{out} = yearly energy output.

Since energy efficiency, η_e, is defined as $\eta_e = P_{out}/P_{in}$,

$$C_B = C_{fu}/\eta_e + C_{cap}/P_{out} \qquad (4.2.11)$$

This equation, although practically very useful, has one drawback. Energy efficiency can often only be determined by measurement, not calculated theoretically. The use of equation 4.2.11 requires prior knowledge of the convertor's efficiency.

Gaggioli & Wepfer apply eqn. 4.2.11 to several energy systems, and conclude that exergy accounting should be developed further, and validated, to show how errors occuring with more conventional energy accounting can arise. In a later paper (Gaggioli & Wepfer 1983), their ideas are developed to construct thermo-economic flow diagrams.

A useful reference, which discusses conventional economic theory in a thermodynamic context, is that of Ayres & Nair (1984). They discuss the link between information theory and entropy (covered in more detail by Tribus (1980)), showing that a decrease in entropy of a system necessarily gives an increase in the information about the system. They conclude that much effort is needed to prevent a catastrophy arising because of depleted coal and oil reserves (sources with high negentropy), suggesting the foundation of an 'information resource' to replace fossil fuels: fusion power or photovoltaic systems being possible alternatives.

Borel (ibid) calculates exergy cost by

$$C_B = C_y / \int (B_m + B_q + B_w) dt \qquad (4.2.12)$$

where C_y = total yearly costs (capital, fuel, etc.),
B_m = mechanical exergy output,
B_q = heat exergy output
and B_w = 'transformation' exergy: work other than from heat or mechanical sources.

He develops this to give the price of heat, C_q, as

$$C_q = C_B(T - T_0)/T \qquad (4.2.13)$$

Borel uses equation 4.2.13 to show that heat costs are variable, depending on output temperature, whereas exergy cost is a fixed value. Heat cost is only the same as exergy cost at infinite temperature. This analysis also shows that heat is more valuable in winter, when T_0 is lower, than in summer.

Much other work has been done on exergy economics, which cannot be covered by this brief review. Two general works, however, are worth mentioning for their non-technical introduction to the subject: Ross (1978) or Gallagher (1979). Further references can be found in the articles reviewed here.

Resource allocation and entropy management

This subject is reviewed only very briefly. Its aim is to show how resources (energy, minerals, food, etc.) should be used to give maximum (thermodynamic) benefit.

In this category comes the work by Sorensen (1985a and 1985b), who plans energy systems based on satisfying a society's 'goals'. These goals are the basic energy requirements needed by various activities, such as biologically-acceptable surroundings (buildings, heating, etc.), food, health, commercial and social activities. Nine types of energy, from low temperature heat to electricity and shaft power, and including food, are used in different proportions to satisfy the goals.

Energy goals are converted into 'free energy' values (a simplified definition of exergy), by using the Carnot coefficient

$$F = D[(T - T_O)/T] \qquad (4.2.14)$$

Assessing the free energy, by the same process, of various renewable and non-renewable energy supplies, Sorensen shows how these can be used to satisfy goals, and therefore suggest which technologies should receive more investment.

Both Sorensen's references suffer from poor definition of 'free energy' (section 2.2 showed that eqn. 4.2.14 can only be used for fossil fuels with care). However, they do represent one of the first attempts to plan energy systems on exergy rather than energy principles.

Two further papers cover this subject: Berry et al (1973) and Tinnis (1981). The first uses 'free energy' (but without defining it or showing how it is calculated) to determine how much free energy is needed (in terms of that contained in the raw materials) to manufacture a car. The second, very specifically, indicates how processes can be improved by attempting to minimise entropy production.

Net energy analysis

This is covered only very briefly to complete the review of thermodynamic methods of system analysis. Net energy analysis calculates either how much energy is output from a system after the energy needed to build and run it has been accounted for, or the net exergy remaining after exergy needed to build and run the system has been subtracted. Good reviews of the techniques can be found in Thomas (1977) or IFIAS (1974), and examples of its application are found in Odum (1978) or Butera (1980).

4.2.4 METHODOLOGY AND EXAMPLES

The methods and equations for calculating exergy and energy quality are developed and discussed fully in section 2.2. Table 4.2.1 summarises the qualities of energy supplies and demands needed for the study of the island of Eigg.

Supply	Quality (%)	Demand	Quality (%)
Hydro electricity	100.0	Electricity	100.0
Wind electricity	100.0	Transport	100.0
Diesel fuel	70.8	Cooking (frying)	42.9
Propane gas	70.7	Cooking (boiling)	22.2
Coal	70.7	Hot water	18.4
Butane gas	70.6	Space heat	4.4
Kerosene	70.5		
Petrol	70.5		
Wood	67.4		
Solar heat	18.4		

Table 4.2.1 Thermodynamic quality of energy supplies and demands

Since energy quality is defined as exergy/energy, the exergy of an energy supply or demand can be calculated knowing the amount of energy and its quality.

Exergy diagrams

One type of diagram, originally used by Cook (ibid), is shown on figs. 4.2.1 and 4.2.2. These relate to the island of Eigg, with energy results coming from the energy survey (chapter 3) and exergy calculated by the equations of section 2.2. To compare exergy flows with their corresponding energy flows, fig. 4.2.1 should be studied in conjunction with fig. 4.2.2 (showing results for Eigg expressed in energy terms). Several conclusions can be drawn from these two diagrams:

1) The first law efficiency of the system is about 50%, whereas the second law value is only 19%. There is clearly a poor match, in exergy terms, between supply and demand.

2) Diesel and petrol conversions have low energy efficiencies, whereas they have the best exergy efficiency (except for hydro).

3) Gas, coal, wood and kerosene have high first law conversion efficiencies, but their exergy efficiencies are only about 10%.

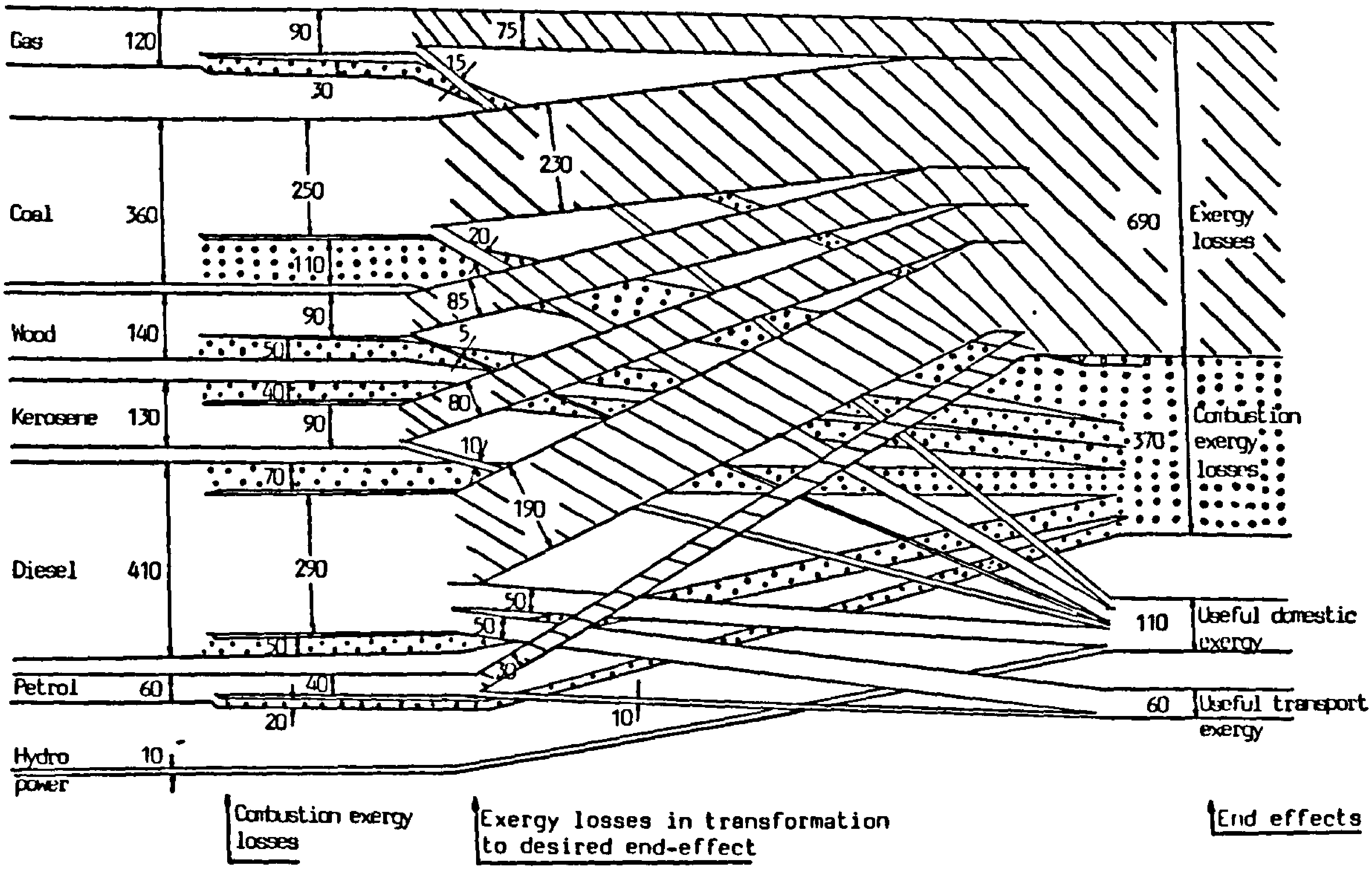


FIGURE 4.2.1 Annual Exergy Flows on the Island of Eigg Units: MWh/y

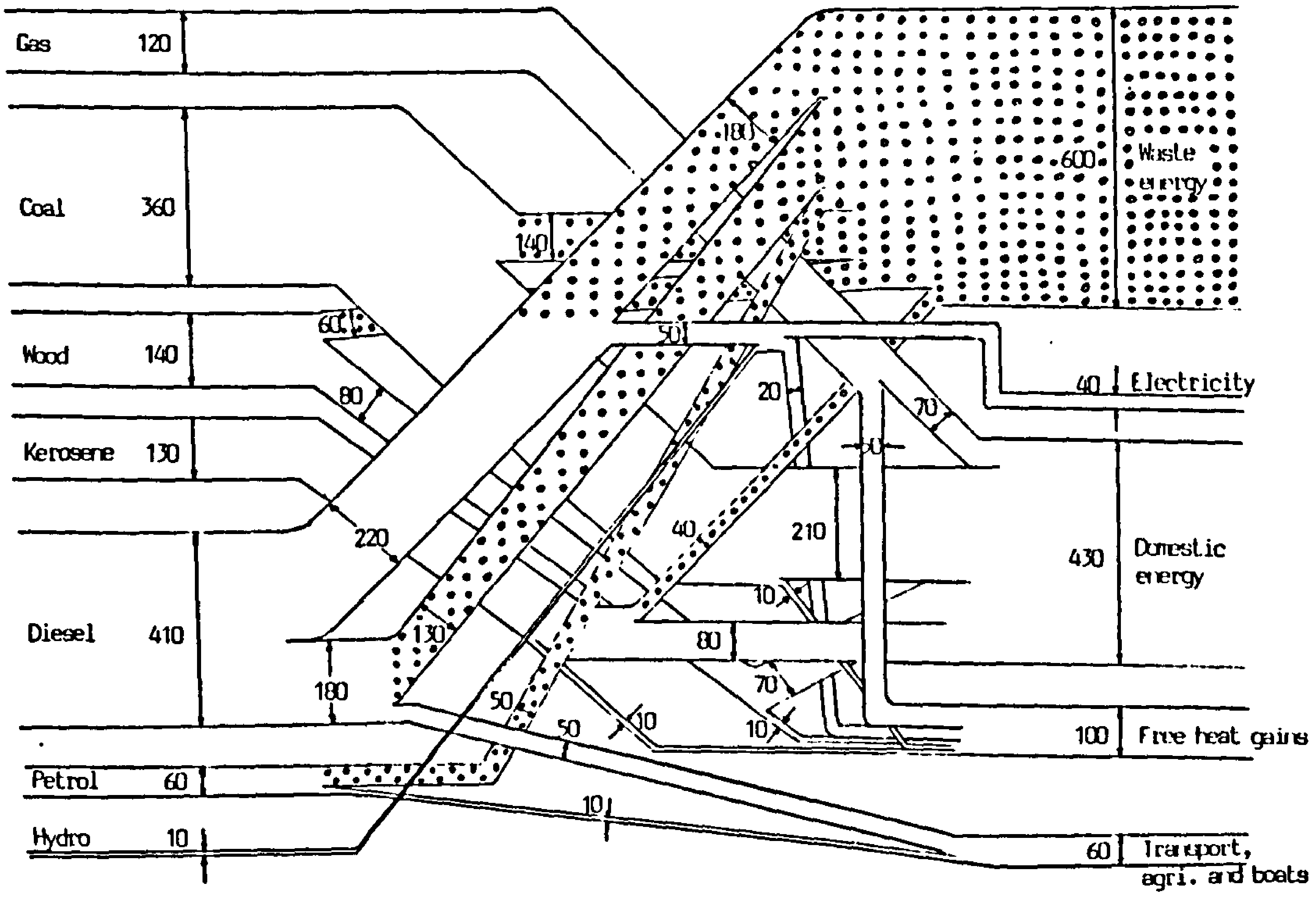


FIGURE 4.2.2 Annual Energy Flows on the Island of Eigg Units: MWh/y

This type of diagram, although undoubtedly useful, is time-consuming and difficult to draw. In addition, two diagrams (of exergy and energy) are required to make comparisons between first and second law efficiencies. Therefore another method for showing exergetic performance (from an original idea by Twidell (1983, personal communication)), which by a single diagram shows both exergy and energy efficiencies, is developed below.

Since energy quality is defined as exergy/energy, the area of a diagram of energy quantity against quality represents exergy. These diagrams can be used to show the primary conversion process for energy sources, discussed in section 2.2 (figure 4.2.3 shows propane combustion), or they can be used to show the conversion of energy from its initial form to its required end form (figures 4.2.4 and 4.2.5).

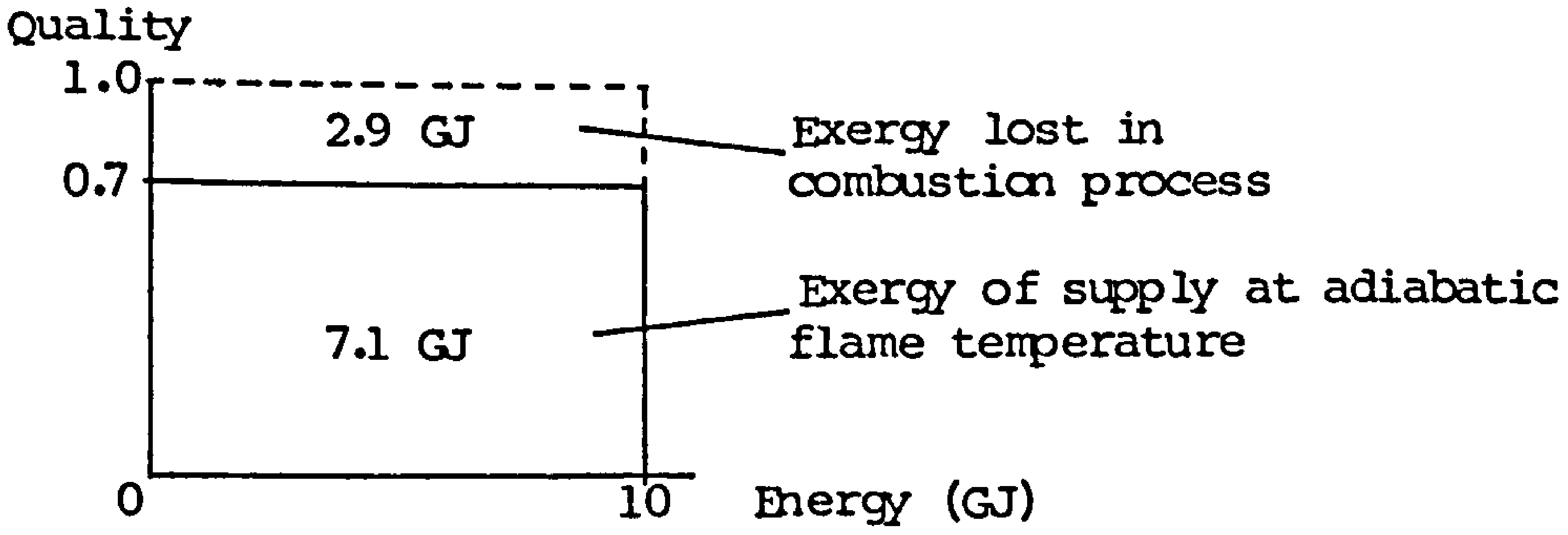


FIGURE 4.2.3 Exergy loss in combustion of propane gas

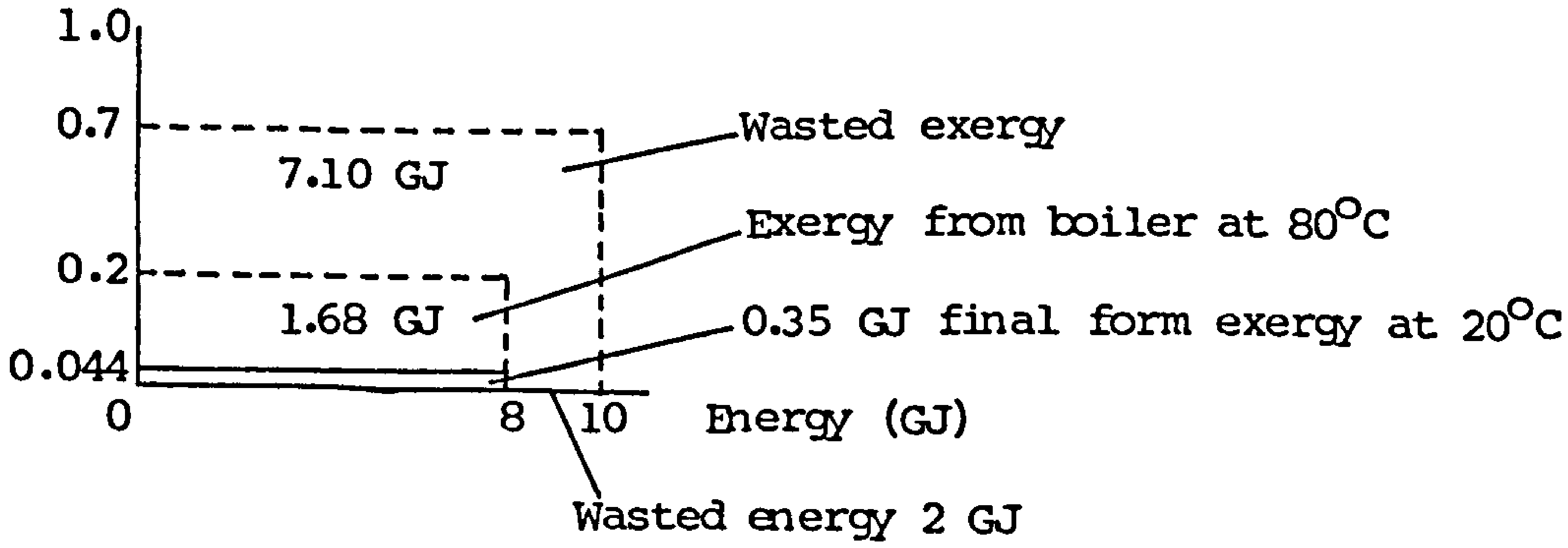


FIGURE 4.2.4 Exergy loss for boiler supplying space heat

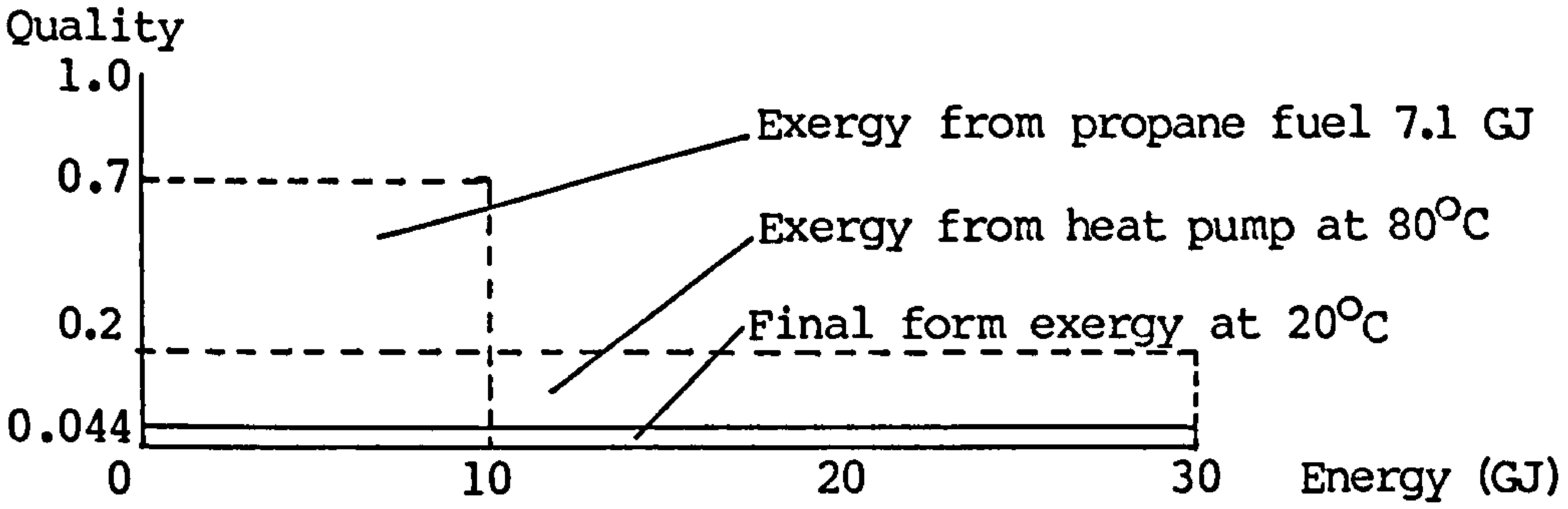


FIGURE 4.2.5 Exergy loss in ideal heat engine-driven heat pump supplying space heating

These diagrams have the advantage that they allow both first and second law efficiency values to be calculated. First law efficiency is determined from the x-axis, second law efficiency from the area (exergy) of the demand or end-form divided by the area of the supply. For example, first law efficiency for burning propane (fig. 4.2.3) is 100%, for a boiler (fig. 4.2.4) it is 80% (but note how first law values can exceed 100%: fig. 4.2.5 showing 340% for a heat pump). Second law values for these processes (efficiencies are determined using final-form energy, not output from the systems) are 71% for propane combustion, 5% for the boiler, and 23% for the heat pump.

Finally as an example of the use of these diagrams, they can be used to show exergy losses for the island of Eigg during the year of the survey (approximate figures only), figure 4.2.6. Several improvements to the energy system on Eigg are suggested by studying figure 4.2.6:

1) There is almost no high quality energy sources used to cover high quality energy demands. Hydro and wind turbines would improve this situation, and eliminate the energy inefficient low to high quality energy conversions currently needed.

2) High quality fossil fuels are currently used to supply low quality cooking and hot water demands. This would be improved by using lower initial quality wood fuel.

3) Better exergy efficiency could be achieved by using low quality solar energy to supply low quality space heating demands.

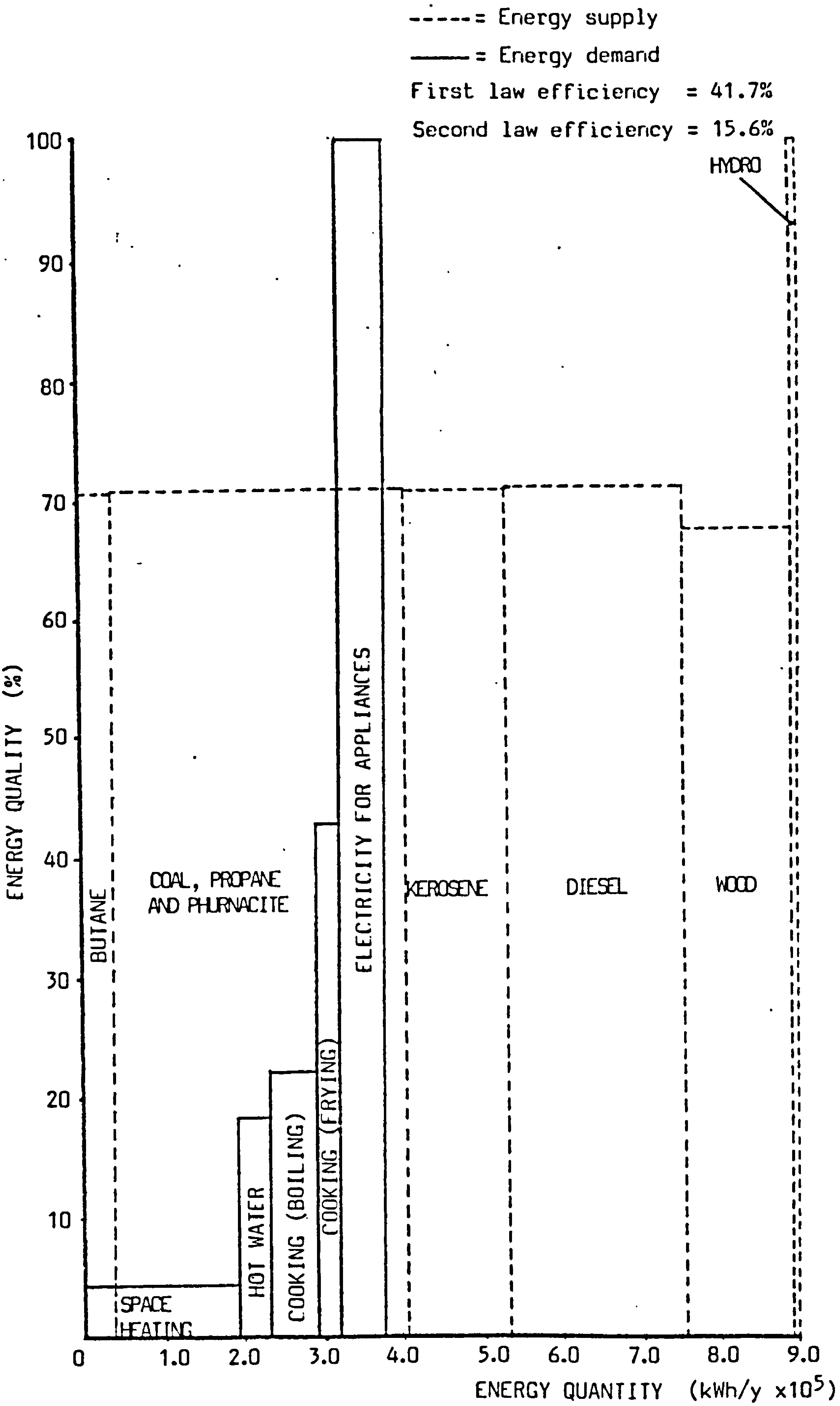


FIGURE 4.2.6 Energy Quality against Quantity Diagram for the Domestic Energy Supply Currently Used on Eigg

4.2.5 DISCUSSION

This section has shown how the methods of thermodynamic analysis, developed theoretically in section 2.2, can be used in a practical context to plan and improve energy systems.

The use of energy quantity against quality diagrams are shown to be a good way of visualising thermodynamic inefficiencies; better and easier to draw than the more popular exergy flow diagrams. They clearly highlight the two important points of thermodynamic theory, namely:

1) That when the quality of energy is increased (for example electricity generation), there are always large energy losses.

2) That if high quality supplies are used to supply low quality demands by a direct process, there are always high exergy losses.

The one disadvantage of such diagrams is that, unless drawn carefully, they do not show which energy source supplies which demand. However, despite this, they give far better insight into the processes and losses involved in energy conversions, and therefore they represent a better method for assessing thermodynamic performance, than simply calculating efficiencies without the use of diagrams.

CONCLUSIONS

This chapter developed two completely different methods of energy systems' analysis which can be used to study energy systems for small communities from entirely different viewpoints.

Section 4.1 described the computer-based economic assessment model developed for this project. The model calculates unit energy costs (£/kWh) for each type of energy supply, and uses these as the parameter by which to choose between different supplies. It's strategy is to use the cheapest supplies first, substituting for the most expensive non-renewable supplies with the cheapest renewables. This strategy was shown to always make the best possible use of equipment in a small community, and is a more rational method than those used by other energy modellers.

Section 4.2 described and discussed a diagramatical method for assessing the thermodynamic performance of the same energy systems analysed by the economic model. Using the concepts exergy and energy quality developed in section 2.2, the diagrams allow easy calculation of second law efficiency, the parameter by which thermodynamic performance is judged.

The development of the economic assessment model allows energy systems to be assessed and improved from what is currently the most widely-accepted viewpoint, that of system cost. Thermodynamic analysis of the same systems, on the other hand, represents a completely different method of systems' analysis, which could be used if the decision parameter was not cost but maximum use of the thermodynamic potential of energy resources.

Applying both assessment methods to the small island of Eigg (chapter 6) allows direct comparison of the two methods, with a view to determining whether attempts to maximise the use of thermodynamic potential leads to economic improvements, or vice-versa.

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CHAPTER 5 COMMUNITY ENERGY PLANNING MODEL INPUTS

Energy planning requires two types of data inputs: energy demands and available energy supplies. This chapter outlines ways of obtaining these for the small Scottish island of Eigg.

Section 5.1 describes how a typical meteorological year was chosen for the island. It also details methods for predicting daily mean wind speed from a yearly or monthly average, and hourly solar radiation and air temperature from mean daily values.

Section 5.2 describes a methodology for simulating river flows from small catchments, as a result of knowing daily rainfall. It shows how these flows can be used to determine hydro-electric power potential, including optimum turbine and supply pipe sizing.

Section 5.3 compares three different methods for obtaining hourly space heat demands for typical, rural or island houses, and applies the methods to a house on Eigg.

Section 5.4 shows how energy demand data were obtained for Eigg, using data from the energy survey of the island (chapter 3), results of house heat modelling (section 5.3) and electricity demand data from the small community of Abertridw in Wales. This section also summarises available energy sources on the island.

Section 5.1 Selection and Prediction of Meteorological Data for a Typical Year on the Island of Eigg

5.1.1 INTRODUCTION

Meteorological data are required for community energy planning for two reasons: to estimate renewable energy potentials and to determine domestic space heating demands, a function of both air temperature and solar radiation.

A year is the most suitable simulation period for the energy planning model (section 4.1), as met. conditions generally recur on a yearly basis, but a year must be chosen which is 'average' in its met. conditions, so that typical performances are determined.

An important condition regarding met. data is that they must be internally consistent: each of the important parameters, wind speed, air temperature and global radiation must correspond correctly to each other. To attempt to match together parameters measured at different places, and maybe at different times, leads to considerable inaccuracies (Met. Office, Edinburgh 1984, personal communication), and may unfairly bias the apparent performance of renewable supplies. Therefore the best way of obtaining consistent data is to record all parameters at the same place and at the same time.

The energy planning model was developed to be applicable to many other areas than Scotland. But when applied to other areas, particularly in the Third World, the nearest met. station might be several hundred kilometers away. However, during energy planning work, some measurements are likely to be made in the area being studied, even if these are only averages made over a day or longer. Therefore methods were developed to allow short-term data to be simulated from longer average values. Daily wind speed from mean monthly or yearly values, and hourly global solar radiation and air temperature from mean daily values can all be simulated using the methods of this section.

Since only the minimum of data is assumed to be available, all the methods in this section are kept as simple as possible. This simplicity has to be balanced against accuracy when using the methods to generate data for energy planning.

5.1.2 SYMBOLS AND UNITS

Symbol	Description	Units
A	Integer variable	-
C	Probability coefficient	-
D_m	Number of days in a month	days/month
D(v)	Number of days in bin of wind speed v	days
F(v)	Probability of wind speed <= v	s/m
H	Hour of the day	-
N	Day of the year	-
P_y	Yearly sum of wind speed cubed	m^3/s^3
T	Air temperature	K
a	Solar radiation coefficient	-
b	Solar radiation coefficient	-
c	Shape parameter	m/s
f(v)	Probability of wind speed having value v	s/m
f(n)	Probability of wind speed being in 'bin' n	-
k	Weibull shape parameter	-
n	Number of bins each side of current value	-
r	Ratio of hourly solar radiation to daily total	-
t	Time step or increment	day, rad or -
v	Wind speed	m/s
$\overline{v}$	Mean wind speed	m/s
δ	Declination of sun at solar noon	o
Ø	Site latitude	o
Φ	Mean hourly global solar radiation rate	W/m^s
Φ_t	Daily total global solar radiation	Wh/m^2day
π	Constant	-
Γ	Gamma function	-
ω	Hour angle	o
ω_s	Sunset hour angle	o

Suffices

c	Current value
d	Daily value
h	Hour h
max	Maximum
min	Minimum
n	Number of 'bins' away from current value
p	Predicted value
s	Number of days remaining in month

5.1.3 SELECTION OF A 'TYPICAL' YEAR FOR THE ISLAND OF EIGG

With the exception of rainfall, and wind speed during February to October 1985, no meteorological data are recorded on the island of Eigg. There are recorded, however: maximum and minimum daily air temperatures on the nearby island of Rhum (6 km north of Eigg), hourly wind speed on the island of Tiree (50 km to the south-west, but separated from Eigg by sea only), and hourly total solar radiation at Dunstaphnage near Oban (about 65 km south east, on the Scottish mainland). These sites are considered near enough to Eigg to assume that their average data can represent Eigg's values.

However the climate can vary significantly between Scottish islands, even those close to each other (Rhum has about twice the annual rainfall of Eigg). For example a windy (hence cool) day on Tiree might coincide with a clear, warm day on Rhum, but with low global radiation recorded near Oban. There is clearly a mis-match between these parameters. The difference between local terrains is also an important factor: Tiree is very flat and open, whereas Rhum is very mountainous, and this also affects the measured parameters. It is therefore assumed that only monthly mean values from the different sites relate to Eigg, since short-term mis-matches are smoothed out, and because longer-term average met. parameters are likely to be better matched than short term ones; the area covered by all sites being only about 5500 km^2, much of which is open sea.

To ensure that the energy modelling does not either unfairly favour or disfavour renewable energies, it is important to choose a year which is 'typical' in terms of its met. data. Long term monthly averages, covering at least 10 years, were available for the four sites (Eigg, Tiree, Rhum and Oban), and these were used to determine the 10-year average daily values for each month of the 'typical' year on Eigg shown on table 5.1.1 overleaf.

Month	Temperature ^{o}C	Global Radiation W/m^2	Wind speed m/s	Rainfall $m x 10^{-3}$
January	4.4	19.0	10.1	4.45
February	4.3	43.3	8.9	3.50
March	6.1	87.5	8.7	3.16
April	7.6	155.2	6.6	3.20
May	10.1	198.8	6.5	2.55
June	12.5	206.7	6.2	3.33
July	13.6	180.2	6.0	4.16
August	13.7	150.7	5.7	4.10
September	12.4	93.2	8.0	5.60
October	10.2	53.7	9.0	6.06
November	6.9	23.3	8.9	5.03
December	5.5	14.0	9.4	5.42

Table 5.1.1 Daily mean meteorological data from 10-year averages for the island of Eigg

For work on house heat demand modelling work (section 5.3) a computer based simulation model (ESP) was used. This has in its data bases at least 15 years of hourly data recorded at met. stations at Lerwick in Shetland, and Eskdalemuir in south-central Scotland. Therefore an obvious way to obtain consistent hourly data was to choose data from these sites which corresponded as closely as possible to the data assumed to apply to Eigg. Although the two sites are a considerable distance from Eigg, the main advantage of using their data was that since all parameters were recorded at the same place and time, they all correspond to each other in the correct way.

Monthly average values (similar to those on table 5.1.1) were obtained for each month between 1976 and 1980 from both Lerwick and Eskdalemuir. These averages were compared with those assumed for Eigg, and the best fitting months were selected to make up a complete year. The daily mean values for each month of the derived year on Eigg are shown on table 5.1.2 overleaf. Rainfall data were obtained from Eigg itself, from the period April 1982 to March 1983. This was chosen because the data could be used as a check for the hydrological model described in section 5.2.

Month	Temperature ^{o}C	Global Radiation W/m^2	Wind speed m/s	Rainfall $mx10^{-3}$
January	5.5	6.2	9.4	6.62
February	4.2	37.0	9.1	1.90
March	6.8	102.1	8.7	5.50
April	8.6	156.2	4.4	2.21
May	7.5	259.9	6.2	2.52
June	11.9	210.4	4.3	1.16
July	11.4	175.1	6.0	1.65
August	11.4	175.1	6.0	6.40
September	11.0	112.0	6.4	8.02
October	8.6	39.4	8.9	3.79
November	8.6	39.4	8.9	8.97
December	4.0	9.0	9.9	6.04

Table 5.1.2 Daily mean met. data for 'typical' year on Eigg

Of the parameters above, the most important to match accurately is wind speed because wind power potential is a function of wind speed cubed, whereas solar power and house heat loss are both linear functions of global radiation and temperature. Therefore a bias was made towards wind speed when choosing representative months.

One problem of using data taken from different months is that of continuity at the end of each month. This was checked, and only small discontinuities (about 2°C in temperature) were found. These, though, have little effect on overall results.

Only one of the above parameters was testable by direct measurement. A logging anemometer was installed on the island which recorded the wind speed distribution. An example of results from the island, with the distribution for the same period of wind speed from the 'typical' year's data is shown on figure 5.1.1. There is poor agreement between the two, possibly because the anemometer's position (fig. 3.1) is sheltered from winds from the north and east. Fig. 5.1.2 compares recorded data and assumed data, with wind speeds from the latter modified to simulate the sheltering effects. Better agreement is noticed, particularly in the power-generating range (greater than 4 m/s), but again this neither verifies or disputes the assumed values.

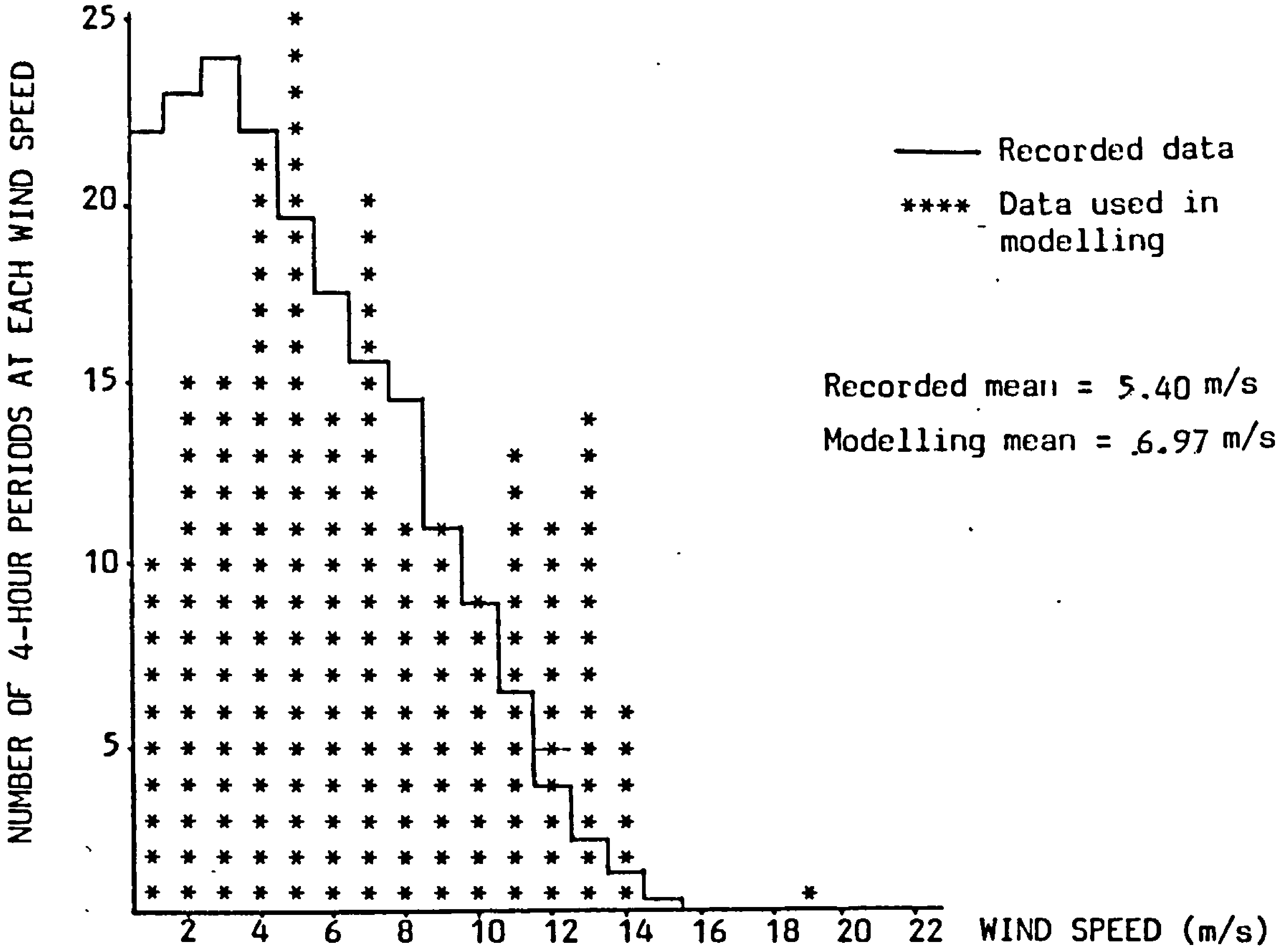


FIGURE 5.1.1 Comparison of Wind Speed Recorded on Eigg and that used in Modelling: 15th March - 15th April

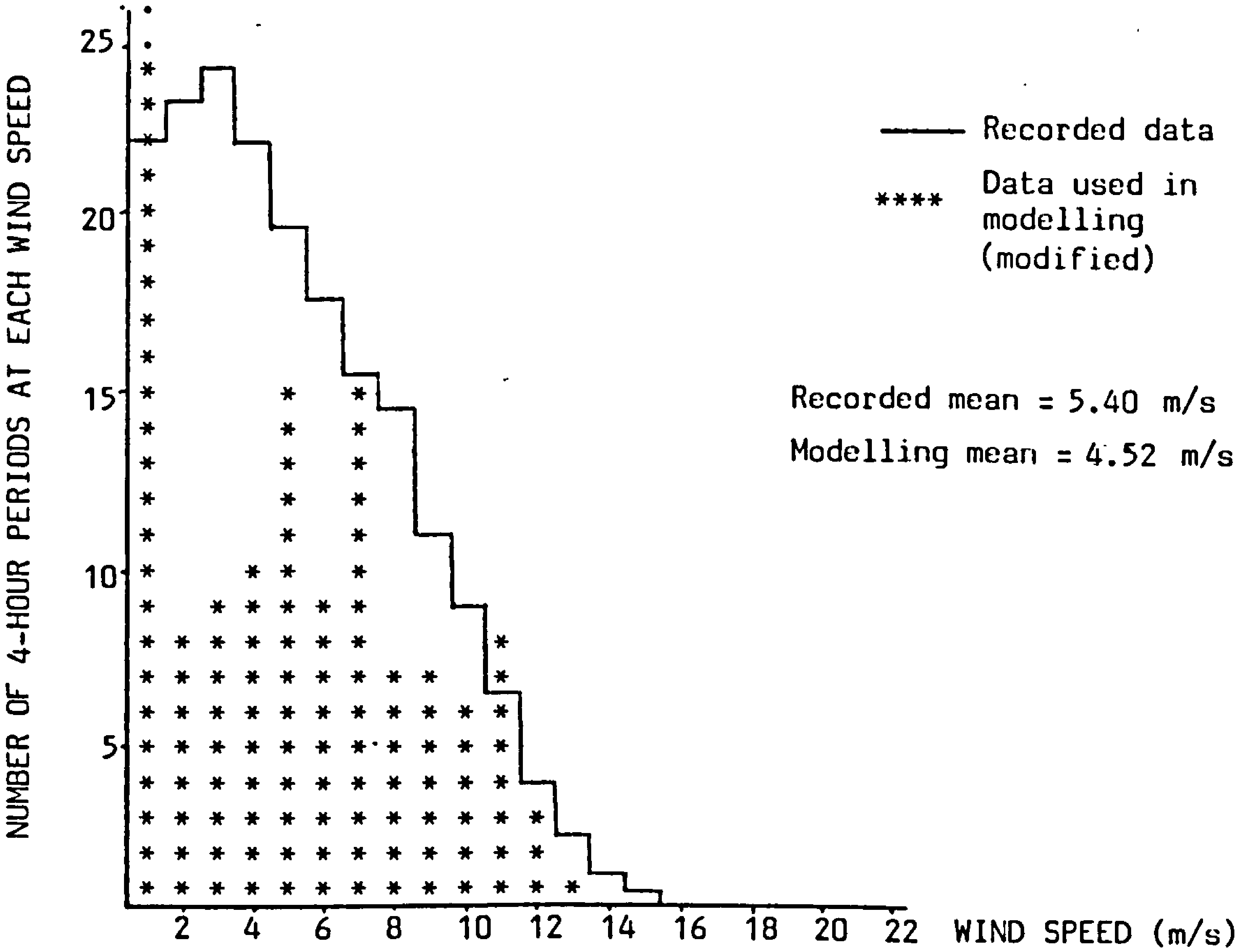


FIGURE 5.1.2 As Fig 5.1.1 but with Recorded Wind Speed Modified to Allow for Sheltering Effects on Anemometer

5.1.4 TWO METHODS FOR SIMULATING DAILY MEAN WIND SPEED FROM AVERAGE MONTHLY OR YEARLY VALUES

5.1.4a Literature review

Methods for simulating or predicting wind speed fall roughly into two groups: those which assume a probability distribution function and fit wind speeds to it, and those which use stochastic methods whereby the current wind speed is determined knowing the previous history of the wind. One other method was found, whereby wind speed at a particular site is simulated knowing only occasional values from that site, but detailed values from other, surrounding sites.

Distribution Methods

A review of some of the distribution methods is given by Elgammal (1982), but a brief review follows here. A distribution often used (Hennessey 1977) is the Wiebull probability density function:

$$f(v) = (k/c)(v/c)^{k-1}\exp-(v/c)^k \qquad (5.1.1)$$

where $f(v)$ = probability of wind speed being v m/s,
k = Weibull shape parameter
and c = shape parameter.

The cumulative probability function (probability of wind speed > v) comes from integrating eqn. 5.1.1 between v_{max} and v, as

$$F(v) = \exp-(v/c)^k \qquad (5.1.2)$$

and this can be used to predict the distribution once c and k have been determined. The shape parameters can be obtained by several methods, for example Bowden et al (1983) and Justus et al (1976).

Other distributions have been proposed to fit wind speed, of which those suggested by Widger (1976) and Olsson et al (1975) have been shown to be reasonable.

Stochastic methods

Only a very brief outline of these methods is given, as they often involve complex mathematical expressions. The references give more detailed descriptions.

Among others, Bardsley (1980), Hennessey (ibid) and Luna & Church (1974) have attempted to use Monte Carlo methods for fitting distributions to wind speed. The problems with such methods (as also for all the previously mentioned distribution methods) are that they do not account for diurnal variation when estimating hourly wind speeds or, more importantly, for the persistence of wind speed. Halliday (1983) shows that for sites in Britain there are long runs (up to 12.2 days) of 'calms' (wind speeds below 5.0 m/s) and long runs (up to 1.5 days) of wind speeds consistently above 16 m/s. These are generally not represented in simulated results, although Sigl et al (1979) developed a method for predicting them. Because wind power is a function of wind speed cubed, failure to account for them leads to an under-estimation of energy available (Elgammal (ibid) presents results for several distributional methods, showing how these, in general, give lower potential energy values than the corresponding recorded data). Some studies, among which are Chou & Chorotis (1981) and Goh & Nathan (1979) have incorporated persistence in their models.

Finally for methods of simulating wind speeds, Barros & Rodriquez Sero (1982) suggest a method whereby weekly average values for a year at a particular site can be estimated. This requires recordings over 2 to 3 months at the site itself, and detailed data over the whole year from other sites. The method they propose is complicated, and no attempt is made to describe it here. However, using data from ten stations spread over a very large area of east and mid-west USA they predict weekly mean values over a year to within about +/-10% of recorded data at a site for which only 13 weeks data were assumed to be available. They speculate that the method could be improved to cover other areas of the world, and to give 48 hour or 24 hour predictions, but as yet this has not been tested.

5.1.4b Description of simulation methods

Both methods presented here were deliberately developed to require the minimum of data inputs. The second method needs only the yearly mean wind speed or monthly mean wind speed, while the first method needs in addition the Weibull parameter k.

If the input is yearly mean wind speed, both methods assume a sinusoidal variation of monthly means about the yearly value, with the amplitude set by the user. Figure 5.1.3 compares the monthly values from data for the island of Eigg (section 5.1.3) with those calculated by the sinusoidal method, assuming the same yearly mean value as the recorded data. Approximate agreement only is observed, showing that this is a limiting assumption.

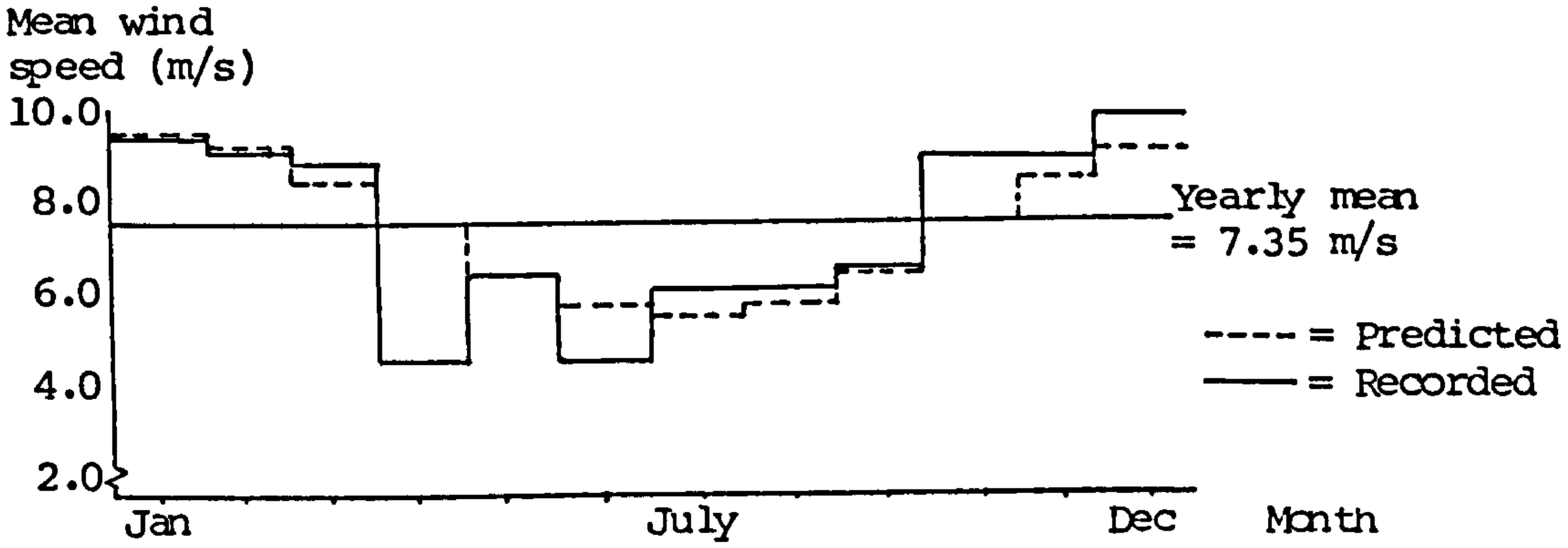


FIGURE 5.1.3 Comparison of Predicted and Recorded Monthly Mean Wind Speed for the 'Typical' Year on Eigg

Both methods predict wind speeds in 'bins' of 1 m/s width each. So, for example, bin 2 represents a value between 1 m/s and 2 m/s. They were developed for use on an Apple II micro computer, but could be used on any machine with a random number generator. The Apple II function "RANDOM MOD (A + 1)" gives a psuedo-random integer between 1 and A.

Method 1

Many researchers have used the Weibull distribution as an approximation of the wind speed distribution over a sufficiently long period (see Literature Review above). Results from the Netherlands

(Wieringa & Rijkoort 1983 and Vermeulen et al 1984) suggest values for the Weibull shape parameter k of:

$k = 2.20$ at sea
$k = 1.95$ inland at over 10m above ground, and on the coast
$k = 1.75$ inland at heights less than 10m above ground

It is inaccurate to assume that these values can be applied universally, but determining more accurate ones would require more data than are assumed to be available. For Eigg a value of $k = 2.0$ is assumed, as a compromise between the sea value and the coastline value.

With $k = 2.0$, the Weibull probability density function reduces to the Rayleigh distribution (Cliff (1977) shows this is reasonable for mean wind speeds greater than 4.7m/s). The mean wind speed is therefore

$$\bar{v} = c\Gamma((1/k) + 1) \qquad (5.1.3)$$

where Γ, the gamma function, is

$$\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}dt \qquad (5.1.4)$$

where t = step or time increment.

When the Weibull distribution is reduced to the Rayleigh function, the gamma function is

$$\Gamma((1/2) + 1) = \sqrt{\pi}/2 \qquad (5.1.5)$$

which substituted in equation 5.1.3 gives the shape parameter c as

$$c = 2\bar{v}/\sqrt{\pi} \qquad (5.1.6)$$

Let D_m be the number of days in a month. The method calculates the probability of each wind speed v from 1 m/s to 25 m/s using the values of c and k above in equation 5.1.1. These probabilities are translated into the number of days in each wind speed 'bin' as

$$D(v) = \text{integer}(f(v)D_m) \qquad (5.1.7)$$

Following this, it is assumed that the probability of the wind speed on any day being in a particular bin, f(v) is given by

$$f(v) = D(v,s)/D_{m,s} \qquad (5.1.8)$$

where $D(v,s)$ = number of days left in bin v,
and $D_{m,s}$ = number of days left to predict in the month.

After each step, one day is removed from the bin in which the predicted value falls, and one day from the days remaining in the month. The total probability for all bins is therefore always

$$\sum_{v=1}^{25} f(v) = 1.0 \qquad (5.1.9)$$

To compare probabilities with the random numbers generated by the computer at each step (ie each day), equation 5.1.9 is multiplied by 1000, and integer values taken, so that

$$\sum_{v=1}^{25} \text{integer}(1000f(v)) = 1000 \qquad (5.1.10)$$

Figure 5.1.4 shows a typical cumulative probability distribution after several days have been predicted. The computer generates a random number between 1 and 1000. A value between 30 and 88, say, represents bin 5 (hence wind speed between 4 m/s and 5 m/s), and this becomes the predicted value. Note that the equal probabilities for bins 9 and 10 on figure 5.1.4 implies no days left in bin 10. A bin with no days left cannot be chosen, so if a random number corresponding to bin 10 occurs, the predicted value would be bin 9.

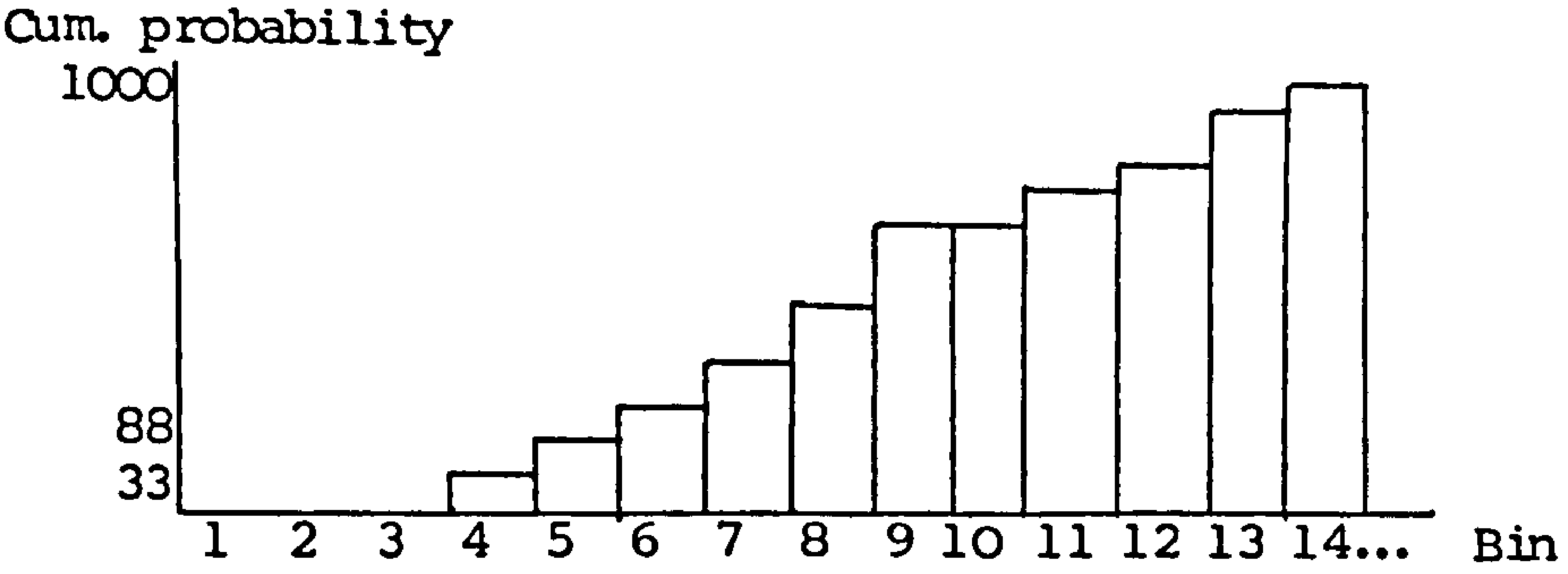


FIGURE 5.1.4 Cumulative probability distribution of wind speeds

Since this method "forces" the values in any month to fit the Rayleigh distribution, there will only be one bin on the last day of each month into which the predicted value can go. However, this value, and all others during the month, depends on the sequence in which the other bins have been filled, so individual daily values are still psuedo-random.

Method 2

This method assumes that the probability of the wind speed moving from its current value to the next value falls proportionately with the size of the jump. No attempt is made to fit the values to a distribution, but the method is such that the mean, at the end of a month, is close to the actual monthly mean.

The probabilities of "jumping" to the next value has the general form, assuming the current value to be bin 9 (8 m/s to 9 m/s), shown on figure 5.1.5. The number of allowable jumps either side of the current value is set by the user at the beginning of a simulation.

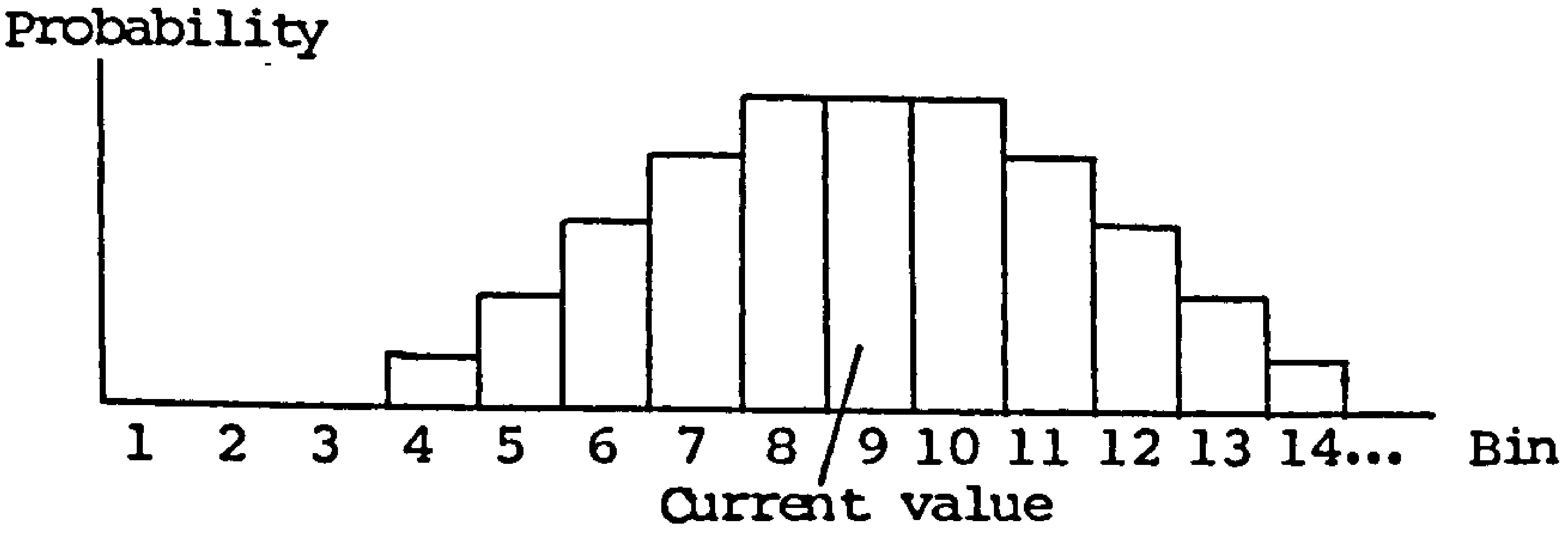


FIGURE 5.1.5 Probability Distribution for Method 2

The total probability for all bins is always 1.0. The probability of jumping to any box is calculated by the following method, where v_c is the current value, and N the number of allowable jumps either side of v_c. The probability coefficient C_c for the current value is set to 1.0. The coefficient of a bin n jumps away from the current bin is given by

$$C_n = 1 - (n - 1)/N \qquad (5.1.11)$$

The coefficients are summed for all bins, and each coefficient divided by the sum to ensure that the total probability is 1.0. Thus

$$f(n) = (1 - (n - 1)/N)/(2\sum_{n=1}^{25}(1 - (n - 1)/N) + 1) \qquad (5.1.12)$$

The same procedure as for method 1 is used so that the random number determines the new value of wind speed. Once this is determined, the probability pyramid of fig. 5.1.5 is recentralised over this value, and equation 5.1.12 recalculated. However, if the new current value is such that the pyramid shape goes outside the allowable range (see figure 5.1.6), the out-of-range bins are ignored, a new total area calculated, and another cumulative probability distribution similar to fig. 5.1.4 (but with fewer bins) obtained. The total area is always 1000, and probabilities set accordingly.

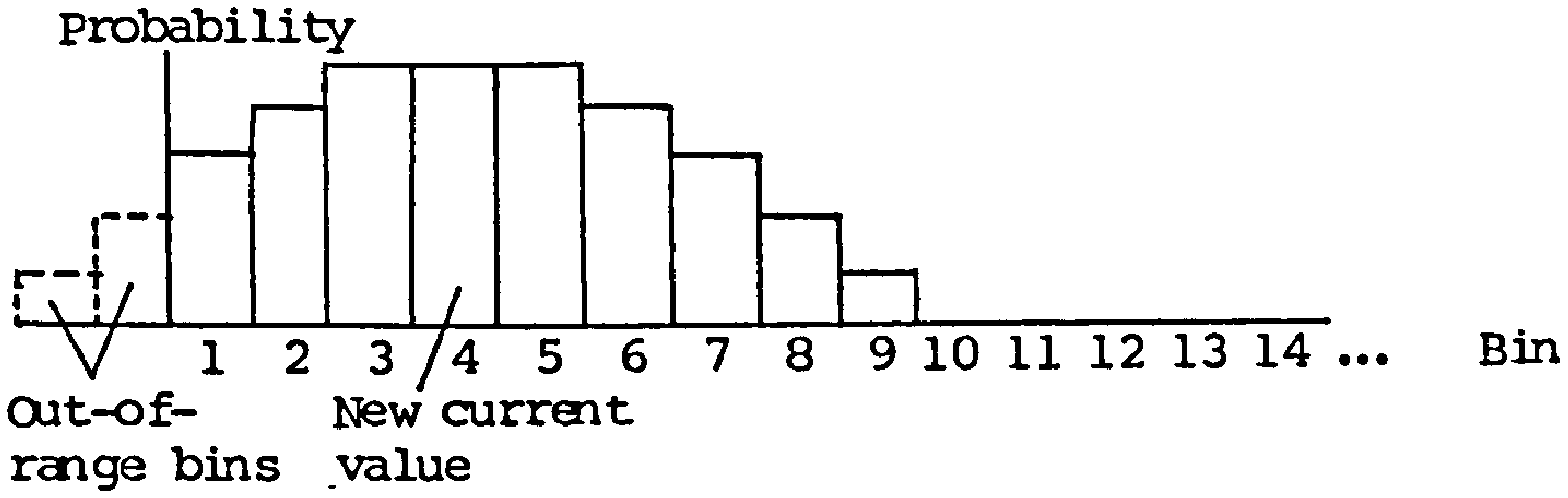


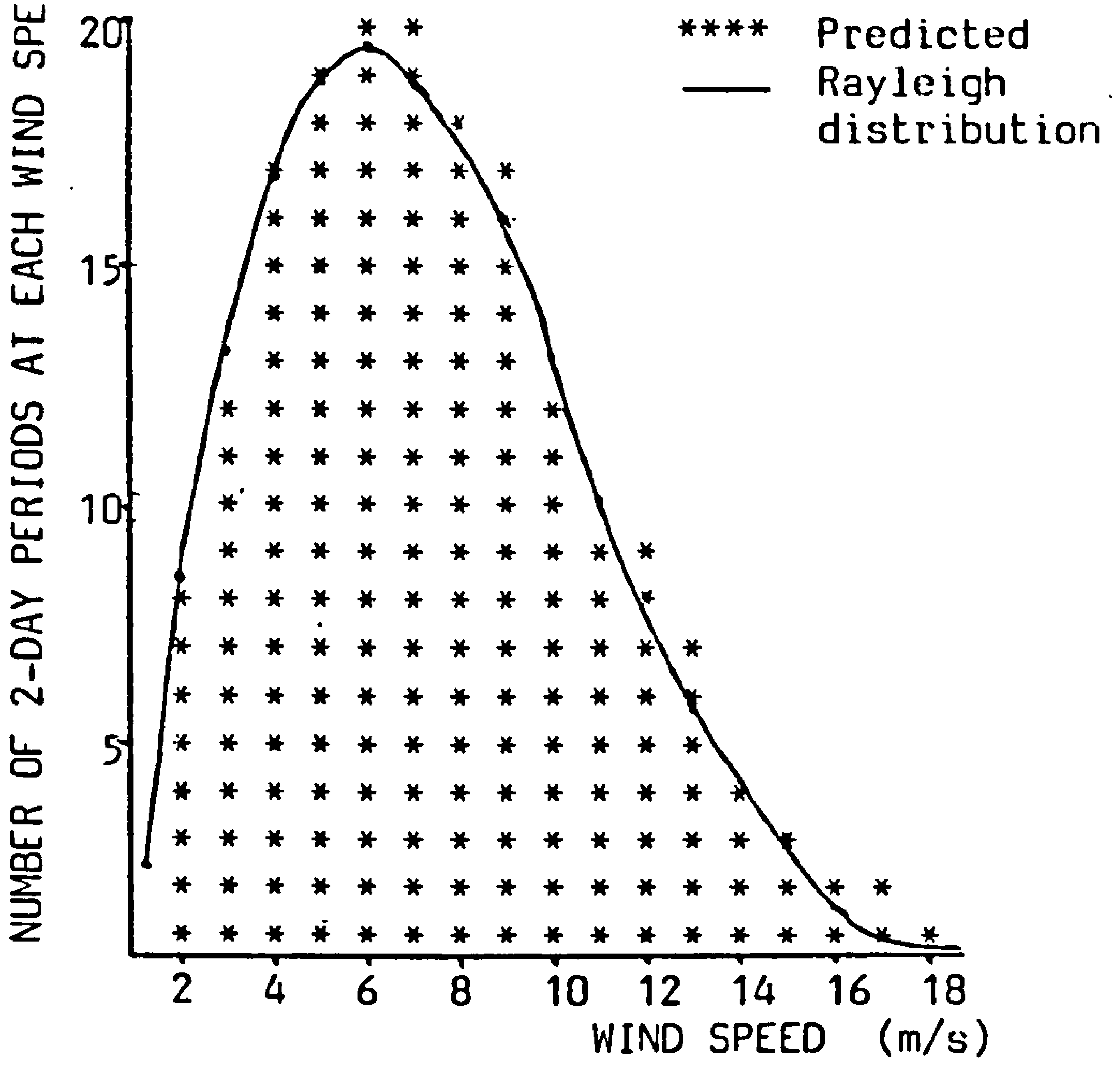
FIGURE 5.1.6 Re-centralised Probability Distribution showing Out-of-range Bins

Because of the nature of this method, it tends to predict values with a monthly mean approximating to the actual mean. Wide excursions from the mean are unlikely, as they could only arise through successive unlikely jumps. However, each run of this method gives a slightly different distribution.

5.1.4c Comparison of simulated and recorded data

The data inputs to both methods were the same monthly means as those for the island of Eigg (table 5.1.2). Figures 5.1.7 and 5.1.8 overleaf respectively compare the simulated results from methods 1 and 2 with the Rayleigh distribution for the same annual mean wind speed. Method 1 follows the Rayleigh distribution almost exactly, whereas method 2 gives a less spread-out distribution centered around the mean.

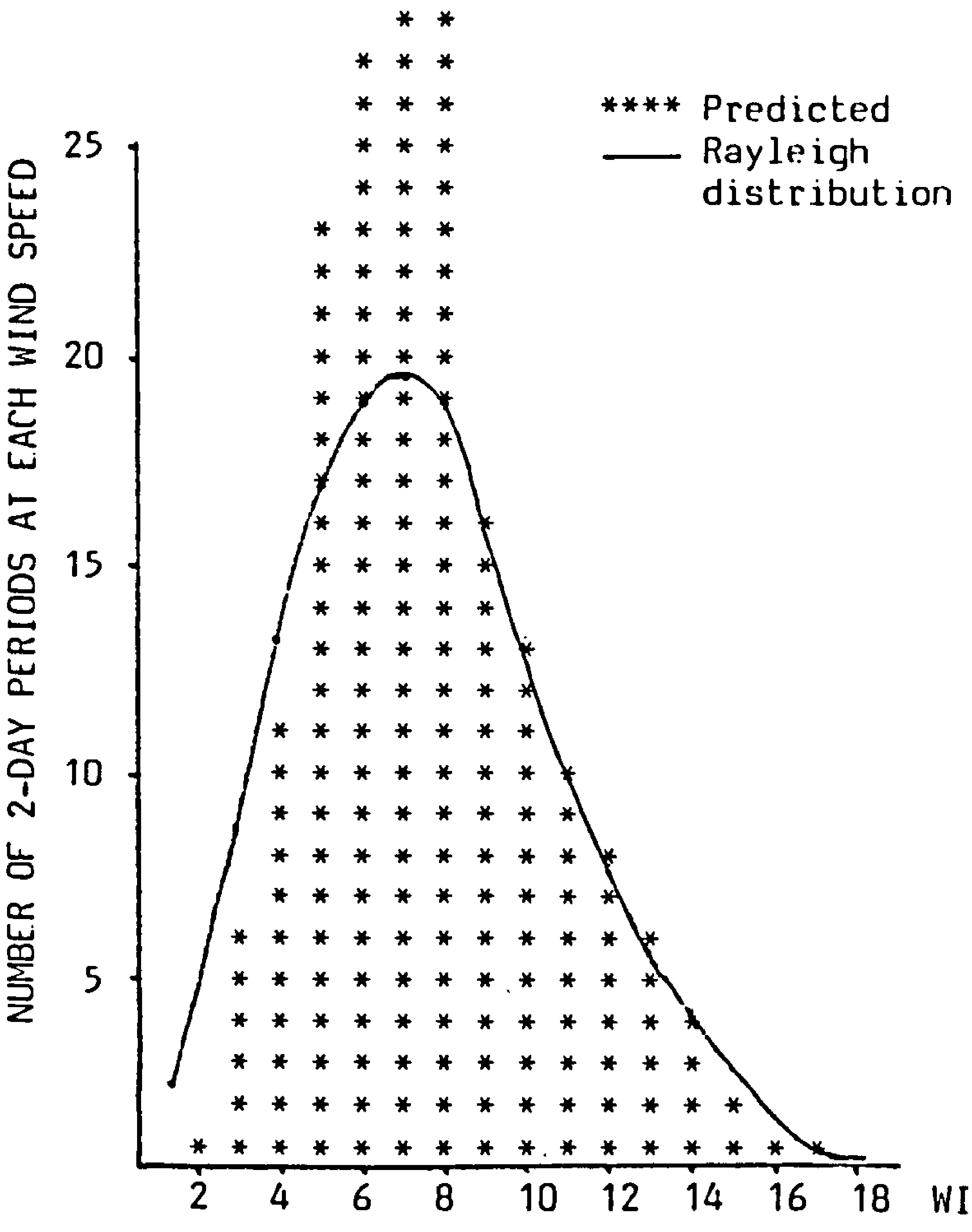
Method 1 has almost no significant autocorrelation (values above about 0.2 show positive correlation), meaning that each predicted value is independent of all previous values. Method 2 shows some positive correlation, implying that there is some persistence.



Autocorrelation

Lag (K) (days)	Autocor. at lag K
1	0.1076
2	0.1313
3	0.1352
4	0.0606
5	0.1208
6	0.0597
7	0.1486
8	0.1641
9	0.0930
10	0.1112
11	0.0933
12	0.2292
13	0.0960
14	0.0453
15	0.1087
16	0.1505
17	0.1285
18	0.1226

FIGURE 5.1.7 Comparison between Predicted Results from Method 1 and the Rayleigh Distribution with the same Yearly Mean Wind Speed, 7.35 m/s



WIND SPEED (m/s)

Autocorrelation

Lag (K) (days)	Autocor. at lag K
1	0.2407
2	0.1442
3	0.1552
4	0.2611
5	0.2059
6	0.1736
7	0.2551
8	0.2885
9	0.1201
10	0.1860
11	0.1691
12	0.2748
13	0.2062
14	0.2107
15	0.1820
16	0.1727
17	0.1558
18	0.1921
19	0.2280

FIGURE 5.1.8 As Fig 5.1.7 but with Predicted Results from Method 2

Figure 5.1.9 compares both simulation methods with the actual distribution obtained from the hourly data for Eigg. There is reasonable agreement, more so for method 1 than for method 2, between the real and the simulated distributions. More important, though, is to compare the available energy figures resulting from the simulated and the real results (from the 'typical' year). These were obtained by

$$P_y = 24\sum_{d=1}^{365} v_d{}^3 \qquad (5.1.13)$$

where 24 = number of hours per day.

The values of v_d in equation 5.1.13 are the average of each bin (ie bin 2 has an average of 1.5 m/s). The results are:

Method 1	$= 5.88 \times 10^6\ m^3/s^3$
Method 2	$= 4.88 \times 10^6\ m^3/s^3$
Real (recorded) daily data	$= 6.24 \times 10^6\ m^3/s^3$
Real (recorded) hourly data	$= 7.27 \times 10^6\ m^3/s^3$

As expected, since method 2 does not predict high wind speeds often enough, its energy estimates are well below the true values. Method 1, however, agrees to within 6% of the energy potential using real daily data (Because of the discretisation of days by the method - such that windspeeds with a probability of less than 0.5 s/m are not predicted - method 1 does not predict high wind speeds either). But equally significant is the error between daily mean and hourly mean real data, the former underestimating the true potential by almost 15%.

It is concluded that care must be taken when modelling to account for errors between using mean daily and hourly real data, as these can be significant.

Suggestions have been made for improvements to method 2. These mainly involve testing real data to obtain a more likely probability distribution than that assumed. Both methods should also be tested by comparing their autocorrelation function with typical autocorrelations from real data. Lack of time has prevented these improvements being made as yet.

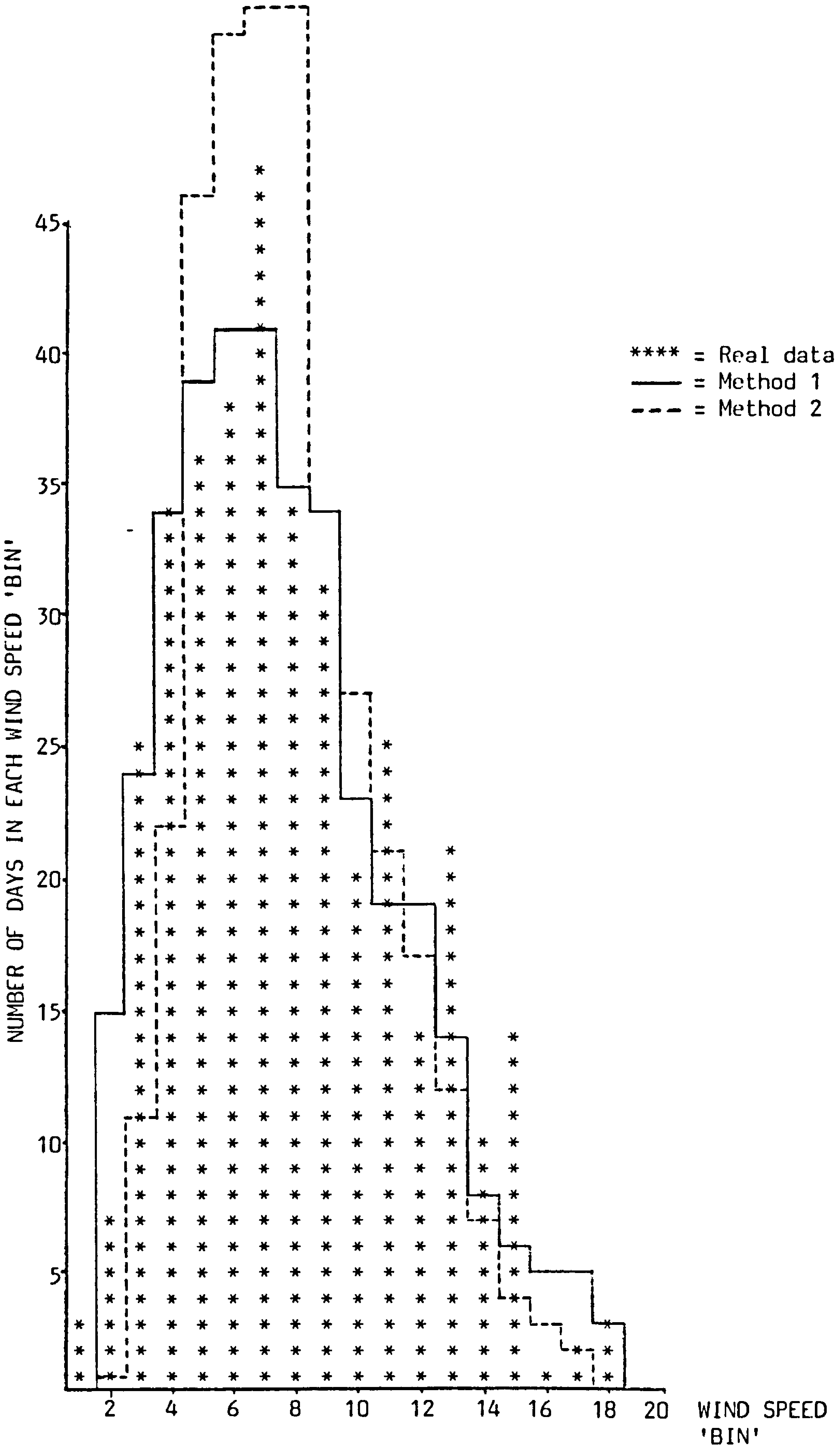


FIGURE 5.1.9 Comparison of Real Wind Speed for the 'Typical' Year on Eigg with Simulated Results from Methods 1 and 2

5.1.5 SIMULATION OF HOURLY GLOBAL SOLAR RADIATION AND AIR TEMPERATURE FROM DAILY MEAN VALUES

Solar Radiation

Daily mean global radiation data are easier and cheaper to collect than hourly values, and daily data collection is more likely to be found in Third World countries. Therefore a method, proposed by Duffie & Beckman (1980) is presented here, for predicting hourly values from daily means. This method requires knowing only the latitude of the site, and the daily mean (or daily total) global radiation.

The declination δ, the angular position of the sun at solar noon with respect to the plane of the equator (north positive) is

$$\delta = 23.4\sin(360(284 + N)/365) \qquad (5.1.14)$$

where N = day of the year, 1st January = day 1.

The sunset hour angle ω_s is then calculated using

$$\cos\omega_s = -\tan\delta\tan\phi \qquad (5.1.15)$$

where ϕ = latitude of site, north positive.

The hour angle (the angular displacement of the sun east or west of the local meridian owing to rotation of the earth on its axis at 15^o per hour), is given by

$$\omega = -15^o(12 - H) \qquad (5.1.16)$$

where H = hour of day.

If the ratio of hourly global radiation to daily total is r_h, this can be calculated from the above equations as

$$r_h = (\pi/24)(a+b\cos\omega)[(\cos\omega-\cos\omega_s)/(\sin\omega_s-(2\pi\omega_s/360)\cos\omega_s)] \qquad (5.1.17)$$

where the coefficients a and b are given by

$$a = 0.4090 + 0.5016\sin(\omega_s - 60) \qquad (5.1.18)$$
$$b = 0.6609 - 0.4767\sin(\omega_s - 60) \qquad (5.1.19)$$

Finally if the daily total radiation $\Phi_t = 24\Phi_d$, where Φ_d is the daily mean rate, the hourly rate of global radiation is:

$$\Phi_h = \Phi_t r_h \qquad (5.1.20)$$

Air Temperature

Two methods are possible for simulating hourly air temperature from daily values: the first requiring the daily maximum and minimum temperatures, the second needing only the daily average. The second method, however, requires an estimate of the likely amplitude of daily variation, so is probably less accurate. Therefore the first method was the one chosen.

Knowing the maximum and minimum daily temperature, a simple sinusoidal variation is assumed, with the maximum occurring at 3 p.m., the minimum at 3 a.m. Thus the value at any hour is

$$T_h = [(T_{max} + T_{min})/2] - [(T_{max} - T_{min})/2]\cos(t - \pi/4) \qquad (5.1.21)$$

where t = time in radians, 00 00 hrs = 0 rad, 24 00 rad = 2π rad.

(For the second method, the amplitude would be quessed, and T_{max} and T_{min} calculated from the daily mean and amplitude)

Figures 5.1.10 and 5.1.11 overleaf compare results from the radiation prediction method on a typical low radiation day (4th March) and a typical high radiation day (25th July) and the temperature prediction method on a low temperature day (8th January) and a high temperature day (25th July) with the recorded data for the island of Eigg. Quite good agreement is seen for both days of the radiation prediction and the temperature prediction methods.

5.1.6 DISCUSSION

The purpose of the energy modelling work in this thesis is to determine a methodology for planning, rather than to accurately model a particular community. However, the island of Eigg was chosen as an example of a small community on which the planning strategy could be tested, so it was important that meteorological data used in the modelling were accurate enough to ensure that results were credible.

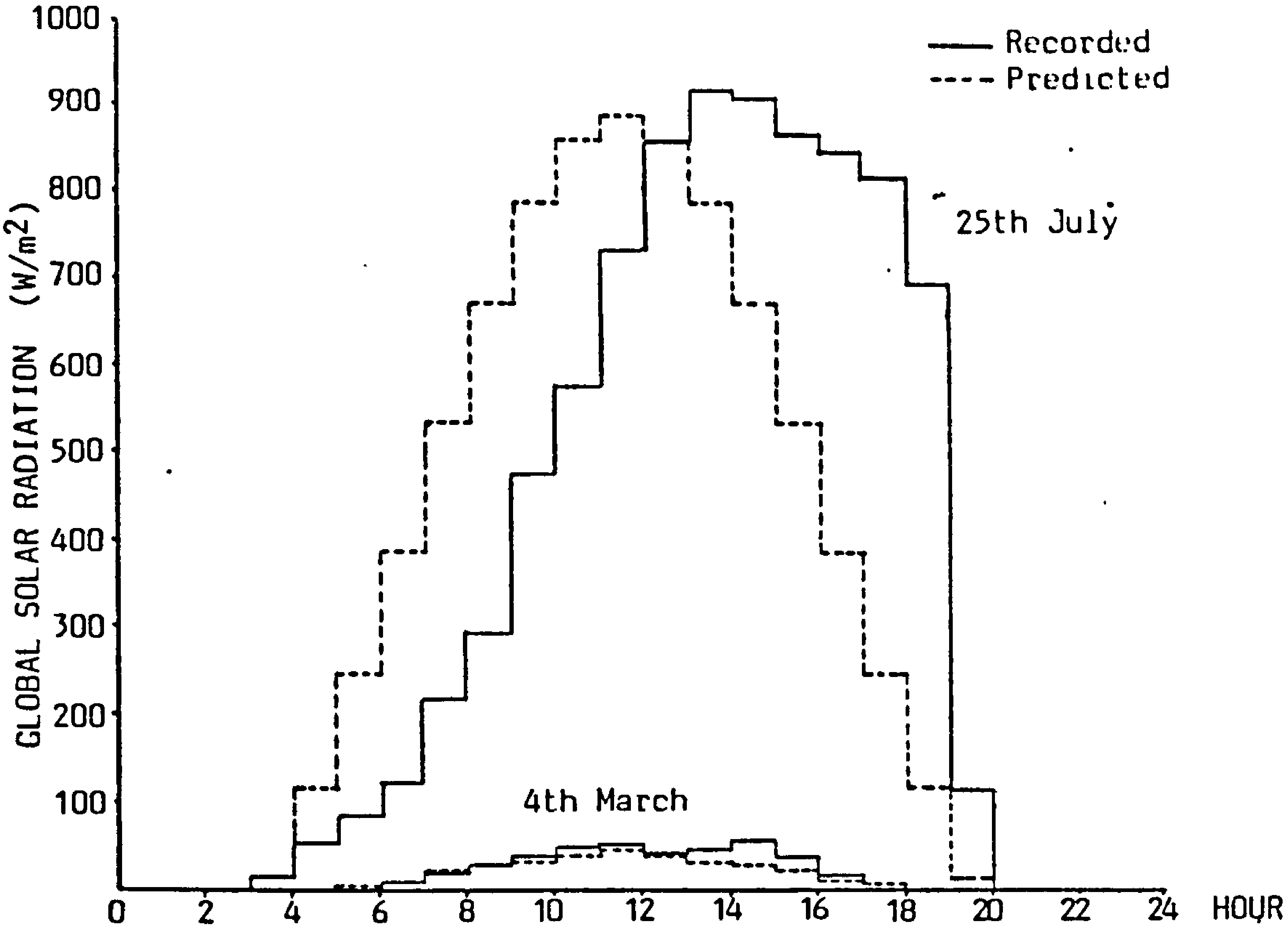


FIGURE 5.1.10 Comparison of Predicted and Recorded Global Solar Radiation for a Low Radiation Level Day and a High Radiation Level Day on Eigg

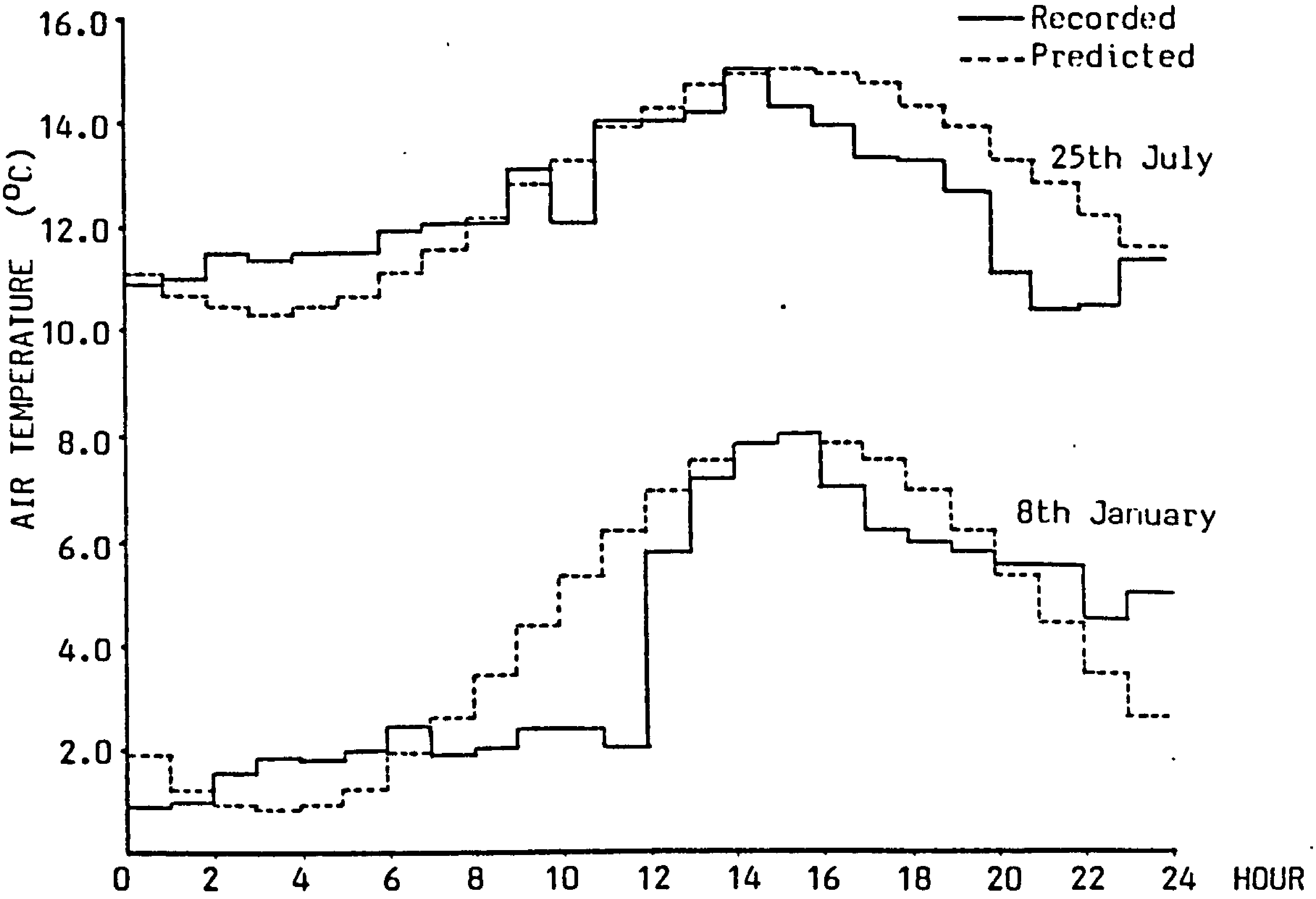


FIGURE 5.1.11 Comparison of Predicted and Recorded Air Temperature for a High Temperature Day and a Low Temperature Day on Eigg

The use of meteorological data from other sites to apply to Eigg is concluded to be reasonably accurate for use in planning work; this approach, though, might not be possible for other communities to which the planning strategy could be applied. Therefore methods were proposed for simulating daily or hourly met. data from the minimum of recorded data; daily wind speeds from mean monthly or yearly values, and hourly global solar radiation and air temperature from mean daily values. These methods are accurate enough for general modelling use, given that more accurate data are assumed to be unavailable. Although not used in community energy planning work, they were tested in house heat demand modelling work (section 5.3).

The results from any of these methods are not intended to be accurate predictions of real values; they only attempt to simulate results having the same long term statistics. More important is that they allow reasonably accurate predictions of renewable energy potentials, without the expense, and time involved, of collecting detailed data over a long period.

As a result of this work the energy planning model could be applied with reasonable accuracy to sites for which only the minimum of meteorological data is available. To achieve consistency of levels of data collection, methods should be developed to simulate radiation and air temperature values from longer-term data. No method has yet been found to simulate temperature, but a method of simulating solar radiation from mean monthly values could possibly be developed from work by Raja et al (1986). The methods proposed by Barros & Rodriquez Sero (ibid) or Gringorten (1966) could perhaps be developed to apply to solar radiation, rainfall and air temperature.

Section 5.2 Prediction of Hydro-Electric Power Available from Small Catchments using a Hydrological Model

5.2.1 INTRODUCTION

Hydro-electric power is one of the cheapest and most reliable energy sources (Chenall & Homer 1985). It produces no atmospheric pollution, and careful planning can minimise its effect on the landscape. Therefore hydro power is an obvious option for community energy supplies, if it is available.

The accurate prediction of potential hydro power is not easy, as long-term measurement of streamflow is costly either in terms of monitoring equipment (V-notch wiers being the most accurate, but not easy to install) or in terms of time (various gauging methods have been proposed but need to be done over long time periods). Measurement of rainfall, however, is both simple and cheap, requiring no specialised equipment. So a method to predict streamflow from rainfall figures allows power predictions to be made easily and without expense.

The main aim of this section is to develop a hydrological prediction model, as this is the most important stage in determining hydro power potential. Since detailed data on soil type, foliage cover, etc. were not available for the island of Eigg, the model proposed needs only daily rainfall and air temperature; both easily] recorded.

The overall strategy of the model is similar to that proposed by Porter & McMahon (1981), although it uses different analytical relationships (where these are more easily applicable, or require less data), than those used by Porter. This work concentrates on small catchments (less than 5 km^2), allowing several simplifying assumptions to be made that:

1) Rainfall is uniform over the whole area of the catchment.
2) Vegetation cover is uniform over the whole catchment.
3) The type of soil, and soil depth, are uniform over the whole catchment.

4) Water stored in puddles, and water running off the catchment surface, flows direct to the stream.

5) Water from soil storage can flow direct to the stream.

Having predicted the daily streamflows, a method is required to determine the power potential of the stream. The formulae needed for this are shown. A graphical method is presented which allows the design streamflow level to be determined; optimum hydro turbine size, and its power potential, can then be calculated knowing the static head of the river and the supply pipe diameter.

The correct choice of supply pipe diameter is important. Too small a pipe gives large head (and therefore power) losses, while too large a pipe would be expensive. A method is presented here of determining the optimum pipe diameter based on pipe cost (increasing with increasing diameter) and power losses (decreasing with diameter).

5.2.2 SYMBOLS AND UNITS

Symbol	Description	Units
A	Catchment surface area	m^2
B	Water flowrate into depression storage	m/day
C	Constant	m^4day/kg
C_f	Field capacity	-
D	Number of hours of daylight, in units of 12 hours per day	1/day
E	Evapotranspiration rate from foliage	m/day
F	Rainfall rate	m/day
G	Flowrate from soil storage to groundwater	m/day
G_s	Flowrate from groundwater to streamflow	m/day
H	Static head	m
H_d	Depression storage level	m
H_l	Level of soil storage above minimum level	m
H_n	Net head	m
H_s	Soil storage level	m
I	Foliage interception rate	m/day
J	Throughflow rate from foliage to soil surface	m/day
K	Infiltration rate parameter	m/day
L	Pipe length	m
M	Surface to depression storage flowrate	m/day
N	Soil storage to groundwater and streamflow rate	m/day
O	Total streamflow rate	m/day
O_a	Total volume streamflow rate	m^3/day
P	Daily mean hydro-power electrical output	kW
P_e	Level to which soil storage falls in 2 days	%
P_s	Saturated vapour pressure	N/m^2

P_t	Total yearly hydro turbine output	kWh/y
Q	Flowrate from soil storage to streamflow	m/day
Q_p	Flowrate in supply pipe to hydro plant	m^3/s
R	Specific gas constant for water vapour	J/(kg K)
R_d	Depression storage to streamflow runoff rate	m/day
R_e	Reynolds number	-
S	Foliage interception storage level	m
S_d	Soil depth	m
T	Atmospheric air temperature	K
U	Yearly unit cost of supply pipe	£/(m y)
U_f	Hydro system 'cost'	£/y
U_l	Value of lost hydro turbine output	£/y
U_p	Unit cost of electricity	£/kWh
U_s	Yearly cost of supply pipe	£/y
U_t	Yearly cost of hydro turbine output	£/y
V	Soil surface to soil storage infiltration rate	m/day
V_s	Infiltration from soil surface to soil storage	m/day
W	Infiltration constant	m/day
X	Rainfall to streamflow rate parameter	-
Y	Constant	-
Z	Infiltration constant	m/day
a	Constant	-
b	Constant	day/m
c	Constant	m^2day K s^2/kg
d	Pipe diameter	m
f	Pipe friction coefficient	-
g	Gravitational acceleration	m/s^2
hf	Pipe friction head loss	m
j	Constant	$s^{1.75}/m^{0.5}$
k	Interflow rate parameter	-
n	Diameter step size	m
t	Time	day
u	Mean fluid velocity in pipe	m/s
η	Hydro-power turbine efficiency	-
ν	Kinematic viscosity of water	m^2/s
ρ_s	Saturated water vapour density	kg/m^3
ρ_w	Water density	kg/m^3
π	Constant	-

Suffices

max	Maximum value
min	Minimum value
x	Day number x
x-y	Day number (x-y)

The units used in this work for rainfall and water flow rates are m/day as opposed to conventional SI unit m^3/s. This is often used by hydrologists as it gives figures independent of catchment area. This is important when rates, vegetation or soil structure are not uniform of the whole area. In this work it allows easy application of the equations to different catchment areas.

5.2.3 LITERATURE REVIEW

This review concentrates only on complete hydrological prediction models, as the number of references for individual flow processes is very large. Two most useful reviews were found in Fleming (1975) and Haan et al (1982), which cover many of the types of model available. Other models were found in Anderson & Burt (1985), Chapman & Dunin (1975) and Porter & McMahon (ibid).

The two main types of model are empirical or theoretical. These both use mathematical relationships to represent physical processes, but because of the complex nature of real water flow processes, theoretical models often include empirical relations, and vice versa.

Empirical and theoretical models can be further split into two categories: fitted parameter or measured parameter (Larson et al 1982). Fitted parameter models need recorded flowrates in order to determine parameters values controlling flowrates and storage levels within the model. Measured parameter models, on the other hand, require parameters which can be satisfactorily determined knowing only the type of catchment. These can be obtained either by measurement or estimation.

Currently-Available Models

Only fairly brief descriptions of models are given here: the references give more detailed descriptions.

Fitted parameter models

Possibly the best known fitted parameter model (FPM) is the Stanford Watershed Model, developed initially by Crawford & Linsley (1966). Since it is an FPM, it usually requires several years of flow measurements for most applications. The water flow processes in the model are represented mathematically as flows or stores, with flows from any store expressed as a function of the current level in that store. It is physically based, but does not require detailed knowledge of physical dimensions or properties. For example, one of the stores represents topsoil storage, but the use of a fitted parameter replaces the need to know soil depth or moisture retention properties. An important feature of the model is that various flows are not constant over the whole catchment area, which is important for larger areas.

Several very simple fitted parameter models have been proposed, for example Blackie & Eeles (1985). They propose, as the simplest model, one in which

$$O = XF \qquad (5.2.1)$$

where O = catchment streamflow rate,
F = rainfall rate
and X = parameter obtained from measured data.

Equation 5.2.1 can be expanded and applied more specifically to intermediate flow processes, thereby obtaining a more detailed model. This very simple method has been modified (for example Meinzer 1942) to predict flood levels, but this is of little use in estimating streamflow rates over long periods of short time steps.

There are many other fitted parameter models available, which are beyond the scope of this brief review to describe. However, they all suffer from the basic limitation, when applied to the island of Eigg catchments modelled in this work, that no flow measurements on the island are available.

Measured parameter models

These models can be split broadly into two types: stochastic models and deterministic models. Stochastic models, described by DeCoursey et al (1982), generate either input data (rainfall, wind speed, etc.) stochastically, and use these as inputs to a model, or are entirely stochastic, generating streamflow knowing only the history of recorded streamflows. Deterministic models use only recorded rainfall, wind speed, etc., values as inputs to a model. All models require a knowledge of at least rainfall rates: the difference between measured parameter models (MPM) and FPM's is basically that the latter do not require measurements of other flow rates.

One model, the Soil Conservation Service (SCS) TR-20 watershed model (U.S. SCS 1965) is widely used in planning and studying small catchment areas. It uses mathematical relationships to determine time-series streamflows from time-series rainfall data (which can be recorded or stochastically predicted), but also requires watershed characteristics and their possible variations to be input. It thus determines results for different combinations of catchment conditions, for example reservoir numbers, size and location, and land use practices. This strategy, while successful, is too complicated for the work on catchments on Eigg, for which only one set of catchment conditions is specified.

A simpler model, and the one on which this work is based, is that described by Porter & McMahon (ibid). This has been applied successfully to two large catchments in Victoria, Australia. Good agreement was obtained between predicted and recorded streamflows, with correlation coefficients of 0.75 for daily predictions, and 0.86 for monthly values (a coefficient of 1.0 would represent an exact fit, 0.0 a complete lack of fit). All flowrates are represented by mathematical expressions, for which constants and rate parameters are easily obtained. Unfortunately Porter does not give values for the constants and parameters, so in some cases more easily applicable expressions were substituted for those used by him in the model used in this work. Since Porter's model is very similar to that proposed in this work, a detailed description is not given here.

5.2.4 DESCRIPTION OF THE HYDROLOGICAL MODEL

The model presented here has been developed for catchments ranging from 1.1 km^2 to 3.1 km^2. In all cases the soil is assumed to be a peat loam, 0.5m deep over the whole catchment. The foliage (uniform over the whole area) is either heather, moss and scrub, or short-cropped grass. It is assumed that all processes and conditions are uniform over the whole area of the catchment, therefore area need not be considered in all equations. Water flows in a small catchment are shown simply by the following figure 5.2.1:

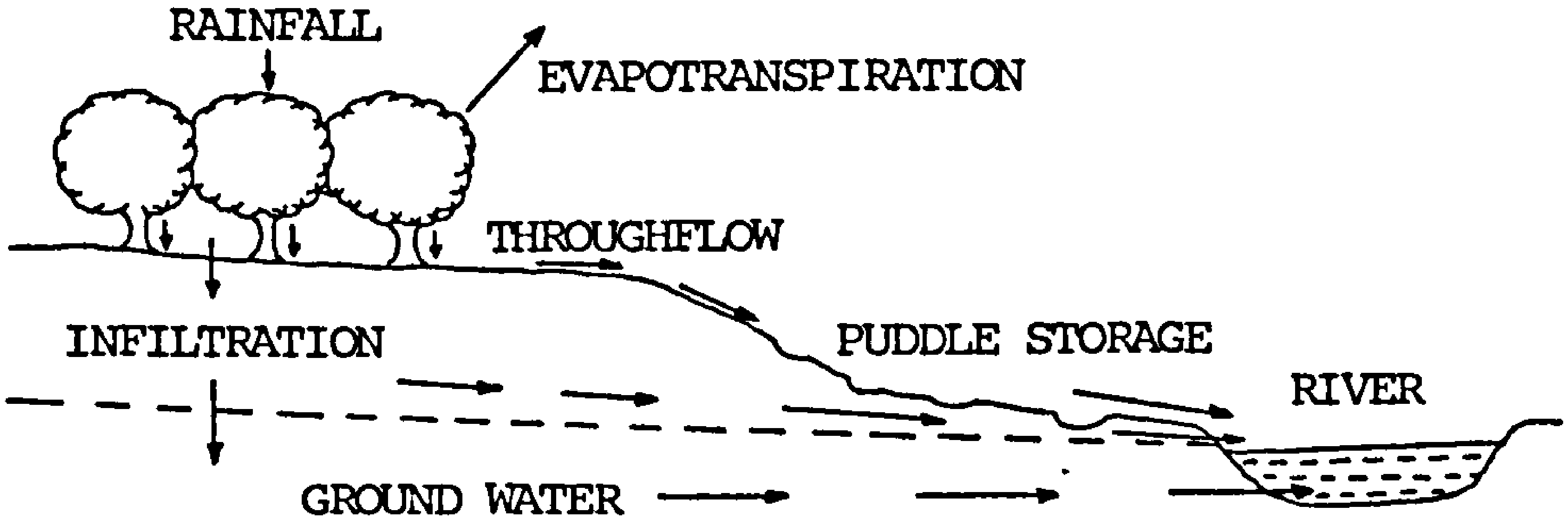


FIGURE 5.2.1 Simplified Picture of Small Catchment Water Flows

Figure 5.2.1 can be shown schematically by figure 5.2.2 below:

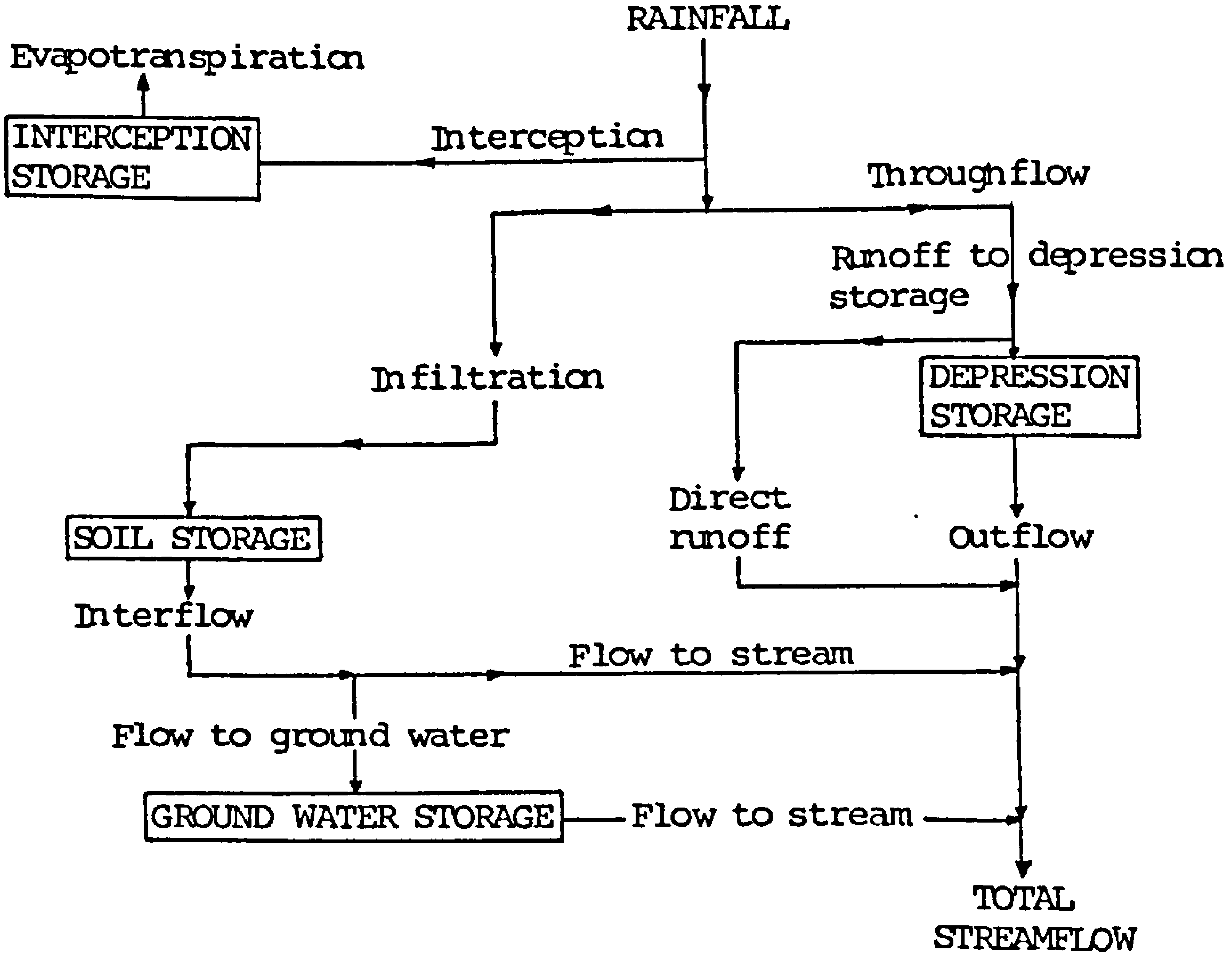


FIGURE 5.2.2 Schematic Diagram of Water Flows in Small Catchments

Some flows are controlled by storage levels. Since the time step of the model is one day the assumption is made that the driving level throughout any day is the level at the end of the previous day. No account is taken of change of level during the day being considered.

Each of the stores and flowrates of fig. 5.2.2 are described and analysed in detail below. The values of various parameters and constants are typical values for foliage and soil types for Eigg. Parameter sensitivity is tested in sub-section 5.2.6. Several of the equations used in this work are empirical, because of the problems of developing analytical relationships for complex physical processes.

Evapotranspiration

Evapotranspiration (ET) is water lost from foliage by direct evaporation, and by transpiration from leaves and stems. ET and interception (water collected by foliage) are the most important rates in determining total yearly streamflow: all water not lost by ET eventually gets into the river, and since total streamflow from the river is important in determining the total yearly energy potential, an accurate method of calculating ET must be used.

An empirical relationship developed by Hamon (1961) was found to be accurate for a wide range of conditions. It has been tested by Hamon (ibid) for 16 areas covering 13 States in the USA, where it was found to be consistent to about +/- 5% of measured data. It has also been successfully applied by Sartz (1972) and Jones (1966).

The evapotranspiration rate is calculated by:

$$E_x = C D_x^2 \varrho_x \qquad (5.2.2)$$

where C = constant, value 0.14 m^4day/kg,
D_x = number of hours of daylight, or potential hours of sunshine
and ϱ_x = saturated vapour density.

The saturated vapour density is calculated by

$$\varrho_x = P_{s,x}/(RT_x) \qquad (5.2.3)$$

where R = specific gas constant for water vapour.

Combining eqns. 5.1.2 and 5.1.3 gives the evapotranspiration rate as

$$E_x = cD_x^2P_{s,x}/T_x \quad (5.2.4)$$

where c = constant, value 3.03×10^{-4} m^2dayKs^2/kg.
and $P_{s,x}$ can be calculated from the value of T_x.

The rate is a function of D_x^2, the hours of daylight, for the following reasons (Hamon ibid): a) because ET only occurs while leaf stomata are open, which they are only during daylight hours, b) because net global radiation gives the heat required for ET, and net radiation is a linear function of daylight hours (ie the radiation is less with increasing latitude and corresponding decreasing hours of daylight). The values for daylight hours (taken as constant during each month) can be obtained from Eagleson (1970).

Interception Rate and Storage

Interception is rainwater which is caught by foliage, and 'stored' on leaves until lost by evapotranspiration. Its rate can be calculated empirically (Blake 1975) for a daily rainfall F_x by

$$I_x = aF_x - bF_x^2 \quad (5.2.5)$$

where a = constant, value 0.2288 (no units)
and b = constant, value 6.50 day/m.

Eqn. 5.2.5 is applicable provided that the storage level does not go above its maximum. The two types of foliage cover on Eigg are: heather, moss and scrub (storage capacity $S_{max} = 2.03\times10^{-3}m$ (Blake ibid)) and short-cropped grass ($S_{max} = 1.20\times10^{-3}m$).

Rain water enters leaf storage by interception, and is lost by evapotranspiration. Therefore if the level in storage is denoted by S, applying a water balance to the store gives

$$S_x = S_{x-1} + I_xt - E_xt \quad (5.2.6)$$

where t = time step, value 1 day.

If $S_x > S_{max}$ or $S_x < 0$ (conditions which cannot exist), the calculated value of I_x from eqn. 5.2.5 must be modified accordingly.

Throughflow

Throughflow is rain water flowing through the foliage to the soil surface. It can be simply calculated as the difference between daily rainfall and daily interception as

$$J_x = F_x - I_x \qquad (5.2.7)$$

Infiltration and Soil Storage

Water is stored in the top-soil of a catchment before either flowing into lower level ground water storage or into a river or stream. The rate at which water enters soil storage is the infiltration rate. It can be calculated by an equation given by either Philip (1957) or Porter & McMahon (ibid) as

$$V_x = K_x + Z \qquad (5.2.8)$$

where Z = constant, value $2\text{x}10^{-3}$ m/day
and K_x = infiltration rate parameter.

Generally the level of soil storage does not fall to zero, even after long dry periods. After two days it falls to a level $H_{s,min}$ which can be expressed as a percentage of the soil depth using the parameter 'field capacity' (Shaw 1983), such that

$$H_{s,min} = S_d C_f \qquad (5.2.9)$$

where S_d = depth of soil
and C_f = field capacity.

For the soil on Eigg the field capacity is 0.29 (Shaw ibid). So $H_{s,min} = 0.5\text{x}0.29 = 0.145\text{m}$. The infiltration rate is highest when the soil is 'dry' (ie $H_s = H_{s,min} = 0.145\text{m}$), and zero when the soil is saturated ($H_s = H_{s,max} = 0.25\text{m}$, the maximum level being $0.5S_d$). This can be accounted for by using a relative storage level H_1 where

$$H_1 = H_s - S_d C_f \qquad (5.2.10)$$

The infiltration rate parameter K_x of eqn. 5.2.8 is given by:

$$K_x = We^{(YH_{1,x-1}/H_{1,max})} \qquad (5.2.11)$$

where W = constant, value $3.0\text{x}10^{-3}$ m/day
and Y = constant, value -0.452 (no units).

Combining equations 5.2.8 and 5.2.11 gives the daily infiltration as

$$V_x = We^{(YH_{1,x-1}/H_{1,max})} + Z \tag{5.2.12}$$

The calculated value of V_x is only limited by one condition; that if the infiltration is greater than the throughflow J_x then

$$V_x = J_x \tag{5.2.13}$$

Soil Surface to Depression Storage Flowrate

Depression storage is water stored in puddles, hollows and small water channels before it flows into the river. The rate of flow into this store is simply the difference between the throughflow and the infiltration, and is calculated by

$$M_x = J_x - V_x \tag{5.2.14}$$

although M_x is subject to the condition that the soil storage level is less than its maximum (see below).

Soil Storage Level

Let the flowrate from soil storage to ground water and streamflow (calculated later) be donated by N_x. The calculated soil storage level on any day x is given by

$$H_{s,x} = H_{s,x-1} + V_x t - N_x t \tag{5.2.15}$$

Eqns. 5.2.14 and 5.2.15 are subject to the conditions that $H_{s,x}$ cannot be more than $H_{s,max}$ or less than $H_{s,min}$. If it is, the values of M_x and $H_{s,x}$ are modified accordingly.

Interflow from Soil Storage to Streamflow and Ground Water

From soil storage, water can flow both to ground water storage and direct to the river (the latter is different to direct runoff from soil surface to streamflow, which never enters the soil). These two flowrates, combined, are called interflow.

Interflow is assumed here (in the absence of any other easily applicable relationship) to be a function of soil storage level, and to fall exponentially with time. The concept of field capacity has been introduced above, and it has also been assumed that the maximum storage level is 0.5 times the soil depth. The equation determining interflow rates requires a knowledge of the percentage of the maximum level to which the storage level falls after two days. This can be given by

$$P_e = C_f S_d / H_{s,max} \qquad (5.2.16)$$

which, expressing $H_{s,max}$ in terms of soil depth, becomes

$$P_e = C_f S_d / 0.5 S_d = C_f / 0.5 \qquad (5.2.17)$$

The interflow rate equation uses the relative storage level H_1 given by eqn. 5.2.10. Neglecting the effects of infiltration on the level during the day being considered, the interflow for any day x is

$$N_x = H_{1,x-1}(1 - e^{(k_x)})/t \qquad (5.2.18)$$

where k_x is the interflow rate parameter, given by

$$k_x = [\ln(P_e H_{1,max}) - \ln(H_{1,x-1})]/2 \qquad (5.2.19)$$

Two conditions apply to the calculated value of interflow:

if $H_{s,x-1} = H_{s,min}$
then $N_x = 0$ (5.2.20)

or if $H_{s,x} < H_{s,min}$
then $N_x = V_x + (H_{s,x} - H_{s,min})/t$ (5.2.21)

Total interflow is split into streamflow Q_x (flow into the river) and flow to ground water storage G_x in the following way, with ground water flow controlled by the soil storage level:

Ground water (this may vary if the interflow is less than the calculated ground water flowrate, see eqn. 5.2.26)

If $H_{s,x-1} < (H_{s,max} - H_{s,min})/2$
then $G_x = 0.001$ m/day (5.2.22)

If $(H_{s,max} - H_{s,min})/2 >= H_{s,x-1} < 0.57(H_{s,max} - H_{s,min})$
then $G_x = 0.002$ m/day (5.2.23)

If $H_{s,x-1} >= 0.57(H_{s,max} - H_{s,min})$
then $G_x = 0.003$ m/day (5.2.24)

Streamflow

If $N_x > G_x$
then $Q_x = N_x - G_x$ (5.2.25)

If $N_x <= G_x$
then $G_x = 0.5N_x$ (5.2.26)
and $Q_x = 0.5N_x$ (5.2.27)

Ground Water to Streamflow

Water from the ground water storage eventually enters the river, although often a long time after it enters the store. It is assumed here that the ground water store acts simply as a delay of 90 days, so

$$G_{s,x} = G_{x-90} \tag{5.2.28}$$

Depression Storage, Outflow and Direct Runoff

The assumption is that all water in depression storage (DS) eventually flows into the river without entering the soil. The flow from DS is called outflow, and it only occurs if the runoff is zero. If DS is full or the rate of water into storage is less than runoff, water (direct runoff) will enter streamflow directly, without entering DS.

If $\bar{H}_{d,x}$ is the depression storage level on day x then B_x, the rate of water into the store is given by the following equation, where $H_{d,max}$ for catchments on Eigg is 0.040 m (Linsley et al 1975):

$$B_x = H_{d,max}(1 - e^{(-M_x/H_{d,max})})/t \tag{5.2.29}$$

The values of direct runoff and DS level are generally:

$$R_{d,x} = M_x - B_x \tag{5.2.30}$$
$$\& \; H_{d,x} = H_{d,x-1} + B_x t \tag{5.2.31}$$

but are modified if $H_{d,x} > H_{d,max}$ or if $M_x = 0$ and $H_{d,x-1} = 0$.

Total Streamflow

For small catchment areas it can be assumed that only one river flows through the catchment, and that all sources of streamflow are close enough to the river to effect the flowrate from the catchment with no time delay. So total streamflow is simply the sum of direct runoff, outflow, soil storage and ground water storage to streamflow:

$$O_x = R_{d,x} + Q_x + G_{s,x} \tag{5.2.32}$$

It is also assumed that the volumes of the various stores are directly related to catchment area so the above flowrate, with units of m/day, is changed to m^3/day by multiplying by catchment area, giving

$$O_{a,x} = A(R_{d,x} + Q_x + G_{s,x}) \tag{5.2.33}$$

5.2.5 POWER OUTPUT AND OPTIMUM SUPPLY PIPE SIZE PREDICTION

Power Output

The total yearly energy potential of a river is obtained by first determining the hydro turbine rating, then summing the energy output of the turbine over the year, knowing the daily streamflow and the corresponding turbine output. To determine the size of hydro turbine to install in a river, the following data are required: static head of the river, design flowrate in the turbine supply pipe, supply pipe diameter and length, and turbine and generator overall efficiency.

The static head is determined by direct measurement or from an accurate Ordnance Survey map, the supply pipe length depends entirely on local terrain, the overall efficiency can be obtained from manufacturer's data and the supply pipe diameter can be calculated using the optimisation process described later. The design flowrate is obtained using a method proposed by the University of Salford (1983).

A flow duration curve for the river, which shows the percentage of the year that the streamflow exceeds certain values, is drawn. An example of this is shown, for one of the catchments on the island of Eigg, on figure 5.2.3 overleaf. The flowrate which is equalled or exceeded for 70% of the year (256 days) is the design streamflow. For the Eigg catchment, this value would be 4000 m^3/day, or 0.0463 m^3/s.

Having determined the design flowrate, and knowing the supply pipe diameter and length, the friction head loss in the pipe is calculated by the following equations taken from Massey (1976). Several of them are empirical relationships, but are all well proven.

The mean flow velocity in the supply pipe is

$$u = Q_p/(\pi d^2) \qquad (5.2.34)$$

and the Reynolds number is obtained by

$$R_e = ud/\nu \qquad (5.2.35)$$

where ν = kinematic viscosity of water, value $1.14\text{x}10^{-6}$ m^2/s.

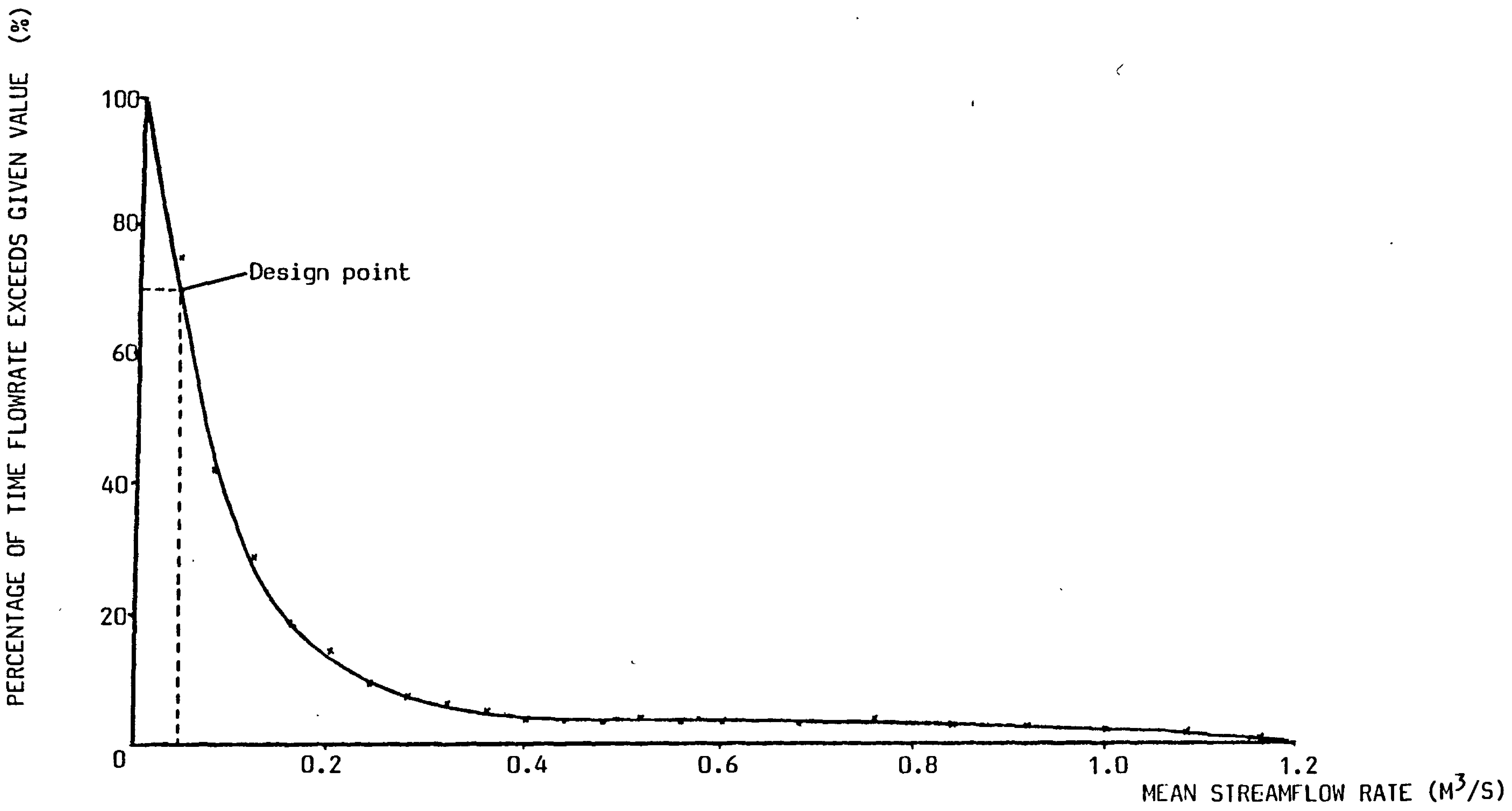


FIGURE 5.2.3 Flow Duration Curve for Laig Catchment. April 1982 - March 1983

In the range of Reynolds number usually found for small hydro turbines (3×10^3 to 1×10^5), the Blasius' relationship can be used, where

$$f = 0.079(R_e)^{-0.25} \qquad (5.2.36)$$

The friction head loss in a straight, constant diameter pipe is

$$hf = 2fLu^2/dg \qquad (5.2.37)$$

Substituting for f in eqn. 5.2.37, giving u in terms of Q_p and diameter d, and substituting values for g (9.81 m/s^2) and ν, leads to

$$hf = jQ_p{}^{1,75}L/d^{4.75} \qquad (5.2.38)$$

where j = constant, value 8.04×10^{-4} $s^{1.75}/m^{0.5}$.

If the height of pipe entry above the turbine is H, the net head available for generating power (neglecting the dynamic term) is

$$H_n = H - hf = H - jQ_p{}^{1.75}L/d^{4.75} \qquad (5.2.39)$$

Finally, the power output for any day x, is calculated by

$$P_v = \rho_w g \eta Q_{p,x}(H - jQ_{p,x}{}^{1.75}L/d^{4.75}) \qquad (5.2.40)$$

and the total yearly energy output is given by

$$P_t = 86400 \sum_{x=1}^{365} P_x \qquad (5.2.41)$$

where 86400 = number of seconds per day.

Optimum Supply Pipe Diameter

The supply pipe cost to a hydro turbine can be a significant part of the installation cost, and is a function of pipe diameter (G. Riva 1985, personal communication). Pipe cost increases with diameter, but head (and hence power) losses decrease. Therefore a method is required to determine the optimum between pipe size and power loss. A hydrological engineer would probably know the correct pipe size to use from experience, but this method was developed because no simple algorithm or empirical method of determining pipe size was found.

A computer program was written which requires: the maximum and minimum supply pipe diameters and their yearly costs (obtained by the Net Present Value method of section 2.1), the diameter step size to be considered between d_{max} and d_{min}, the supply pipe length and the unit cost U_p of electricity from the turbine (see sub-section 4.1.4b). The total potential yearly output of the turbine for d_{max} is calculated using eqns. 5.2.40 and 5.2.41. The total value of the output is then

$$U_{t,max} = U_p P_{t,max} \tag{5.2.42}$$

At d_{max} power losses are assumed to have zero cost. The yearly cost of the supply pipe, of length L, would be

$$U_{s,max} = U_{max} L \tag{5.2.43}$$

If the diameter step size is n, the program next considers the diameter $d = d_{max} - n$, so the value of P_t will be smaller than that using d_{max}. If the yearly value at d is U_t, the value of energy lost is

$$U_l = U_{t,max} - U_t \tag{5.2.44}$$

Using linear interpolation between U_{max} and U_{min} the pipe cost is

$$U_s = L[U_{max} - ((U_{max}-U_{min})(d_{max} - d)/(d_{max} - d_{min}))] \tag{5.2.45}$$

This will be less than $U_{s,max}$ from eqn. 5.2.43. The 'total cost' of the system with diameter d can be calculated by

$$U_f = U_s + U_l \tag{5.2.46}$$

The steps are repeated for each value of d between d_{max} and d_{min}; the optimum diameter occuring when U_f is a minimum.

5.2.6 PRESENTATION OF VALIDATION AND SENSITIVITY RESULTS

Although no direct measurements of streamflow were possible on Eigg, two ways of testing the model were available: 1) comparing the known power output of a hydro turbine installed on the island with the predicted output using the methods above and 2) comparing predicted with recorded streamflows for another catchment from which recorded data were available. These tests are shown below.

Because the model does not rely on accurate knowledge of soil, foliage cover, etc., it should be relatively independent of these parameters in order to be accurate in its predictions. The sensitivity of the model to various parameters is also presented in this section.

Eigg Burn Power Output Prediction

This burn is one of two on Eigg which have hydro turbines installed. It has a catchment area of 3.1 km^2, with a static head of 33.5 m, and the turbine is a 4.5 kW (electrical) A.C. machine. The streamflow prediction was carried out using daily rainfall (summarised as weekly averages on fig. 5.2.4) for the period April 1982-April 1983. The parameters used in the model (list A) are shown in table 5.2.1.

Data for the hydro turbine were obtained from Burnett (1984, personal communication), who installed it. He estimated that 1/10 of the total streamflow passes through the turbine, which has an overall efficiency of 50%. The supply pipe is 50m long, of which half has a diameter of 0.10m, and half a diameter of 0.15m.

Interception: Max. capacity $S_{max} = 2.03x10^{-3}$ m, rate constants a = 0.2288, b = 6.50 day/m
Evapotrans: Constant c = $3.03x10^{-4}$ m^{2}day K s^2/kg
Soil storage: Max. level $H_{s,max} = 0.25$ m, min. level $H_{s,min} = 0.145$ m, soil depth = 0.5 m, field capacity = 0.29, percentage of $H_{s,max}$ after 2 days $P_e = 0.2$
Infiltration: Rate constants $W = 3.0x10^{-3}$ m/day, Y = -0.452 $Z = 2.0x10^{-3}$ m/day
Dep. storage: Max. level $H_{d,max} = 0.040$ m, level after 1 days' fall = $0.01H_{d,max}$

Table 5.2.1 Parameter list A for Eigg catchment

The predicted streamflows (summarised as weekly means) are shown on figure 5.2.5. This confirms the observation made by inhabitants of Eigg that the burn never runs dry. Comparing figs. 5.2.4 and 5.2.5 the 'flashy' nature of the burn is also seen, there being a quick response to changes in rainfall.

The yearly mean power output of 1.67 kW predicted by the model compares well with the known average output of the turbine (Burnett ibid) of 2.00 kW; within the hoped-for accuracy range of +/- 20%, and reasonable bearing in mind the inaccuracy of the estimation of the amount of total streamflow generating power.

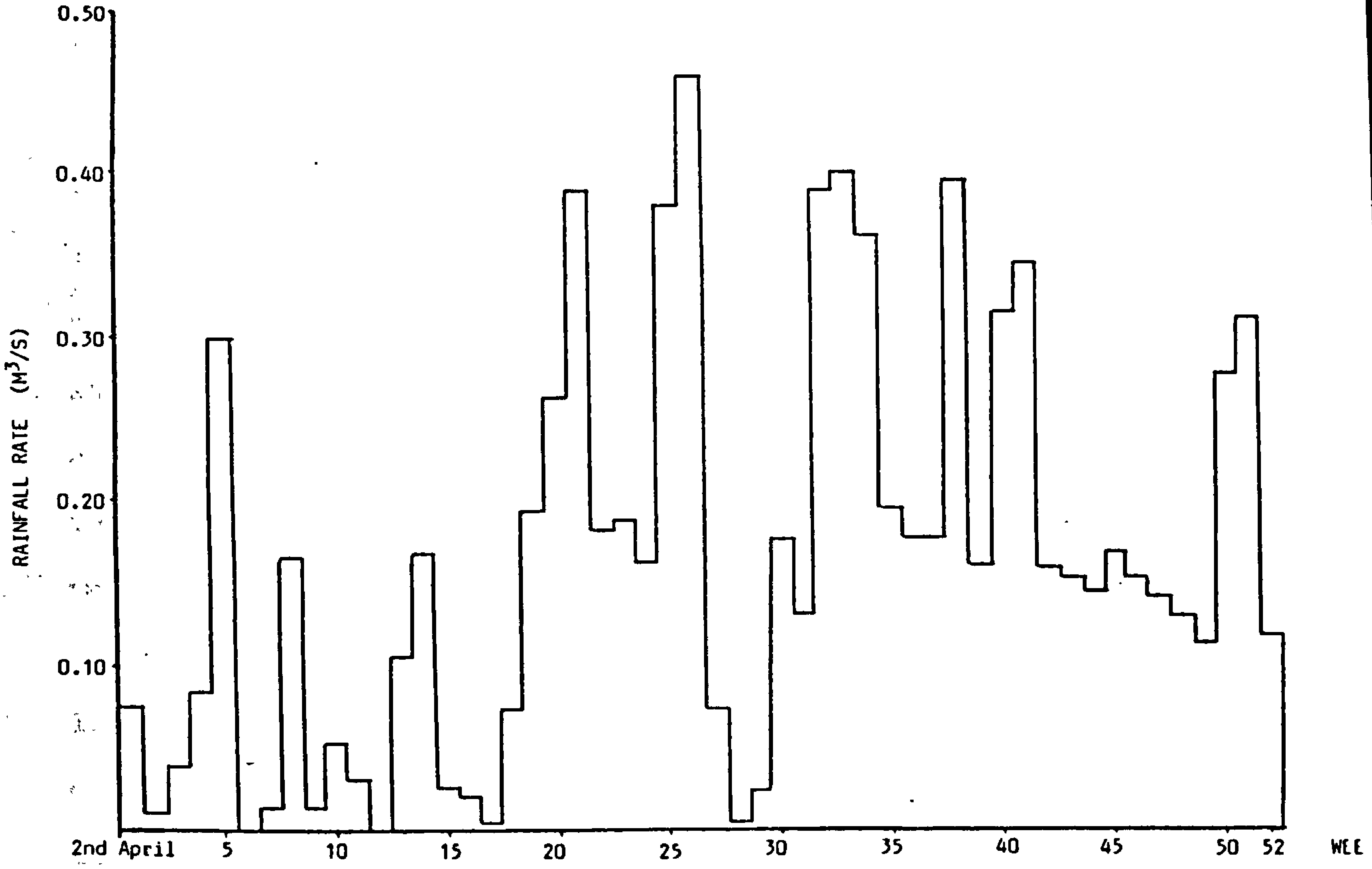


FIGURE 5.2.4 Weekly Rainfall Rate on Laig Catchment April 1982 - March 1983

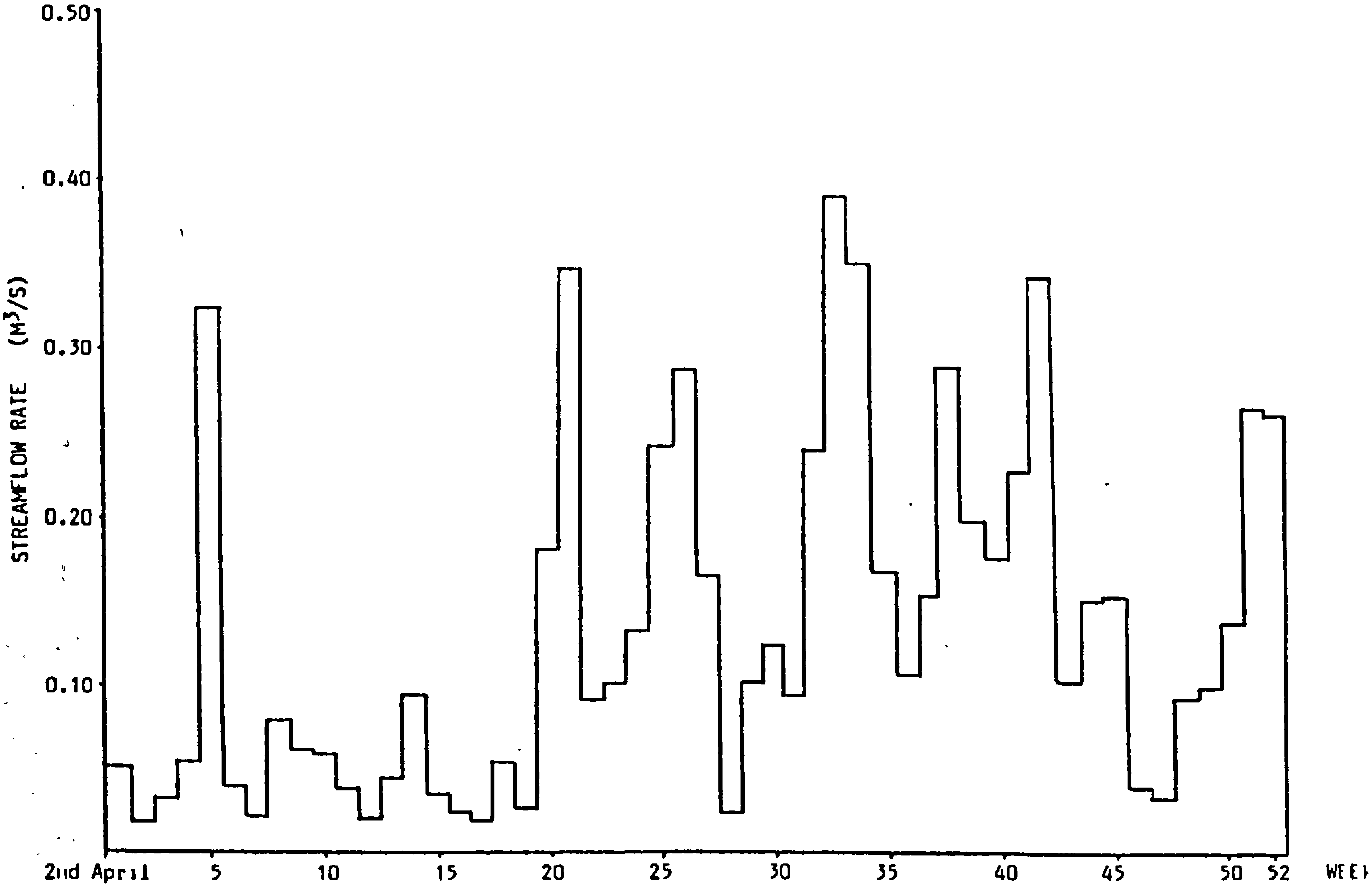


FIGURE 5.2.5 Weekly Mean Streamflow Rate from Laig Catchment April 1982 - March 1983

Predicted and Recorded Streamflow for the River Divie

The river Divie catchment area is 165 km^2, well outside the suitable range of the model in this work, so the assumptions made about small catchments do not accurately apply. Nonetheless, an attempt was made to predict daily streamflow using the prediction model with the same parameters as those in table 5.2.1, retaining the same assumptions as for smaller catchments. Rainfall values used in the model were those recorded for the catchment over the same period as streamflow measurements.

The initial prediction results had a standard deviation of 1.52 m^3/s with both predicted and recorded values having a yearly mean of 2.58 m^3/s (the evapotranspiration rate having been set in the model to ensure this). One attempt was made to obtain better agreement between recorded and predicted data, by increasing the time constants of all stores to slow down the response time of the model. The results are shown on figure 5.2.6 (the model only predicts from the seventh week of the year, because of limited data when a longer time delay is put on ground water storage). There is better agreement than with the first prediction: the standard deviation having fallen to 1.31 m^3/s.

Sensitivity Analysis

A test was made on the Eigg catchment described above to determine the effects of various parameter changes on the model's predictions. This was done by changing one or more of the storage levels and rate parameters listed on table 5.2.1 at a time. Keeping all other parameters the same, the changes are shown on table 5.2.2.

The sensitivity results are shown as weekly averages on figure 5.2.7. Most of the changes have little effect on the general shape of the streamflow pattern, but merely change its magnitude (small effects only were noticed in daily values). So it appears that the model is, in general, insensitive to individual parameter changes.

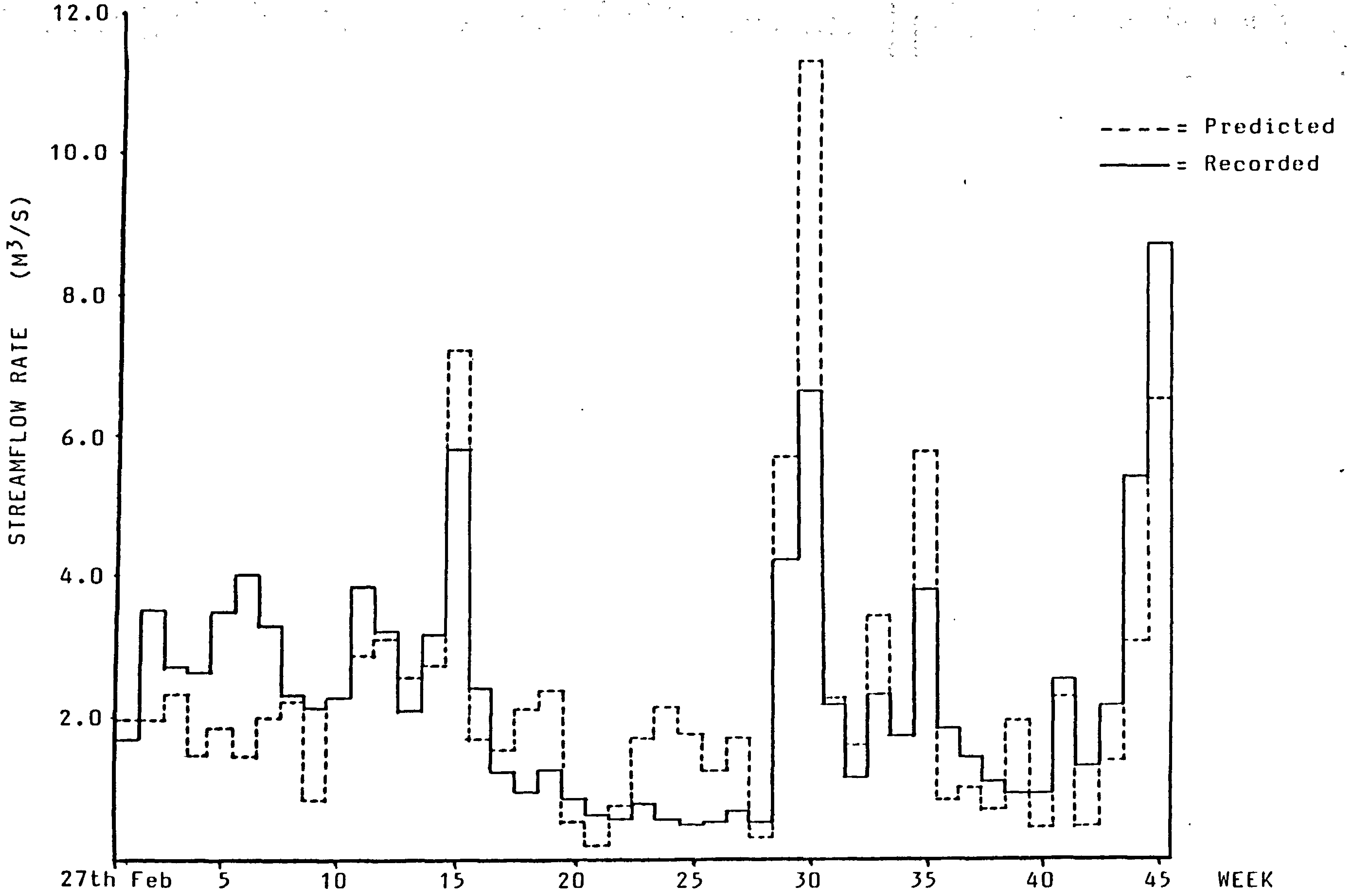


FIGURE 5.2.6 Comparison of Recorded and Predicted Mean Weekly Streamflow Rates for the River Divie. February 1983 - December 1983

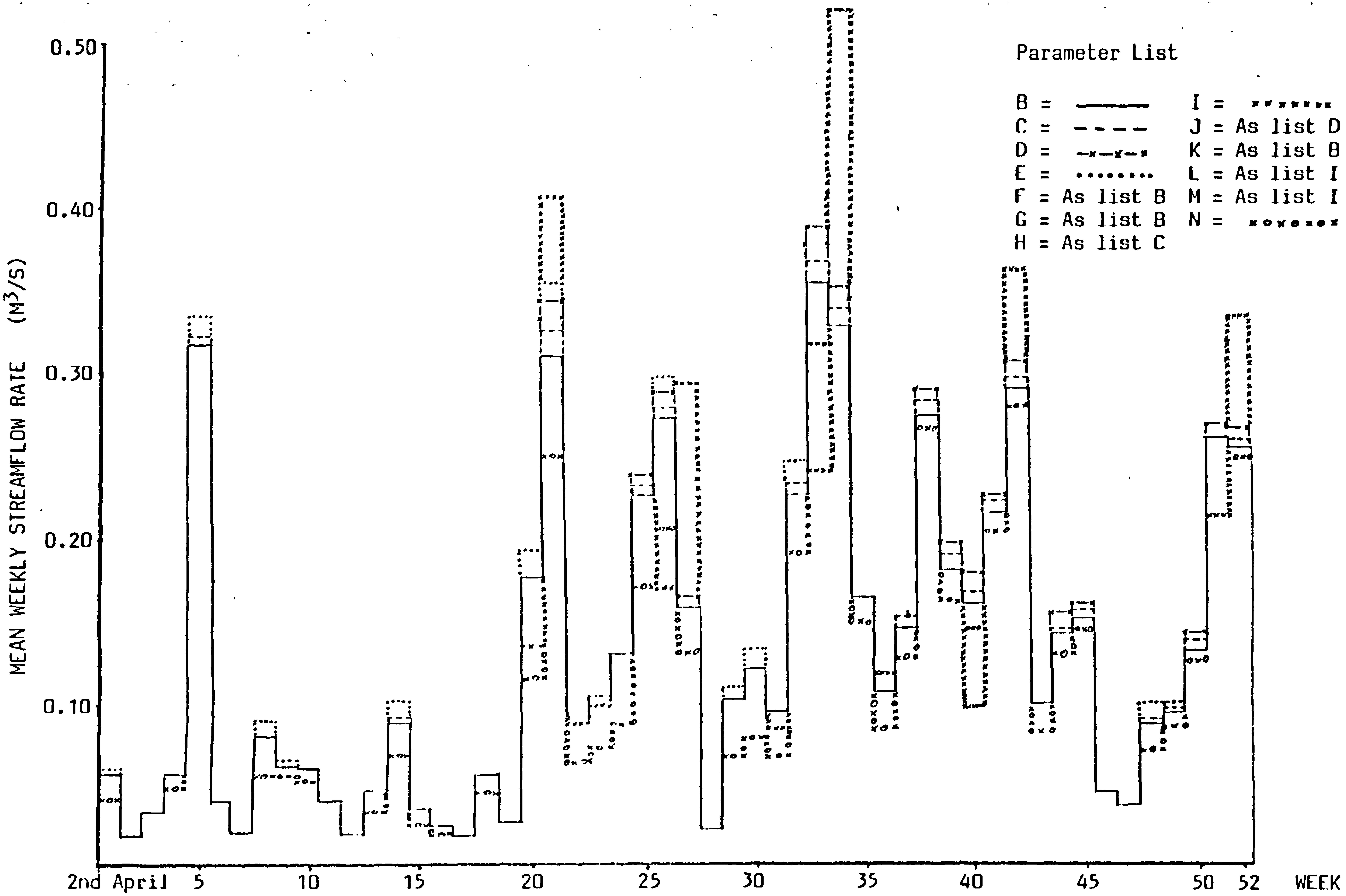


FIGURE 5.2.7 Results of Sensitivity Analysis on Weekly Mean Streamflow Rates from Laig Catchment

List	Change
B	Evapotrans. constant $c = 0.50$ m^{2}day K s^2/kg
C	Evapotrans. constant $c = 0.40$ m^{2}day K s^2/kg
D	Interception storage capacity $S_{max} = 3x10^{-3}$ m
E	Interception storage capacity $S_{max} = 1x10^{-3}$ m
F	Soil storage percentage so that $P_e = 0.3$ after 2 days
G	Soil storage percentage so that $P_e = 0.1$ after 2 days
H	Infilt. rate constants $W = 0.004$ m/day, $Z = 0.003$ m/day
I	Infilt. rate constants $W = 0.002$ m/day, $Z = 0.001$ m/day
J	Dep. storage time const. so $H_d = 0.1H_{d,max}$ after 1 day
K	Dep. storage time const. so $H_d = 0.2H_{d,max}$ after 1 day
L	Interception rate constants $a = 0.30$, $b = 8.00$ day/m
M	Interception rate constants $a = 0.40$, $b = 9.00$ day/m
N	Evapotrans. constant $c = 0.6$, interception storage capacity $S_{max} = 4x10^{-3}$ m and consts. $a = 0.40$, $b = 8.00$ day/m

Table 5.2.2 Parameter changes for sensitivity analysis

5.2.7 DISCUSSION

The purpose of this work was to develop a hydro power prediction method for small catchments which is easy to use and has simple data requirements: this has been achieved with the development of a method needing only daily rainfall, air temperature and easily obtained turbine data, and which is relatively insensitive to parameter changes.

The prediction method comprises three steps: streamflow prediction from daily rainfall, optimum supply pipe diameter calculations and optimum hydro turbine sizing knowing mean daily streamflows. These steps, taken together, allow the prediction of daily mean power output of a hydro turbine.

Two ways of checking results were tested, and within the limitations of these checks the method was shown to be sufficiently accurate for use in community energy planning work.

Section 5.4 details five catchments on the island of Eigg to which the method was applied, allowing power predictions to be made for use in the community energy planning model described in section 4.1 and chapter 6.

Section 5.3 Modelling Space Heat Demand for a Typical House on the Island of Eigg

5.3.1 INTRODUCTION

Space heating is often the single largest energy demand in small communities (Twidell & Pinney 1985, Good et al 1982, Atiku et al 1986 and Canadian Min. of Energy 1982), and can be more than 50% of the total energy demand. Therefore any modelling of community energy demands must have an accurate method of assessing space heat needs.

Space heat demands may be found by energy survey (Chapter 3), but the results of a survey may not be accurate because:

a) Fuel prices may be high, so that houses are under-heated, or heated in fewer rooms than if prices were lower.

b) Energy supply equipment may have low efficiency, leading to a higher apparent demand.

c) Houses might be poorly insulated or draughty, giving higher than necessary demands.

A thorough energy census found the current demand for space heating on the island of Eigg. But for the reasons above the census probably under-estimates the demands which would exist if energy was cheaper and more readily available and if houses were better insulated and draught-proofed. So to obtain more reasonable demand levels for houses on Eigg (to be used for energy planning), methods of simulating the demand are investigated, based on a knowledge of building size and shape, weather conditions and assumed comfort levels.

A single house, comprising four heating zones, was chosen to be 'typical' of the majority of all houses on Eigg. The house was 'typical' in approximate terms of size of zones, type of construction, comfort levels, occupancy levels and levels of insulation and draught-proofing. The four zones are the kitchen, living room, one general room and three bedrooms (treated as one zone).

One of the objectives of the community simulation work is to investigate the use of renewable energies to provide space heat.

Therefore the models should account for three features:

1) Correlations of heat demand with wind speed and solar radiation.
2) Short-term fluctuations of renewable energies with time, so a modelling time step as short as possible should be used.
3) Thermal storage of the building, as this can smooth out some of the fluctuations in renewable energy supplies.

5.3.2 SYMBOLS AND UNITS

Symbol	Description	Units
A	Surface area	m^2
I	Current	A
Q	Heat transfer rate	W
R	Resistance	Ω
R_L	Longwave radiation rate	W/m^2
S	Air change rate	m^3/s
T	Air temperature	K
T_e	Sol-air temperature	K
ΔT	Temperature difference	K
U	Overall heat transfer coefficient	W/m^2K
V	Voltage	V
a	Absorption coefficient	-
b	Constant	1/s
c	Constant	1/m
c_p	Specific heat capactity of air	J/(kg K)
d	Constant	m^2K/W
e	Constant	$1/K^3$
f	Constant	$1/K^2$
i,k	Constant	W/K
j	Constant	Ws/mK
l	Constant	m^2
m	Constant	ms
n	Constant	W/K^4
p	Constant	1/K
r_s	External surface resistivity	m^2K/W
u	Wind speed	m/s
v	Room volume	m^3
ρ	Air density	kg/m^3
ϵ	Emissivity	-
σ	Stefan-Boltzman constant	W/m^2K^4
Φ	Global radiation rate	W/m^2

Suffices

c	Building element or zone c
o	External
sky	Sky
1,2,3,4	Zone 1, 2, 3 or 4
r	Roof
w	Wall

5.3.3 LITERATURE REVIEW

The three main types of building heat models are: 'steady-state' models which do not account for heat storage within the building fabric, and non steady-state and electrical analogue models which do study storage. A good cross-section of model types is to be found in CIB (1982) containing 32 papers on building modelling.

Steady-State Models

In the steady-state class many models exist, of greater or lesser complexity; a typical example being Uglow (1980). This describes a simple model where an overall heat transfer coefficient for each element (walls, ceilings, etc.) of the dwelling is determined. Heat transfer rates can then be calculated using the basic equation

$$Q_c = U_c A_c \Delta T \qquad (5.3.1)$$

where Q_c = heat transfer rate through element c,
U_c = overall heat transfer coefficient of element c,
A_c = area of surface c
and ΔT_c = temperature difference either side of element c.

A ventilation heat loss term can be added to eqn. 5.3.1, and Uglow refers to work by Warren (1978) on ventilation rates in houses. The model makes many simplifying assumptions, that:

1) Air temperatures are uniform over an element's surface.
2) Air temperatures in rooms, and outside, are uniform.
3) Heat transfer does not occur between adjoining elements.
4) Heat storage effects can be neglected.
5) Radiative heat transfer is small.
6) Shading effects can be ignored.

However, models of this type have the advantage of being very simple to formulate. Radiative heat transfer can be partially accounted for using the function of sol-air temperature (see 5.3.4b below), and shading effects can be included with careful selection of temperatures. Because of their simplicity, two models in this work are this type.

Non Steady-State Models and Methods

Models of the non steady-state type are far more complex than the steady-state ones. The heat transfer equations needed to account for the effects which steady-state models ignore are complex, and methods with varying levels of simplification have been derived to solve them. A well-proven model of this type is called Environmental Systems Performance (ESP), described in Clark (1983 and 1985). Details are given in 5.3.4a. ESP was chosen for this work because of its proven accuracy and its ready availability through the Dept. of Architecture of Strathclyde University.

Three main types of non steady-state models exist: response factor methods, numerical methods (of which ESP is an example) and electrical analogues (see overleaf). Response factor methods can further be split into time domain functions and frequency domain functions. The fundamental basis of the time domain method is to determine the response of a building to a specific unit excitation (for example a step change in temperature), then to combine the various responses to different excitations (temperature, solar radiation, etc.) to produce an overall response to all driving functions. Stephenson & Mitalas (1967) give a good description of this method.

Frequency domain (or harmonic) methods assume that met. data can be represented by series of periodic cycles. The response of the building to each driving parameter is calculated, then superposition theory used to calculate the response of the building to all driving parameters combined. This is the method used by the Chartered Institute of Building Services (CIBS) in their "admittance" method (Louden 1968).

Both response factor methods, and several numerical methods, are covered thoroughly by Gough (1984), to which the reader is referred. However, response factor methods were considered impractical because of the difficulties involved in implementing them, and solving the resulting equations, for practical buildings.

Electrical Analogue Methods

Electrical analogue methods were far more widely used in the 1950's than they are today. The principle behind them is that heat transfer paths can be represented by an equivalent electrical circuit. Resistors are the equivalent of thermal resistance and capacitors of heat storage, while current represents heat flow and voltage difference is the equivalent of temperature difference. General descriptions of this method are found in Williams (1952) or Burnand (1951).

The values of capacitance and resistance required to represent a building, as well as model time in comparison with real time, are not practical for most cases. Therefore scaling methods were devised, which are described in Day & Burberry (1976) or Nottage & Parmelee (1954).

Once the circuit has been formulated, two methods are available for solving it. The first involves the construction of an actual electrical circuit, described by Day et al (ibid) or Buchberg (1955). These models are quite accurate, but become more complex as heating patterns become more complex. The second method is to solve the circuit analytically. While this is easy for simple cases, it is far more difficult for practical systems (especially where the heating pattern changes during the day). Basnett (1974) and Nottage & Parmelee (ibid), though, have developed mathematical methods for circuit analysis.

The main factors against analogue models are a) the cost of building a dedicated analogue computer, b) the complexity of mathematical solution of the equivalent circuit, and c) the widespread availability of digital computers. For these reasons, very few references to this method are found nowadays, although one useful reference was Forrest (1979), who developed and tested a general-purpose analogue circuit which was applied to three houses in Scotland.

5.3.4 DESCRIPTION OF THE MODELS

5.3.4a The Environmental Systems Performance Model

A detailed description of the Environmental Systems Performance (ESP) model, together with examples, is given in Clark (1983 & 1985). A simplified description is presented here.

ESP is a non steady-state computer model, available commercially from the Dept. of Architecture of Strathclyde University. It needs 500 Kbytes of memory space to run the program and about 3.8 Mbytes of disc storage for results. It comprises 10 separate programs covering such things as meteorological prediction, building construction and dimensions handling, casual heat gains profiles and results analysis.

The building to be studied is divided into a number of zones (for example three rooms and a loft space). A representation of the building is then set up by the computer, which puts 'nodes' at important places within the building: air volumes, surfaces, occupants, windows, etc. Between each node and all other nodes with which it is thermally connected, a differential heat transfer equation is set up. The differential (ie infinitesimally small) elements are replaced by finite (ie measureable) values. The heat balance equations also account for heat storage. The equations therefore link all the energy flows between nodes in terms of space and time.

Since many nodes are linked to each other, it is possible to express all the equations in matrix form, accounting for variations in both space and time. ESP uses a matrix solution technique to solve its heat balance equations, which it does for each time step making up the total simulation time.

The matrix, when applied by ESP to a building, might typically be 1000x1000 values, and the repeated solution of such a large matrix for each time step of a simulation would be very time consuming. Therefore ESP partitions the matrix into sections, so that only those portions which change with time need be solved. For a full understanding of the matrix algebra involved, the reader is referred to Clark (ibid) or a general mathematics text such as Heading (1963).

ESP is able to account for the following:

a) Transient heat conduction through the building, and therefore the associated time lag and thermal storage effects.

b) Time-dependent sensible and latent heat gains from appliances and occupants (casual gains).

c) Infiltration and natural ventilation.

d) Longwave radiation exchanges between internal surfaces, and between external surfaces and the surroundings.

e) Shortwave radiation onto external and internal surfaces.

f) Heating or cooling plant type, and position and type of control point.

For this study the effects of wind on heat demand were investigated. Initially ventilation and air flow rates were set to zero, then a second simulation run with rates governed by the relations from Warren (ibid) having the general form

$$S = v(b + cu) \qquad (5.3.2)$$

where S = air change rate,
v = room volume
and u = external wind speed.

The value of c is $2.44\text{x}10^{-5}$ m^{-1} for all rooms, and b has the value $5.08\text{x}10^{-4}$ s^{-1} for the kitchen, $2.30\text{x}10^{-4}$ s^{-1} for the three bedrooms (treated as one zone), the general room and the living room and $6.47\text{x}10^{-4}$ s^{-1} for the loft space. All ventilation is to the outside, with no airflow between zones.

The control node for these simulations was the zone air temperature. The heating plant was a convective system exchanging energy at the zone air point: there was no cooling plant. Casual gains (heat from appliances, lights and people) are specified in the form of daily profiles. ESP needs these to be split into latent and sensible gains, and convective and radiative components.

5.3.4b The Sol-air model

The sol-air model is a steady-state model, so ignoring heat storage. Heat transfer through the building structure is calculated using temperature differences either side of a wall, floor or ceiling, with equations similar to eqn. 5.3.2. However, rather than use external air temperature, it uses the function sol-air temperature (ASHRAE 1981). This is the external temperature which would give the same rate of heat transfer through a building element as if the rate had been calculated accounting for air temperature and solar radiation effects. Sol-air temperature T_e is calculated using

$$T_e = T_o + [r_s(a\Phi - \epsilon R_L)] \qquad (5.3.3)$$

where r_s = surface resistivity (0.05mK/W for walls, 0.04mK/W for roofs)
a = absorption coefficient (0.45 for walls, 0.85 for roof),
Φ = global radiation rate,
ϵ = emissivity of outer surfaces (value 0.9)
and R_L = longwave radiation from a black surface at T_o.

Longwave radiation from a black surface (Duffie & Beckman 1980) is

$$R_L = \sigma(T_o^4 - T_{sky}^4) \qquad (5.3.4)$$

where σ = Stefan-Boltzmann constant, and the sky temperature T_{sky} can be derived from an empirical relationship of Swinbank (1963), found to give good agreement with recorded data in the range 7°C to 28°C

$$T_{sky} = 0.0552T_o^{1.5} \qquad (5.2.5)$$

Walls and roofs are treated as black surfaces, and it is assumed that R_L for walls is zero, since heat gain from the ground to the wall is about the same as the loss from the wall to the sky (ASHRAE ibid). From eqns. 5.3.3, 5.3.4 and 5.3.5 the sol-air temperature for a roof is

$$T_{er} = T_o + d\Phi - e(T_o^4 - fT_o^6) \qquad (5.2.6)$$

where d = constant, value 0.034 Km^2/W,
e = constant, value $2.04 \times 10^{-9}\ K^{-3}$
and f = constant, value $9.3 \times 10^{-6}\ K^{-2}$.

For walls, with R_L zero, the sol-air temperature is

$$T_{ew} = T_o + d\Phi \qquad (5.2.7)$$

where d = constant, value 0.0225 Km^2/W.

This model uses the same thermal data as ESP with three exceptions: 1) the loft space is not considered as a separate zone, but an overall heat transfer coefficient for the ceiling, loft and roof (per m^2 of ceiling) is used (CIBS 1980 and BRS 1975), 2) a similar equivalent coefficient is used for the floor, joists and foundations (expressed in terms of internal-external air temperature difference, rather than internal air-soil temperature difference) and 3) no doors are considered: walls are assumed to be continuous except for windows. Ceilings and floors account for 20% and 10% respectively of total heat loss, so errors caused by using the equivalent coefficients are small. Figure 5.3.1 shows the schematicised heat flows in the building.

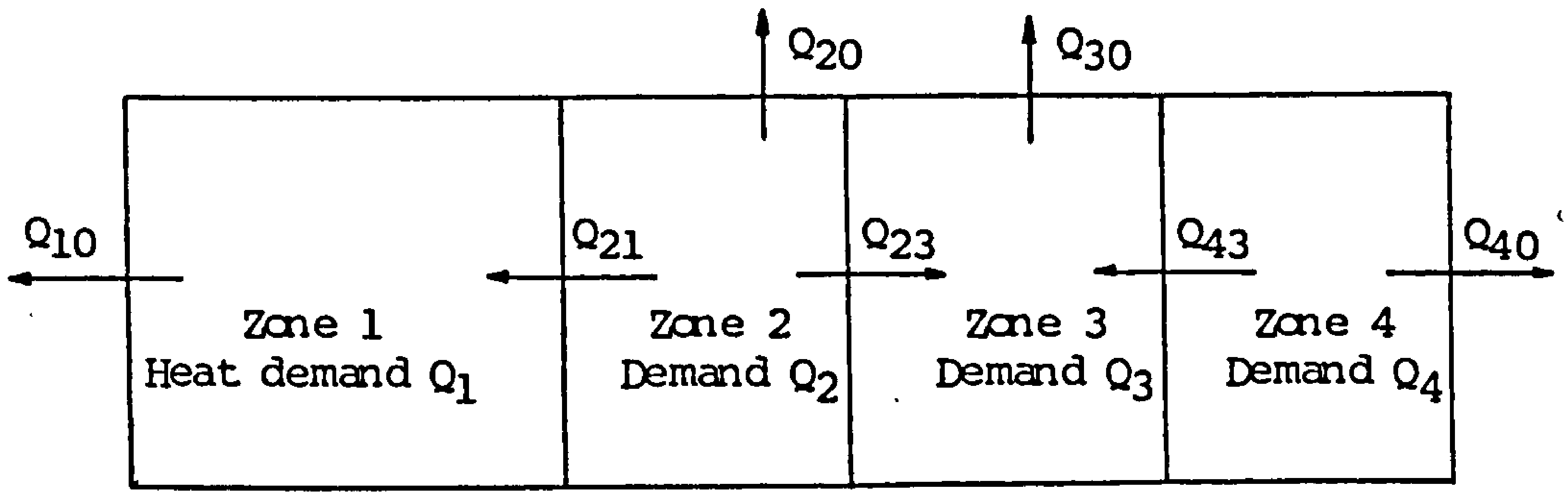


FIGURE 5.3.1 Simplified Heat Transfer Paths in Building

The formulae used for heat transfer are all of the type

$$Q_c = U_c A_c \Delta T \qquad \text{cf (5.3.1)} \qquad (5.3.8)$$

For ventilation heat loss, the equations are of the type

$$Q_c = S_c \rho v_c C_p \Delta T \qquad (5.3.9)$$

where S_c = air change rate from zone c, given by eqn. 5.3.2
and v_c = volume of zone c.

In both eqns. 5.3.8 and 5.3.9 ΔT for external elements is the internal air temperature-external sol-air temperature difference. Combining eqns. 5.3.8 and 5.3.9, and applying them, as an example, to zone 1, an equation of the following form results

$$Q_1 = (i + ju)(T_1 - T_o) + k(T_2 - T_1) - (l + mu)\Phi + n(T_o^4 - pT_o^6) \qquad (5.3.10)$$

where i, j, k, l, m, n and p are all constants.

Equations similar to eqn. 5.3.10 can be formulated for each of the zones and solved to give the heat demands in each zone.

This model uses similar data to those used by ESP; the same values for casual gains, the same equations for air change (except for the loft) and the same meteorological data. But this model is also tested with simulated hourly values of solar radiation, air temperature and mean daily wind speed as described in section 5.1.

5.3.4c The Internal-External Air Temperature Difference Model

This model is exactly the same as the sol-air one, except that air temperatures only are used rather than sol-air temperatures. The same building parameters, casual gains and meteorological data are used as for ESP, and this model is also tested with predicted weather data.

5.3.4d Electrical Equivalent Circuit Model

This model uses the idea that a heat transfer path can be represented by a series of electrical resistors and capacitors. The driving temperature differences are replaced by voltages, and heat flows by the currents in the circuit. The electrical equation is

$$V = IR \qquad (5.3.11)$$

The corresponding heat transfer equation would be

$$T = Q/UA \qquad \text{cf } (5.3.1) \qquad (5.3.12)$$

Therefore resistance represents the value of 1/UA for each element. Using a similar comparison of equations, capacitors represent the term $1/mC_p$, where m is the element mass and C_p its specific heat.

Figure 5.3.2 overleaf shows the circuit representing the house on Eigg. However the circuit was not solved because of a) the time and expense involved in building the circuit, and b) the difficulty of accounting for varying outputs of the heater (a current source) mathematically. Nonetheless, this method is presented here as a possible method which falls between the steady-state models and ESP in its complexity.

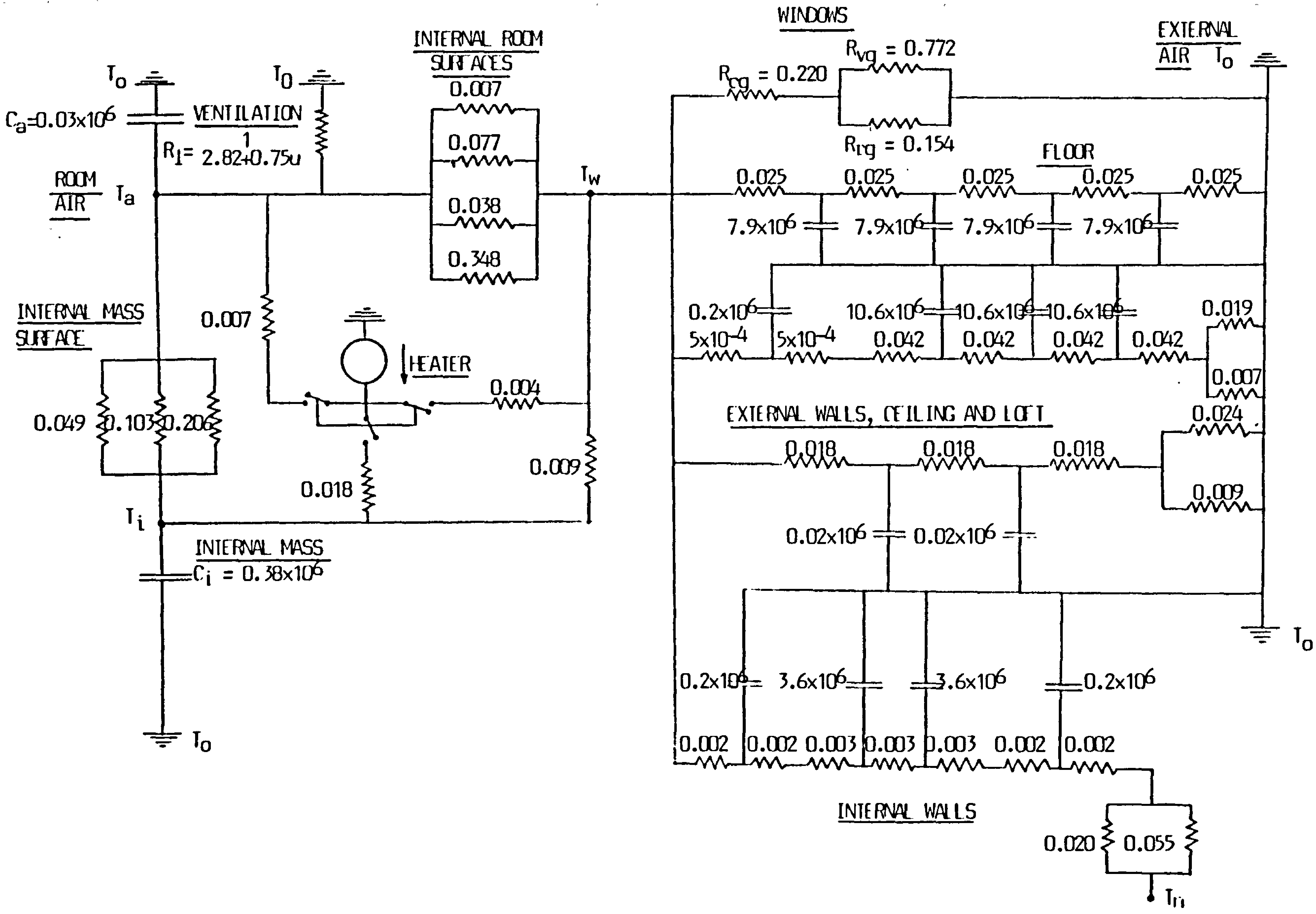


FIGURE 5.3.2 Electrical Equivalent Circuit for the 'Typical' House on Eigg

5.3.5 DESCRIPTION, DIMENSIONS, THERMOPHYSICAL PROPERTIES AND CASUAL GAINS OF THE TYPICAL HOUSE

Description

The house to be studied is divided into four zones:

Zone 1 is three bedrooms treated as a single zone, with a constant temperature of 15°C throughout the day.

Zone 2 is the kitchen, in which the temperature is constant at 21°C from 7 am to 11 pm, then 15°C from 11 pm to 7 am.

Zone 3 is a multi-purpose room with constant daily temperature 15°C.

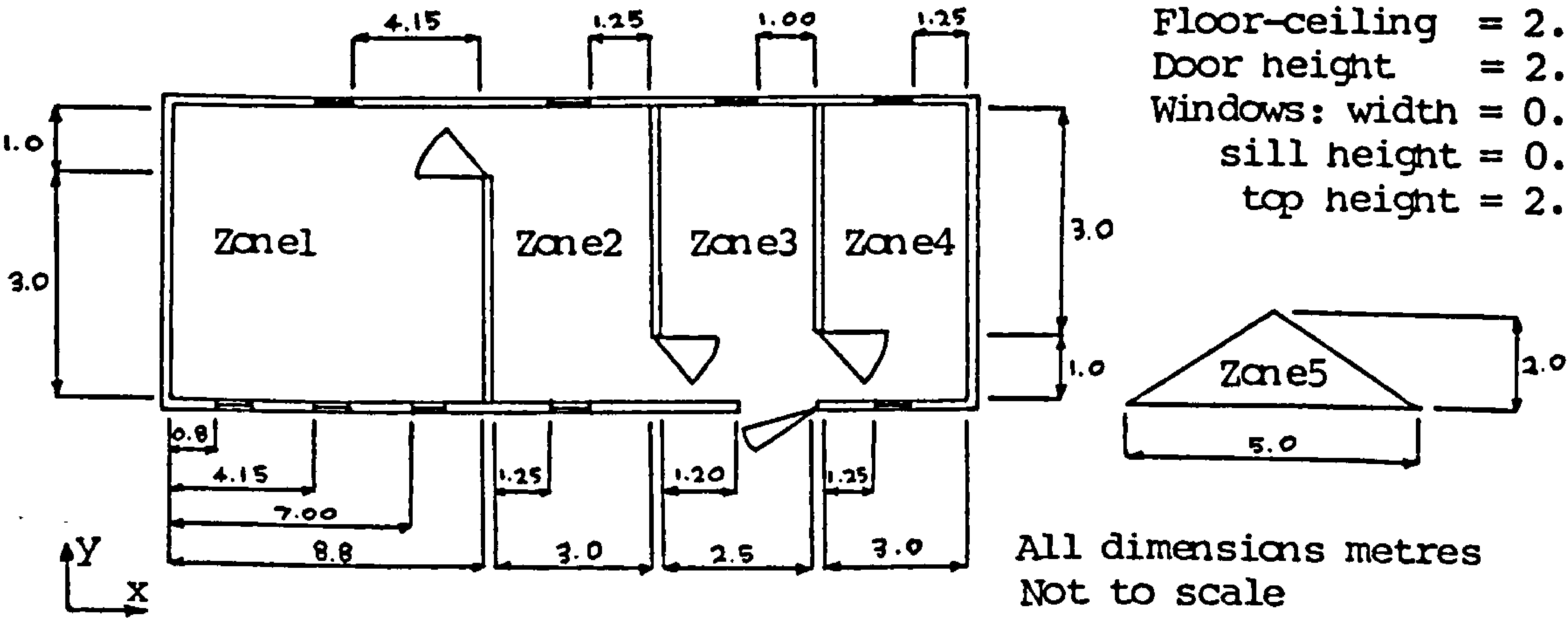
Zone 4 is the living room, the temperature being 21°C from 6 pm to 10 pm, then 15°C from 10 pm to 6 pm.

(ESP treats the loft as a zone, but without temperature constraint)

The building for all models has the same dimensions and type of construction. Since ESP requires the most detailed data and dimensions, these are described below.

Dimensions

Figure 5.3.3 shows the overall dimensions of the house.



Floor-ceiling = 2.2m
Door height = 2.0m
Windows: width = 0.5m
sill height = 0.9m
top height = 2.2m

All dimensions metres
Not to scale

FIGURE 5.3.3 Dimensions of House

Thermophysical Properties

ESP requires the thermophysical properties and dimensions of all elements making up a zone enclosure. Table 5.3.1 (relating to zone 1) lists the properties and thickness of each element, numbered from the outside in. Door and window heat transfer coefficients are 6.00 W/m^{2}K and 5.70 W/m^{2}K respectively.

Surface	Element number	Conductivity $(W/m^2 K)$	Density (kg/m^3)	Specific heat (J/kg K)	Thickness (m)
1	1	2.900	2650.0	900.0	0.4840
	2	0.420	1200.0	837.0	0.0160
2	1	0.420	1200.0	837.0	0.0160
	2	2.900	2650.0	900.0	0.3000
	3	0.420	1200.0	837.0	0.0160
3	1	2.900	2650.0	900.0	0.4840
	2	0.420	1200.0	837.0	0.0160
4	1	2.900	2650.0	900.0	0.4840
	2	0.420	1200.0	837.0	0.0160
5	1	0.190	960.0	950.0	0.0400
	2	0.190	950.0	840.0	0.0100
6	1	1.280	1460.0	879.0	2.0000
	2	1.400	2100.0	650.0	0.1000
	3	10.000	-	-	0.1000
	4	0.140	600.0	1210.0	0.0100
	5	0.055	198.4	1360.0	0.0050

	Element	Description	
Key: Surface 1, 3 & 4	1	Stone	External walls
	2	Gypsum plaster	
Surface 2	1 & 3	Gypsum plaster	Internal walls
	2	Stone	
Surface 5	1	Glass wool insulation	Ceiling
	2	Gypsum plaster	
Surface 6	1	Earth	Floor
	2	Concrete	
	3	Air gap	
	4	Floorboards	
	5	Carpet	

Table 5.3.1 Thermophysical properties of building elements for zone 1

Casual Gains

Heat gains from occupants, appliances, lights, etc. can be an important proportion of the total heat demand. So a typical casual gains profile was determined for each zone. That for zone 2 is shown on fig. 5.3.4. The gains are from people, fridge, cooker and lights.

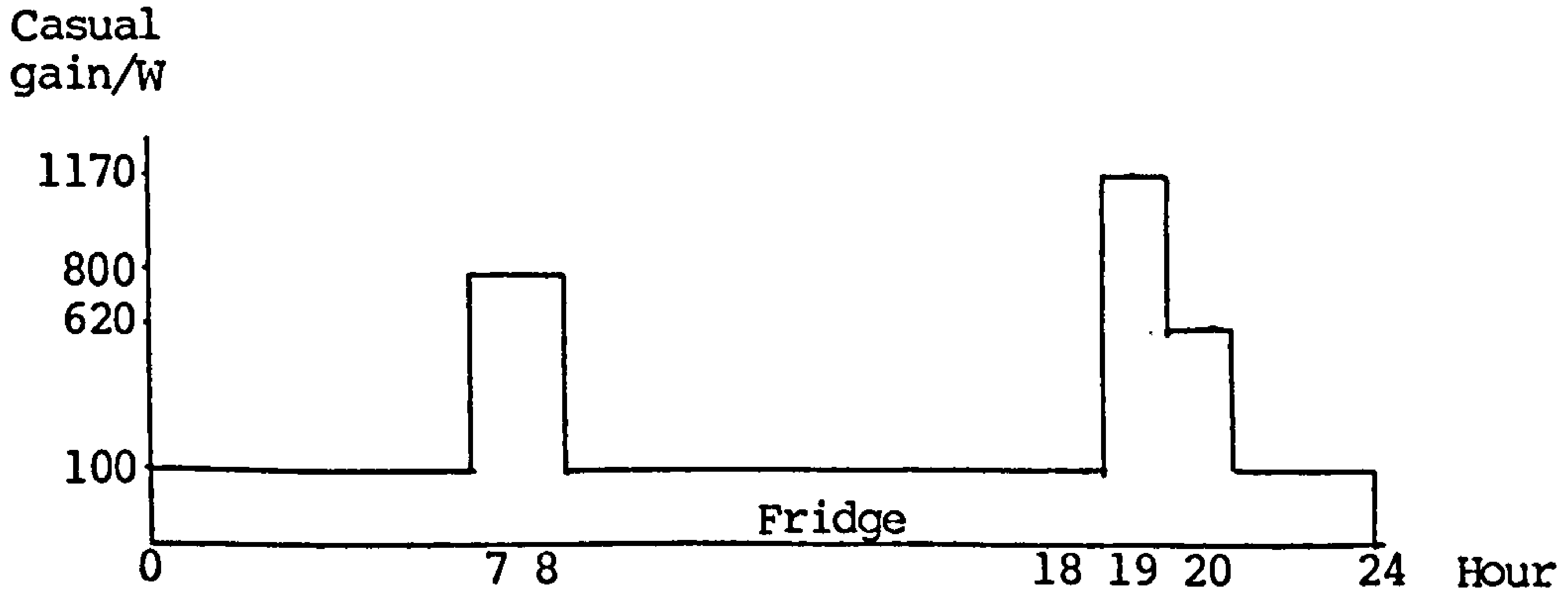


FIGURE 5.3.4 Casual Heat Gains Profile for Zone 2

5.3.6 PRESENTATION AND DISCUSSION OF RESULTS

The main objective was to test the two steady-state models in their simplest form (using predicted weather data) against ESP (which always uses real data). March was chosen as a typical month from which to show results. Other months' results are discussed but not presented. All figures are for zone 2, the kitchen, chosen as an example. It is assumed that ESP gives the most accurate results, so the success of the simple models is judged by their closeness to the ESP values.

Figs. 5.3.5 and 5.3.6 compare the three models, using predicted met. data in the simple models. Hourly results for three days in March are shown on fig. 5.3.5. These results, and those from a low-radiation month (January) and a high-radiation month (May) can be summarised by:

1) The air-temperature-only (ATO) model agrees well with ESP in March, giving demands on average only 10% higher. It follows the shape of ESP's results in January and May, but results are typically higher by 20% and 30%.

2) The sol-air model gives poor agreement with ESP both in shape and magnitude during March and May, but agrees well with ESP in January, both in shape and magnitude.

A daily time step was tried in all models to see if this would give better agreement between them. The results from March (fig. 5.3.6), and those from January and May can be summarised as:

1) The ATO model results for March follow those of ESP, but give demands higher by about 20% on average. In January and May they follow ESP results, but values are about 15% and 35% higher respectively.

2) The sol-air model in March gives poor agreement with ESP in shape, but magnitude differences are only about +/-15%. It agrees well in shape during January, but overestimates the demand by typically 15%. It differs widely in shape during May compared to ESP, but has better magnitude agreement than ATO.

The two simple models were tested with the same real hourly data as used by ESP for the typical month of March. The results are shown on figs. 5.3.7 and 5.3.8. There is no immediately-noticeable improvement, and in fact only small differences (smaller on a daily than an hourly basis) are seen between using real and predicted weather data.

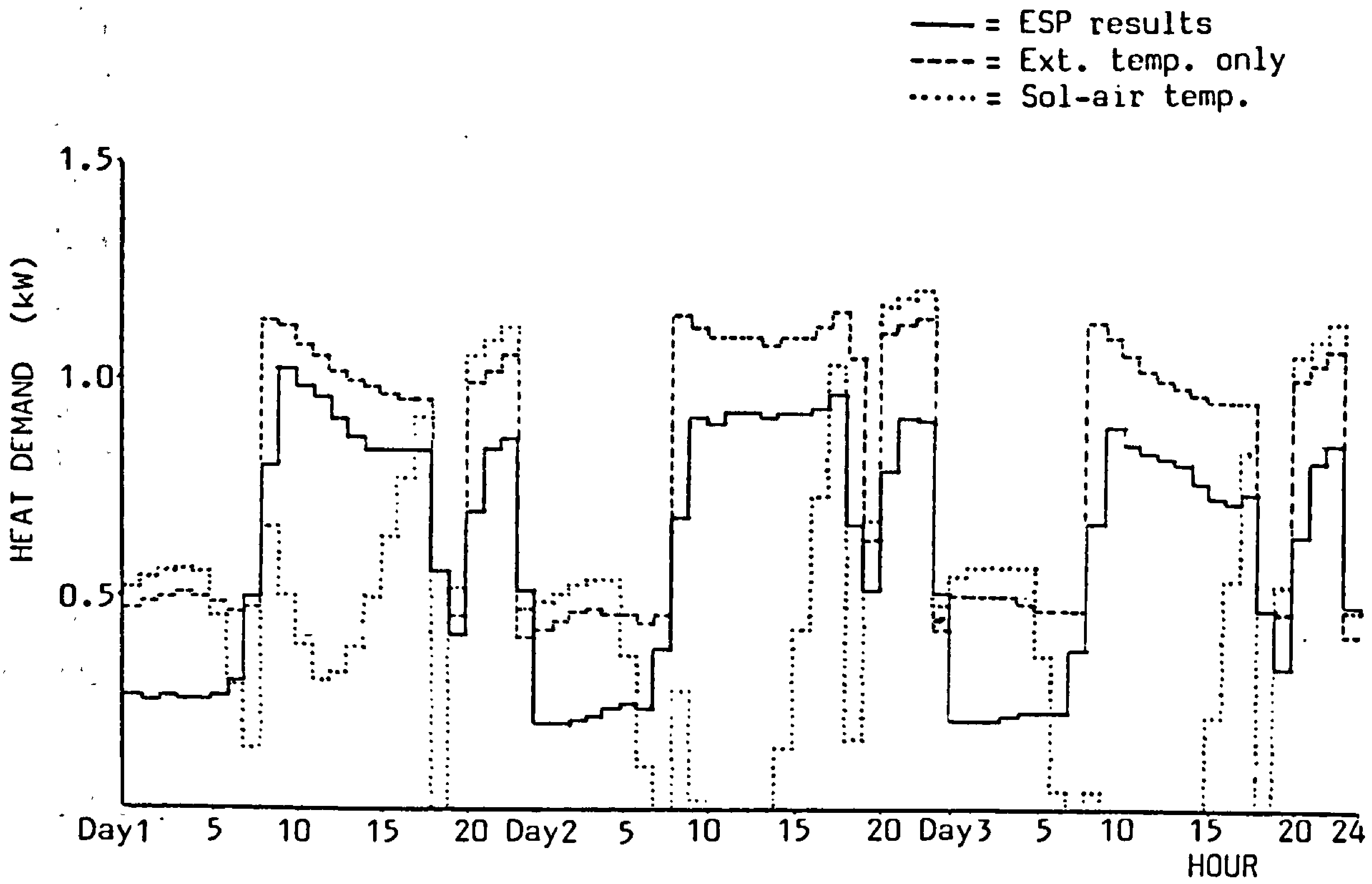


FIGURE 5.3.5 Hourly Heat Demand in Zone 2 for the First 3 Days in March Using Predicted Weather Data in Steady-State Models

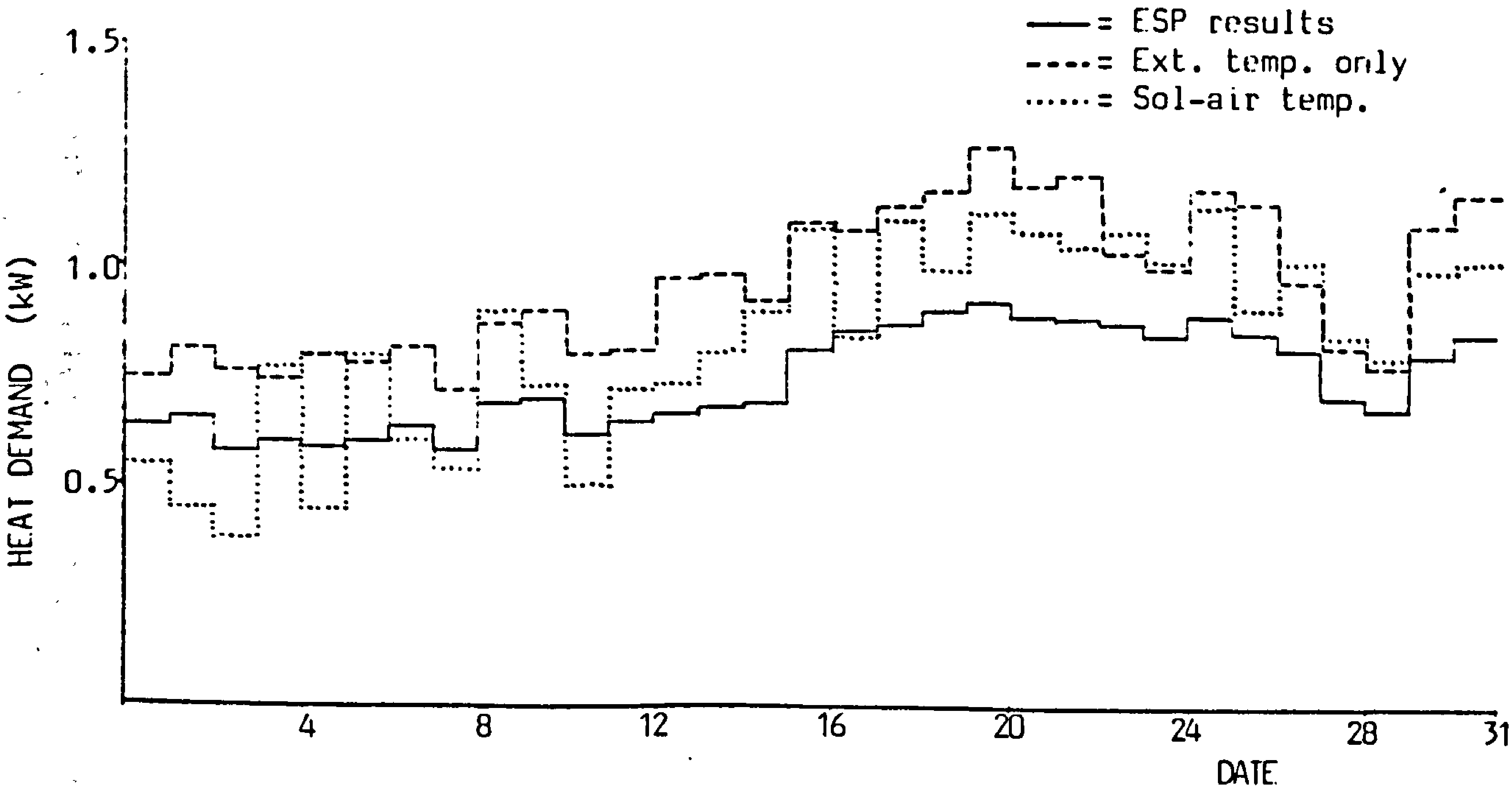


FIGURE 5.3.6 Mean Daily Heat Demand in Zone 2 for March Using Predicted Weather Data in Steady-State Models

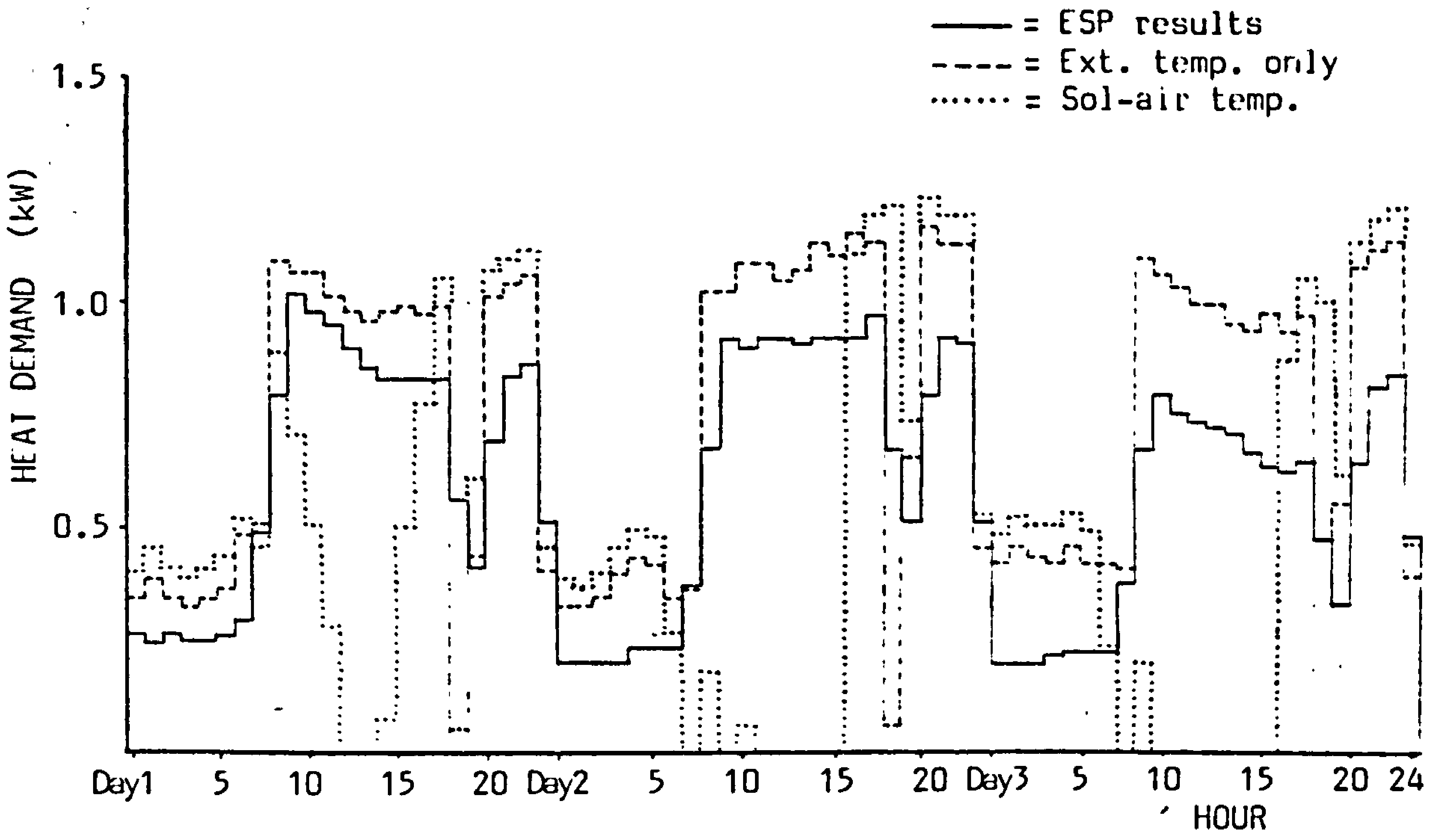


FIGURE 5.3.7 Hourly Heat Demand in Zone 2 for the First 3 Days in March Using Real Weather Data in all Models

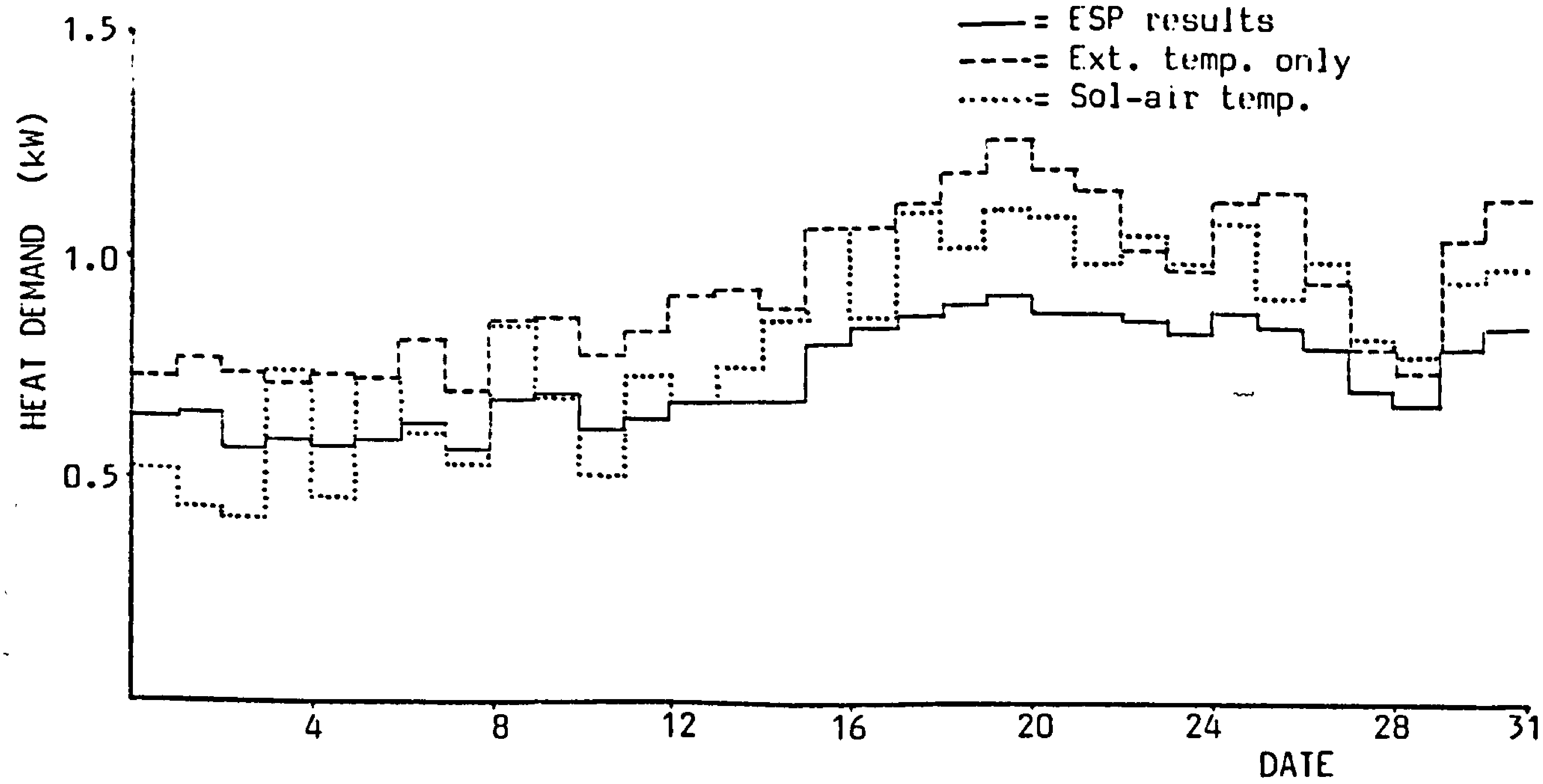


FIGURE 5.3.8 Mean Daily Heat Demand in Zone 2 for March Using Real Weather Data in all Models

The importance of casual gains was tested in the ATO model for a daily time step in March. The results from fig. 5.3.9 show that casual gains are indeed important, being typically 20% of total heat demand on a daily basis (sometimes between 50% and 100% on an hourly basis).

A further objective of this work was to correlate wind speed with building heat loss, to assess the match between available wind power and heat demand. ESP simulations were run for the high wind speed month of January, in which the ventilation rates were first set to zero, then made constant, then controlled by eqn. 5.3.2. The results (fig. 5.3.10) show that wind loading is an important factor, accounting typically for 35% of total demand. Similar simulations were run for the low-windspeed month of April, and although wind-related losses were lower, they were still about 30% of the total heat demand.

5.3.7 DISCUSSION

The main aim of this section was to find a suitable means of predicting space heat demands for houses found in remote or island communities. Three methods were tested for a house on the island of Eigg in Scotland; the sophisticated Environmental Systems Performance (ESP) model and two steady-state models, one of which accounting for solar radiation. Assuming ESP's results to be the most accurate, neither of the steady-state models can consistently reproduce the building heat demands. Errors range from +/-10% to +35% both on an hourly and a daily time step. This is too high for most modelling work.

ESP is too large to be easily available as a general planning model. Therefore it is concluded that an acceptable model, which could be easily and accurately applied, has not been found. Further development of electrical analogue methods might give a suitably accurate method in between the complexity of ESP and the simplicity of the steady-state models.

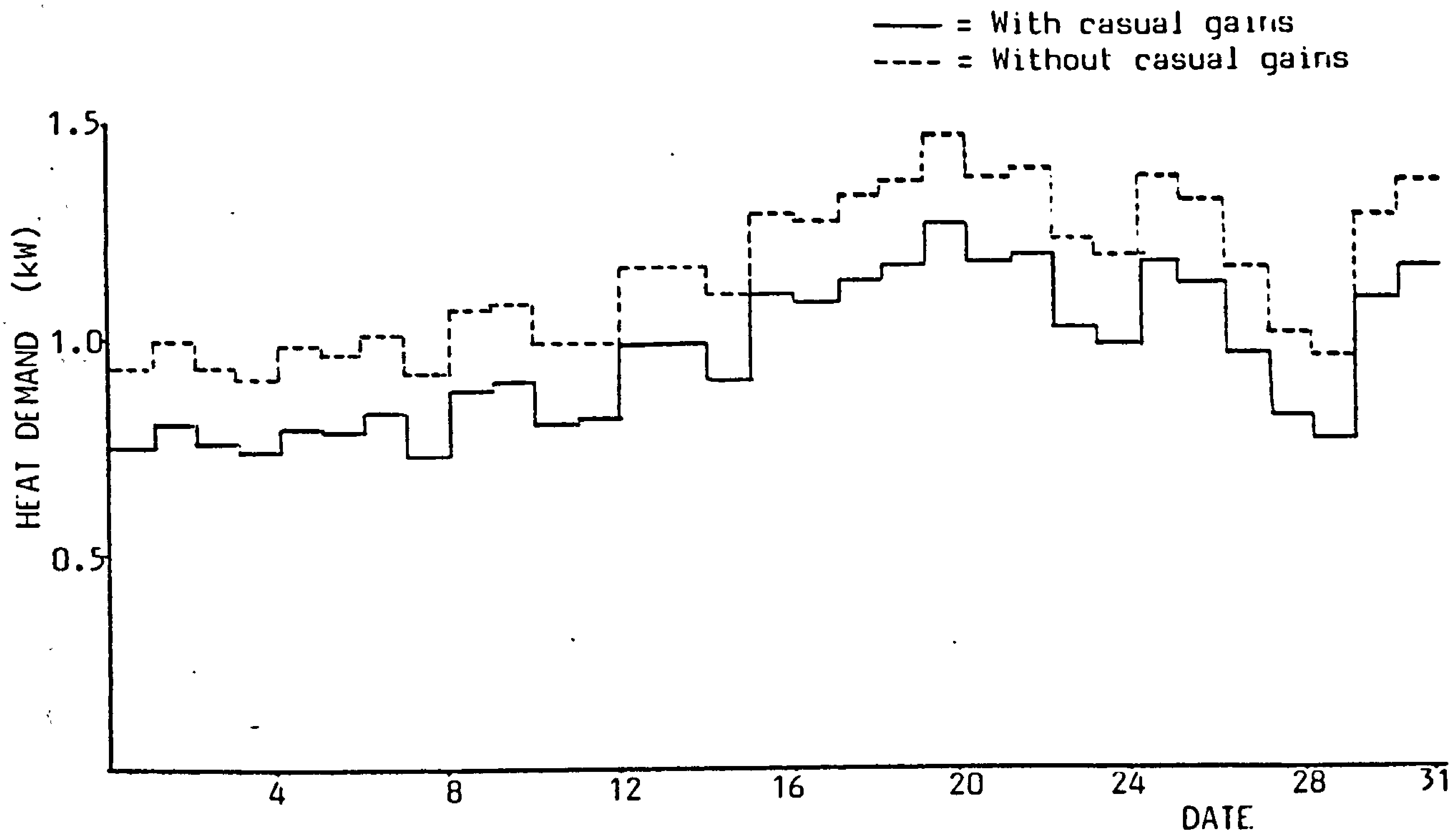


FIGURE 5.3.9 Effects of Excluding Casual Heat Gains on Mean Daily Heat Demands for Zone 2 in March using Air Temperature Difference Only Model

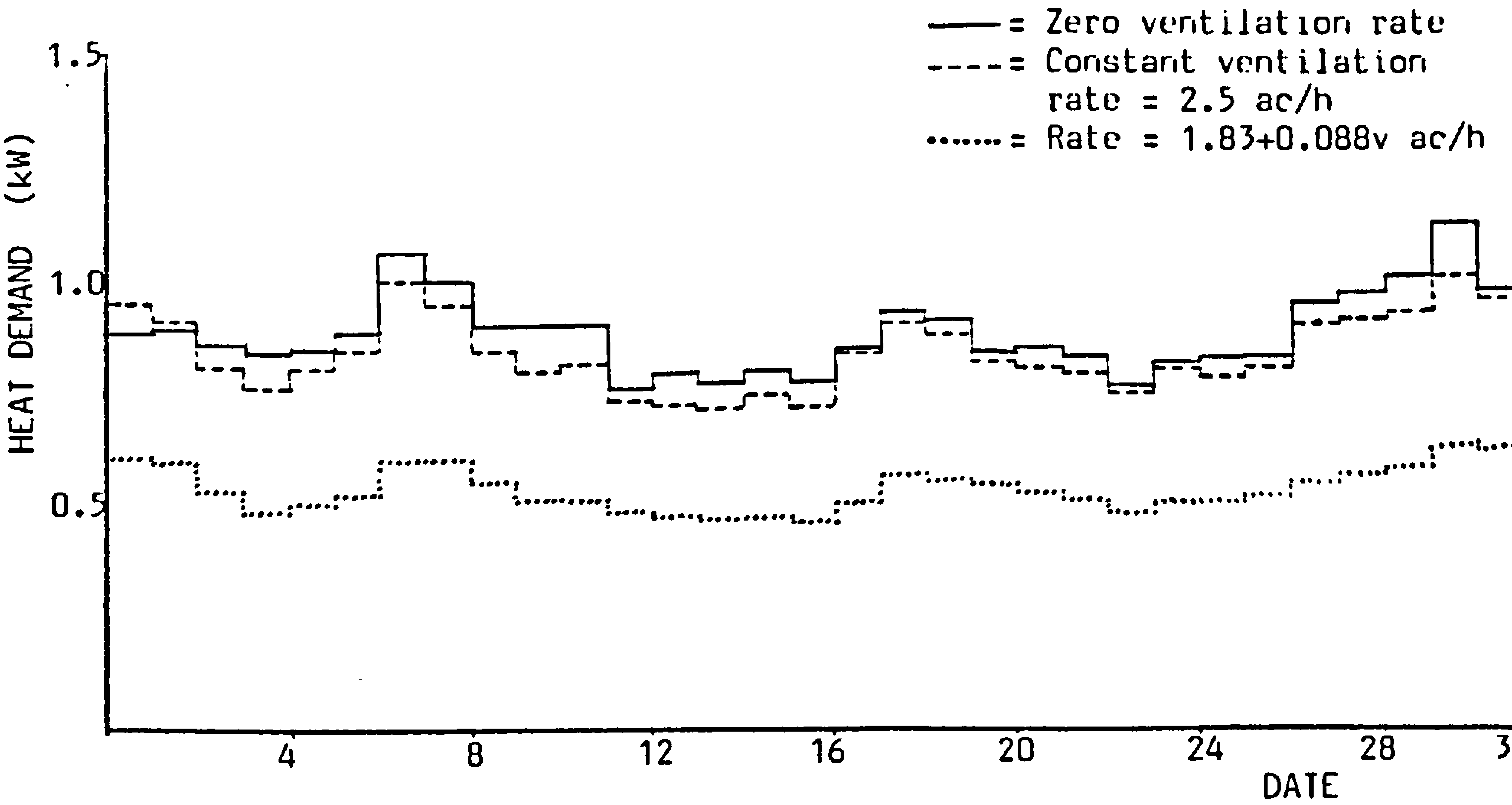


FIGURE 5.3.10 Effects of Varying Ventilation Rates on Mean Daily Heat Demands for Zone 2 in March using ESP

Section 5.4 Energy Demands and Available Supplies on the Island of Eigg

5.4.1 INTRODUCTION

Energy planning of any sort requires detailed knowledge of both energy demands and energy sources which can be used to meet those demands. The accuracy of supply and demand data is crucial to the results of energy planning, since low accuracy data can only lead to low accuracy planning results.

The small Scottish island of Eigg was chosen as an example of a small, rural community, on which the energy planning strategy of this thesis could be tested. Although a detailed census of current energy demands on the island was undertaken (Chapter 3), the results from this (for reasons discussed in chapter 3 and section 5.3) are not necessarily representative of the energy demands if changes were made to the ways of supplying and using energy. Infield & Puddy (1984) and Sinclair et al (1984) have shown that in communities where energy supplies become more available, and cheaper, the demand increased.

This section discusses ways for determining reasonable energy demand levels for the island of Eigg, which can be used in energy planning work. The four types of demand are cooking, hot water, space heat and electricity for appliances. These are assessed as final-form levels (the demand level at the output of the supply equipment), allowing demands to be calculated independently of supply equipment efficiency and fuel type.

Two levels of demand are presented: the current level existing on Eigg (that found by the census for the year 1983-1984 but modified to account for more realistic space heat and electricity demands) and the level assumed to occur given cheaper and more available supplies.

This section also presents results from applying the hydrological model (section 5.2) to five catchments on Eigg, and determines wood fuel potential on the island.

5.4.2 CURRENT AND IMPROVED ENERGY DEMAND LEVELS FOR THE ISLAND OF EIGG

Current energy demands used in modelling work are obtained by reference to the energy census of Eigg (chapter 3). However, they differ from the census results in that the space heating demands are taken from the house heat modelling work of section 5.3 and electricity demand levels are taken from another small community.

Four types of demand are specified: space heat, hot water, cooking and electricity. The electricity demand is for appliances only; excluding electricity for cooking, water or space heating. Similarly hot water does not include that used for space heating from a central heating system.

Space heating

Space heating demand levels were obtained from modelling a typical house on Eigg (section 5.3), comprising four types of zone. Temperature levels and ventilation rates in the house were those recommended by the Chartered Institute of Building Services (1979a & 1979b). The demands of each zone are shown in table 5.4.1.

Zone	Total yearly demand (kWh/y)	Maximum mean hourly demand (kW)	Minimum mean hourly demand (kW)
Kitchen	5100	1.502	0.000
Living room	3650	1.649	0.000
Bedrooms	6670	2.319	0.000
General room	2020	0.769	0.000

Table 5.4.1 Space heating demands for typical house on Eigg

Every house on the island was visited during the census, and this allowed the types of zone in each house to be determined. The demand for each house was therefore made up of combinations of the demands from the above zone types. For current energy demands, only those zones which are at present heated are considered. For the improved demand levels, all zones in each house are heated according to their type.

Hot water

Hot water demands were mainly from census results, as these were found to be reasonable when compared with those of mainland Britain (Leach et al 1979). For houses with very low demand (because water had to be heated on the cooker), a more reasonable level was assumed, taken from other houses on Eigg having similar occupancy and comfort levels.

The census obtained only daily total energy demand (kWh/d). This is converted to hourly demands by assuming a constant mean hourly demand rate between 7 a.m. and 12 p.m. and zero demand overnight.

Cooking

These demands were obtained mainly from the census. Cooking was done by gas or ranges, and the demand is the sum of these if a house had both. A similar process as for hot water was used to assess cooking demands for houses where the census demand was unrealistically low.

The census found approximate hourly mean demands for most houses, but where hourly data were not available a typical usage pattern was assumed, based on daily total energy usage and personal experience during the census. The hourly pattern for a day is assumed to be the same for all days throughout the year.

Electricity

Although the census found the daily electricity demands for those houses on Eigg which have access to an electricity supply (13 houses have access to diesel generators, and 2 to hydro turbines), it would be difficult to convert these to true demands given cheaper and more convenient electricity. Even those houses with electricity supplies tend to have a limited number of electrical appliances, because of the expense and inconvenience of running diesel generators.

The census established that people would prefer higher demand levels and a wider range of appliances. It is assumed for this study that if electricity became cheaper and more available, the demands would become similar to those for houses on the British mainland (this is the method suggested by the United Nations (1974)).

The small (40 houses) community of Abertridw in Wales had been monitored over a total period of 94 days: demand data being averaged over a 5 minute period (Slack 1983). These were for appliances only, and did not include cooking, water or space heating. Five houses were chosen with demands ranging from high to low (table 5.4.2). Only 14 days of continuously recorded data were available, so the hourly demand pattern (obtained by summing and averaging the 5 minute values for each hour) is assumed to recur every 14 days.

Level	Total yearly demand (kWh/y)	Maximum mean hourly demand (kW)	Minimum mean hourly demand (kW)
Low	540	0.243	0.000
Average low	1410	1.160	0.107
Average	2420	1.674	0.029
Average high	4930	1.800	0.192
High	7160	3.720	0.250

Table 5.4.2 Electricity demand statistics for Eigg

When modelling the current energy supply system on Eigg, houses with existing electricity supplies were given an appropriate demand level from those above. For improved demand levels, all houses were assumed to have a demand level estimated from personal experience gained during the energy census.

Table 5.4.3 shows total annual energy demands for each house on Eigg, comparing assumed demands with those found by the census (excluding candles, gas lights and gas fridges). The differences between census demands and those used in the model come mainly from significant overheating of the houses on Eigg during the summer months, caused by cooking ranges from which the level of space heating is difficult to control. There are also slight differences caused by the islanders only running their generators in the evening, whereas Abertridw has electricity throughout the day.

House	Modelling demand	Census demand
1	40.0	40.3
2	15.4	15.3
3	13.0	14.9
4	19.7	23.5
5	18.8	24.6
6	11.3	18.2
7	12.1	18.1
8	8.3	4.7
9	10.8	21.1
10	21.3	32.0
11	13.7	23.7
12	6.2	5.5
13	8.6	14.0
14	13.3	8.1
15	7.2	14.0
16	22.8	21.7
17	13.0	14.4
18	9.0	26.7
19	8.3	15.4
20	14.3	11.7
21	20.5	20.9
22	6.3	8.3
23	8.3	12.1
24	16.3	27.2
25	8.6	4.4
26	13.8	16.4
27	13.7	15.4
Total	374.6	472.6

Table 5.4.3 Current annual energy demands on Eigg. Units kWh/y x 10^3

For the improved level of demand (table 5.4.4) each house is heated in all zones and has an electricity demand (hot water and cooking stay the same). This level is 33% higher than total demand from the census, so giving a large improvement in comfort and energy usage.

	Annual energy demands used in modelling				
House	Cooking	Hot water	Space heat	Electricity	Total
1	4.2	2.9	33.8	7.2	48.1
2	4.9	1.3	17.4	0.5	24.1
3	3.5	2.0	19.5	2.4	27.4
4	3.3	2.7	19.5	4.9	30.4
5	3.9	1.2	26.2	4.9	36.2
6	1.6	2.2	17.4	2.4	23.6
7	2.2	1.1	24.1	0.5	27.9
8	1.3	1.9	5.1	0.5	8.8
9	4.2	1.0	15.8	0.5	21.5
10	1.6	2.3	15.4	7.2	26.5
11	0.7	2.8	24.1	1.4	29.0
12	2.1	0.5	5.1	1.4	9.1
13	1.7	1.8	15.4	1.4	20.3
14	2.9	0.4	9.1	4.9	17.3
15	0.9	0.6	15.8	2.4	19.7
16	4.8	2.0	17.4	4.9	29.1
17	6.8	1.1	9.1	0.5	17.5
18	1.7	2.2	17.4	2.4	23.7
19	2.6	0.6	9.1	0.5	12.8
20	8.1	1.1	22.1	2.4	33.7
21	1.7	2.8	17.4	7.2	29.1
22	2.3	0.4	10.8	1.4	14.9
23	0.8	2.4	15.4	2.4	21.0
24	3.8	1.3	17.4	2.4	24.9
25	3.4	0.2	5.1	1.4	10.1
26	4.1	0.9	7.1	1.4	13.5
27	1.2	2.5	17.4	4.9	26.0
					626.2

Table 5.4.4 Improved annual energy demands on Eigg. Units kWh/y x 10^3

5.4.3 HYDRO-ELECTRIC AND WOOD FUEL POTENTIAL ON EIGG

Hydro-electric potential

There are five burns on the island of Eigg (figure 5.4.1 overleaf) which have hydro power potential. Their areas, static heads and supply pipe length are shown on table 5.4.5. The method of sizing hydro turbines presented in section 5.2 was used to determine the approximate sizes of turbine to install, and the annual energy output from each catchment. These are also shown on table 5.4.5 (turbine sizes were modified to those for which cost data were available).

Catchment	Area km^2	Static head (m)	Supply pipe length (m)	Electrical rating (kW)	Annual potential output (kWh/y)
Laig	3.1	33.5	50	11.0	85100
Cleadale	2.1	25.0	50	8.5	53700
Lodge	1.6	20.0	100	8.5	48600
Kildonan	1.6	30.0	300	8.5	55800
G.P.O.	1.1	20.0	600	3.0	22100

Table 5.4.5 Details of hydro power on Eigg

Wood fuel potential

Various references dealing with woodland in similar climatic areas to Eigg were used to determine the likely wood fuel potential on the island. Values for potential yield varied from 6 tonnes dry wood/ha/y to 12 tonnes dry wood/ha/y (Mitchell 1981 and Gen. Technology Systems Ltd. 1981). These figures relate to about a 12 to 20 year rotation of fast-growing, single stem trees, such as Sitka Spruce.

There are currently about 50 ha of established woodland on Eigg. However, the tree stock is varied, and does not consist only of fast-growing trees. A further 50 ha of fast growing spruce trees were planted during 1983, but these will not mature for several years. It is assumed that if the current woodland was used, and replaced immediately by faster growing trees, the consistently-available wood fuel potential would be at the lower end of the yields given above, namely 50x6 = 300 tonnes dry wood/y. This has an energy content of 1.35×10^6 kWh/y.

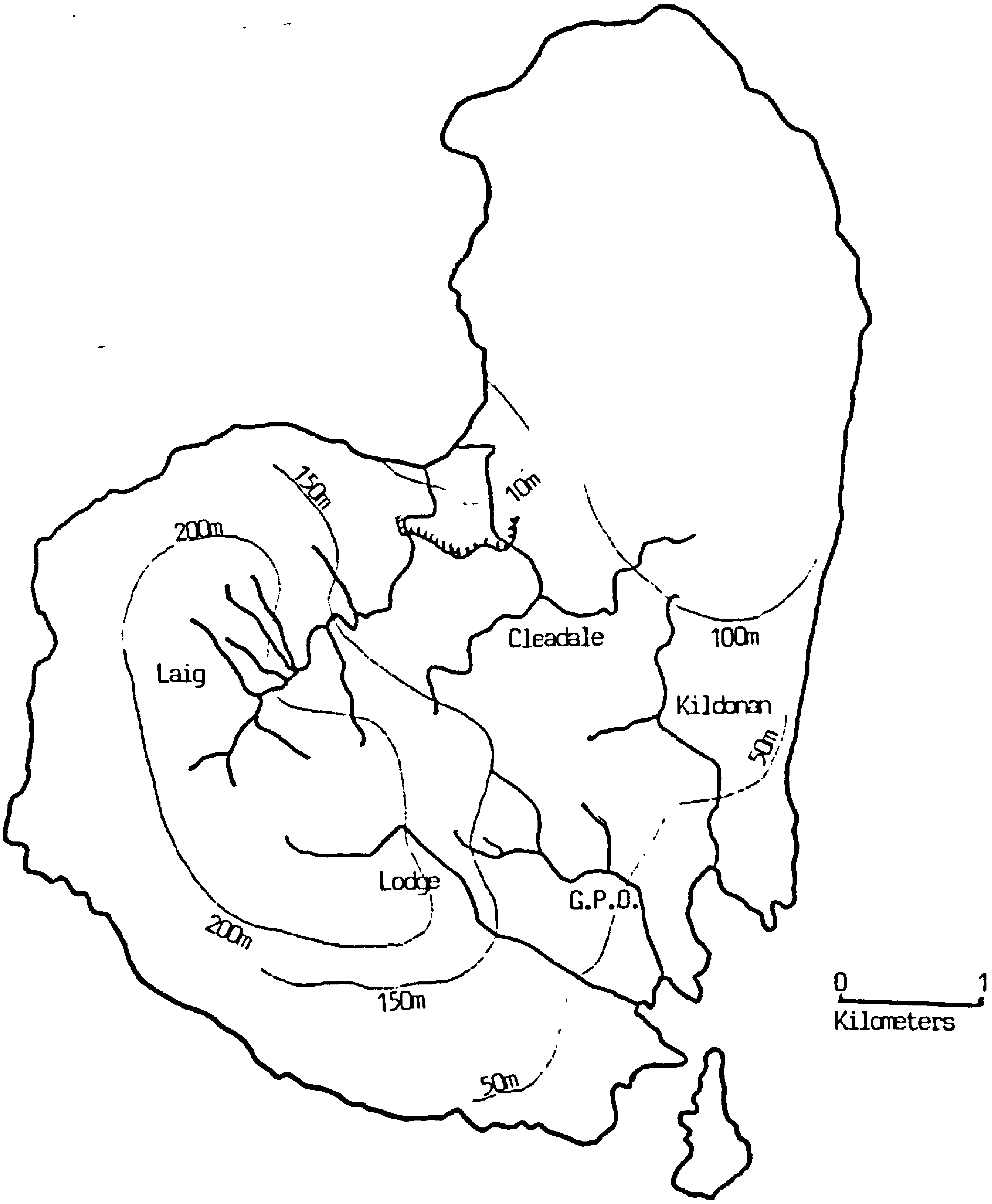


FIGURE 5.4.1 Catchment Areas on Eigg

This potential compares with 0.14×10^6 kWh/y currently used on Eigg, with a unit price of 0.009 £/kWh. This price is high in comparison with that suggested by Fraser (1981) of 0.007 £/kWh for commercially-developed woodland, but wood fuel is only used on a fairly ad hoc basis on Eigg. The potential of 1.35×10^6 kWh/y is taken to be the maximum possible, and tests were carried out to see the effects of limiting this potential, for example while current woodland is gradually replaced by fast growing trees.

5.4.4 DISCUSSION

The main aim of this thesis is to develop a strategy for energy planning, rather that to accurately model the island of Eigg; yet to still obtain results useful and relevant to the island. The methods of determining energy demands presented in this section keep to this aim, giving demand levels which are reasonable, based on personal experience of the island, and knowing demands which occur in other areas.

Implicit in this work is the assumption that the islanders want increased comfort and energy usage levels. There is no doubt that many people on the island would like improved levels if energy costs could be reduced, but to assume that they would like levels of usage and availability similar to that, for example, on the mainland of Britain is not always justified. On the other hand, to install energy supply equipment to only supply energy in the evenings (as many of the diesel generators on Eigg do currently) would not be cost-effective. Therefore the success of the energy supply systems proposed in this work depends to a certain extent on energy demand levels and patterns changing.

This section has summarised and applied the methods of sections 5.2 and 5.3 to the island of Eigg, giving reasonable energy demands and potential energy supplies (hydro-electricity and wood fuel) which are necessary inputs to energy modelling of the island.

CONCLUSIONS

This chapter has brought together methods of obtaining data for small communities which are needed for any energy planning work. Methods were investigated for each of the following:

1) Determining meteorological data, important in assessing renewable energy potential.

2) Simulating space heating in buildings, possibly the largest, and therefore most important, energy demand in a small community.

3) Predicting hydro-electricity and wood fuel energy potential, both of which can be important and cost-effective energy supplies.

4) Assessing reasonable levels of energy demand for small communities which are needed in any energy planning work.

Taken together, these methods allow the energy planning model developed in this thesis to be applied to many communities, without the need for expensive or time consuming data collection over long periods. Although more work is needed to verify some of the methods, without them it would have been almost impossible to acquire the data needed for simulating the island of Eigg with any degree of accuracy.

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CHAPTER 6 PRESENTATION AND DISCUSSION OF ENERGY PLANNING RESULTS FOR THE ISLAND OF EIGG

The two methods of planning energy systems for small communites are applied to the island of Eigg. Economic assessment, using the planning model of section 4.1, and thermodynamic assessment, using the method of section 4.2, of different energy supply systems for the island are presented.

The existing energy system on Eigg (section 3.3) is simulated and compared with results from the island energy census, with good agreement. One optimisation of this system is run, giving cost savings of £4000 per year in fuel costs.

A system for supplying the increased energy demands on the island (section 5.4) is specified and improved in 6 simulations, showing a logical optimisation process. Hydro and wind turbines and solar panels are introduced, and coal is totally replaced by wood fuel.

The sensitivity of the optimum system to limited renewable energy supplies is tested, and the model was also run using daily and weekly simulation time steps: these give annual costs 26% and 13% higher respectively than simulating with an hourly time step.

One simulation to optimise second law efficiency of the system, relying heavily on heat pumps, was run. This gives a second law value of 36.6%, against that of the optimum economic system's efficiency of 17.9%. First law efficiencies vary between 43% and 170% for the higher demand systems.

6.1 INTRODUCTION

The objective of economic assessment is to determine, using currently-available energy equipment, an optimum energy supply system for Eigg. The system should be cheaper, but give higher levels of comfort (with respect to energy use) than the existing system on the island. The objective of thermodynamic assessment is to improve, again using currently-available energy equipment, the thermodynamic efficiency of energy use on the island. The final aim is to compare results, to see if economic improvements suggest thermodynamic improvements, or vice-versa.

Energy demand data for the island are those determined in section 5.4. Two levels are simulated: the approximate level of demand existing currently on Eigg and an improved demand level, giving over 30% higher energy usage on average. Potential renewable energy supplies are those determined from the 'typical' meteorological year on Eigg (described in section 5.1), and hydro potential is assessed by the method of section 5.2.

It is not possible to show all results of each simulation in detail or, therefore, to see why equipment ratings are changed, equipment removed from the simulation, etc. The reasons for changes are presented briefly, but are not justified by showing results. Section 4.1 gives an example of how optimisations are undertaken. In general: fuel sources are substituted, if possible, by cheaper sources, equipment ratings changed if the useful output is considerably different from the potential output, or if there is an energy shortage, and equipment left out of a simulation if it is hardly ever used.

Similarly it is not practical to test many different energy supply equipment ratings and combinations, because of the time needed to run each simulation. Therefore, for example, hydro turbine and wind turbine rating changes are not tested.

6.2 PRESENTATION OF RESULTS

Data for the various simulations are given in appendix 2: only important changes are detailed here. Each simulation incorporates improvements suggested by the previous simulation.

6.2.1 Economic results

The energy census of Eigg took no account of equipment capital cost, so only yearly fuel costs were found. The results in this section show total costs (including capital and maintenance costs), and also fuel-only costs, as this allows direct comparison with census results. Showing fuel costs also allows for the fact that much equipment already exists on the island, and therefore has little, if any, capital cost.

Fuel usage figures are inputs to equipment, not outputs. These are obtained by dividing equipment output by efficiency.

Simulation 1

This simulation represents, as closely as possible, the current energy system on Eigg. Energy demand levels are the lower levels of section 5.4. Table 6.2.1 compares simulation and census results.

	Census results		Simulation results		
Fuel type	Amount used (kWh/y)	Fuel cost (£/y)	Amount used (kWh/y)	Total cost (£/y)	Fuel cost (£/y)
Propane	11500*	440	11100	420	420
Butane	34800*	1530	38900	1840	1710
Coal	309300	4330	235300	3890	3290
Phurnacite	47600	1000	21900	390	460
Wood	140200	1260	131200	1480	1180
Kerosene	128700	3090	37000	1320	890
Diesel	223300	6250	394600	11940	11050
Hydro	3500	0	40400	430	0
	898900	17900	910400	21710	19000

Energy shortfall = 6300 kWh/y
Notes: * = Cooking and water heating only.

Table 6.2.1 Results of simulation 1

The simulation choses cheaper supplies first, so it replaced the more expensive fuels (kerosene, phurnacite and coal) by cheaper supplies (hydro and butane gas). Fuel used by diesel generators is higher from the simulation, probably because they supply the demand when cheaper supplies are overloaded. This does not happen on the island. The model does not allow for direct gas heating (which on Eigg is 44000 kWh/y) so this is replaced in the simulation by other sources.

System changes

Since the island could produce about 1.35×10^6 kWh/y of wood fuel, and this easily covers all the solid fuel requirements, all ranges (coal, phurnacite and kerosene burning), stoves and open fires are converted to burning wood, which is considerably cheaper. It is hoped that wood, via ranges, will displace the more expensive gas used for cooking. Propane gas is slightly cheaper than butane, so all butane cookers and gas water heaters are changed to use propane. Most diesel generators are over-rated, so their ratings are reduced accordingly.

Simulation 2

This improves the current energy system on the island, using the changes suggested as a result of simulation 1. The same demand levels are used, and table 6.2.2 gives the results.

Fuel type	Amount used (kWh/y)	Total cost (£/y)	Fuel cost (£/y)
Propane	52900	2060	2010
Butane	0	0	0
Coal	0	0	0
Phurnacite	0	0	0
Wood	478400	6920	4310
Kerosene	0	0	0
Diesel	248100	8200	6950
Hydro	45400	500	0
	824800	17680	13270

Energy shortfall = 13400 kWh/y

Table 6.2.2 Results for simulation 2

Significant savings have been made with this system, being £5700 per year for fuel (a 30% saving), or £4030 per year for total costs (19% saving) when compared to simulation 1. Compared with census results the savings on fuel are £4600 (26%). Further optimisation of this system is possible, but was not attempted.

Simulation 3

This introduces the higher levels of energy demand (33% higher compared with census results) of section 5.4. Since many more rooms have to be heated, wood burning stoves are introduced to those zones. All ranges are uprated, to attempt to displace more propane gas, and a range is given to houses which did not previously have one.

Since all houses now have electricity demands, diesel generators are specified for all houses. But to rationalise capacity, and reduce capital costs, houses which are close together share a generator. So there are five electricity grids each connecting two houses.

Table 6.2.3 shows the results from this simulation. Costs have risen by £5140 pa for fuel only, compared with the energy survey, and total costs by £7010 pa compared with simulation 1 (30% and 32% rises respectively). But energy usage has also increased by 33%, representing a large increase in the islanders' comfort levels and living standards.

Fuel	Amount used (kWh/y)	Total cost (£/y)	Fuel cost (£/y)
Propane	44600	1700	1700
Wood	855600	11260	7700
Diesel	458400	14920	12840
Hydro	55300	840	0
	1413900	28720	22240

Energy shortfall = 22100 kWh/y

Table 6.2.3 Results of simulation 3

System changes

There is considerable potential for hydro electric power from five burns on Eigg, so turbines are specified for each burn. The island is split into three electricity grids, and all houses receive energy from a grid. Three wind turbines are also specified, one for each grid. Although the grids are expensive (£1000 per 0.1km for 6.75km, 3.5km and 5.0km), they allow diesel fuel to be replaced by much cheaper hydro and wind energy, and also allow the diesel generators to be better sized.

All houses are given wood-burning ranges, and some range output ratings are changed. All houses now have propane cookers, but gas water heaters are excluded from further simulations, as they are more expensive than other hot water sources.

Simulation 4

This introduces the hydro and wind turbines recommended above. Table 6.2.4 gives the results, showing a considerable improvement; total costs are £1260 pa (7%) cheaper than is currently paid for fuel costs alone, even allowing for a 33% increase in energy usage.

Fuel	Amount used (kWh/y)	Total cost (£/y)	Fuel cost (£/y)
Propane	12500	470	470
Wood	659200	8700	5930
Diesel	13900	470	390
Hydro	211000	5020	0
Wind power	34300	2050	0
	930900	16710	6790

Energy shortfall = 0 kWh/y

Table 6.2.4 Results of simulation 4

System changes

The number of diesels is cut, and their ratings changed, to reduce the considerable over-capacity. There is a time mismatch between wind and hydro energy and demand, with less than 10% of potential wind energy, and only 80% of hydro energy, being used by the community. To try to improve this, all houses with three or more space heating zones are given central heating (CH) systems, to provide some energy storage.

Ranges are allowed to supply the CH systems, and where a house has a stove in its second zone, this also supplies the system. All other stoves are removed, cutting the total number in the community from 68 to 24. This has a further advantage of making the system far more practical: 68 stoves in 27 houses would be almost impossible to look after.

Simulation 5

Table 6.2.5 shows the results of this simulation. Different results from those expected occur. On the positive side the wind and hydro usage has risen from 9% and 80% of potential to 17% and 84% respectively. However, removing wood stoves means that wind and hydro turbines are unable to meet the full demand, even with the storage of CH systems, and this has had to be met by more expensive diesel fuel. The total cost is £4000 pa (27%) higher than simulation 4, but this is partly offset by this system being more practical.

Fuel	Amount used (kWh/y)	Total cost (£/y)	Fuel cost (£/y)
Propane	17300	660	660
Wood	586500	8840	5120
Diesel	44000	1530	1090
Hydro	223200	6010	0
Wind power	64400	4120	0
	935400	21160	6870

Energy shortfall = 30000 kWh/y

Table 6.2.5 Results of simulation 5

System changes

One further optimisation of this system is run, replacing open fires by more efficient, hence cheaper, wood stoves. Several ranges, and a few stoves, are up-rated by 0.5kW, to try to displace the diesel fuel used for space and water heating.

Simulation 6

This makes the above changes and introduces solar water heating panels for all houses. These supply the CH of houses with systems, and so give space heating and hot water. For houses without CH they supply hot water only. Table 6.2.6 lists the results of this simulation, showing a slightly reduced cost compared with the previous simulation, more owing to changing open fires than by introducing solar panels. Solar panels are generally too expensive, and have little or no effect.

Fuel	Amount used (kWh/y)	Total cost (£/y)	Fuel cost (£/y)
Propane	14800	560	560
Wood	568700	9020	5120
Diesel	34900	1200	980
Hydro	220200	5840	0
Wind power	55100	3460	0
Solar	300	20	0
	894000	20100	6660

Energy shortfall = 12700 kWh/y

Table 6.2.6 Results of simulation 6

The results show that only a small percentage of the potential output of the wind turbines is used. For example, the results from one turbine are shown on table 6.2.7. Potential supply exceeded demand more often than the demand exceeded the supply, implying that a smaller wind turbine would be better matched to the demand. Without electricity storage, though, it is unlikely that the total amount of wind energy used could be significantly increased, especially since typical unit costs are 0.024 £/kWh for wood and 0.063 £/kWh for wind energy.

	Demand exceeded supply by			Supply exceeded demand by	
	60%/100%	20%/60%	+20%/-20%	20%/60%	60/100%
Wind turb. on grid 1	1421	294	1392	714	4939

Table 6.2.7 Results for wind turbine. Units: hours

System changes

One diesel generator is over-sized so is removed, and solar panels are also removed from most houses.

Simulation 7

Electric heat pumps are introduced into this simulation, to try to use less energy to supply the demand. The heat pumps can be powered by any of the generators (hydro, wind or diesel) on each grid. They are only specified for houses with CH systems (so they give space and water heating). Table 6.2.8 lists the results.

Fuel	Amount used (kWh/y)	Total cost (£/y)	Fuel cost (£/y)
Propane	13200	500	500
Wood	606900	9640	5460
Diesel	9500	330	270
Hydro	214200	5650	0
Wind power	33500	2060	0
Solar	100	10	0
Hydro-driven HP	-*	210†	0‡
Wind-driven HP	-*	210†	0‡
Dies.-driven HP	-*	0	0
	877400	18610	6230

Energy shortfall = 100 kWh/y

Notes: * = Fuel used to drive HPs included in each generator's total.
† = Cost of heat pump only, not fuel cost.
‡ = Fuel costs included in hydro, wind and diesel totals.

Table 6.2.8 Results of simulation 7

This simulation is very successful, having reduced total costs (compared with sim. 1) by £3100 pa (14%) and fuel costs by £4020 pa (22%) compared with census results, even though energy usage is 33% higher. Although this system is £1900 pa (11%) higher than simulation 4, it is far more practical, and would be much easier to operate.

There is a big fall in diesel usage, indicating that this had been used in previous simulations to supply space and water heating. Heat pumps both make energy cheaper, and reduce the amount of energy input to the system. The amount of wind energy used is reduced, probably because the total demand is reduced.

System changes

Several changes are made following this simulation:

1) All solar panels are removed, as they supply very little energy.
2) Heat pumps are removed from several houses, as these are more expensive than other supplies. Other heat pumps are de-rated to give better matching of capacity.
3) Some wood stoves are de-rated, and a few removed. Small energy shortfalls will be met by other, more expensive supplies.
4) Diesel generator ratings are further improved.

Simulation 8

Having made the changes above, table 6.2.9 shows the results.

Fuel	Amount used (kWh/y)	Total cost (£/y)	Fuel cost (£/y)
Propane	13000	490	490
Wood	636000	9380	5720
Diesel	12600	430	350
Hydro	213400	5650	0
Wind power	35500	2200	0
Hydro-driven HP	-	40	0*
Wind-driven HP	-	370	0*
Dies.-driven HP	-	20	0*
	910500	18580	6560

Energy shortfall = 100 kWh/y

Notes: * = Fuel costs included in each generator's total

Table 6.2.9 Results of simulation 8

This simulation makes little difference to the total cost, and has in fact increased the fuel cost by £330 pa. But it has improved the usage factors of the various equipment, which is important. COSTCALCS (see sub-section 4.1.4b) makes assumptions about the proportion of the potential output of energy devices actually used. Table 6.2.10 lists these, giving values derived from the results of simulation 8.

Device	Assumed usage factor	Real usage factor from results
Hydro turbines	0.80-1.00	0.80
Wind turbines	0.80-1.00	0.09
Diesel generators	0.40	0.03
Ranges	0.70-1.00	0.63
Stoves	0.25	0.26
Heat pumps	0.25	0.10*

Notes: * = Heat pumps with non-zero outputs.

Table 6.2.10 Assumed and calculated usage factors

Most usage factors are significantly different from those used when calculating unit energy costs. Therefore running RECALCS would give different unit costs, changing the total system costs. Assuming that equipment lifetimes do not change with usage, the change in system cost would be from £18500 pa to £39000 pa. Although this is now higher than that currently paid by the islanders, no account was taken of equipment usage factors in previous simulations. In fact simulation 8 has the best usage factors of all simulations, so is still the best system. Unmodified results are retained for comparison in section 6.2.3, rather than attempting to modify all previous results.

Simulations 9, 10, 11 and 12

These four simulations, in turn, test the system of simulation 7 for limited supplies of renewable energy. Simulation 9 cuts wind energy by an average of 20%, simulation 10 cuts hydro potential by 25% and simulation 11 reduces wood potential to 150000 kWh/y (when wood fuel is exhausted ranges and stoves burn coal). Finally simulation 12 combines all these limitations, to test the system for a 'worst possible' year. Tables 6.2.11 and 6.2.12 show results.

	Simulation 9			Simulation 10		
Fuel	Amount used (kWh/y)	Tot. cost (£/y)	Fuel cost (£/y)	Amount used (kWh/y)	Tot. cost (£/y)	Fuel cost (£/y)
Propane	16700	630	630	13900	530	530
Wood	640700	9940	5770	645200	10230	5810
Diesel	14700	520	410	14500	500	410
Hydro	196600	5850	0	188900	5180	0
Wind	27200	2370	0	36500	2270	0
Solar	100	10	0	100	10	0
Hydro HP	-	220	0*	-	190	0*
Wind HP	-	290	0*	-	310	0*
Dies. HP	-	0	0	-	0	0
	896000	19830	6810	899100	19220	6750

Energy shortfall = 100 kWh/y in both cases.
* = Fuel costs included in generator's costs

Table 6.2.11 Results of simulations 9 and 10

The simulations show how important wood is as a cheap fuel for the island. Nonetheless the system copes adequately with the reduced energy supplies, giving a total cost only £9300 pa (43%) higher than the current system on Eigg, but £11200 pa (63%) lower for fuel costs only, in the worst possible year. It seems likely, therefore, that this

	Simulation 11			Simulation 12		
Fuel	Amount used (kWh/y)	Tot. cost (£/y)	Fuel cost (£/y)	Amount used (kWh/y)	Tot. cost (£/y)	Fuel cost (£/y)
Propane	12100	460	460	16500	630	630
Wood	150000	2530	1350	150000	2690	1350
Diesel	44600	1520	1250	69300	2430	1940
Hydro	249700	7050	0	222200	7750	0
Wind	146900	9260	0	118500	10920	0
Solar	600	30	0	1100	70	0
Coal	135600	3720	1900	196400	4060	2750
Hydro HP	-	770	0*	-	1330.	0*
Wind HP	-	1040	0*	-	1080	0*
Dies. HP	-	30	0*	-	60	0*
	739500	26410	4960	774000	31020	6670

Energy shortfall = 100 kWh/y in both cases.
* = Fuel costs included in generator's costs

Table 6.2.12 Results of simulations 11 and 12

system would be acceptable, since such limited years are unlikely to occur often, and the islanders also benefit from a large increase in comfort and energy usage levels.

When wood fuel is limited, the total energy needed (as inputs) by the system is more than 100000 kWh/y less than that required by simulation 7. Although this is more expensive, it is more efficient, owing to increased use of more efficient wind and hydro turbines.

Simulation 13

This simulation uses practical equipment chosen to maximise second law efficiency. All houses are given heat pumps and CH systems, supplying all zones in each house. This allows them to supply both space heating and hot water. All wood stoves and ranges are removed, ensuring that maximum use is made of the heat pumps (otherwise they would be more expensive than wood fuel). Table 6.2.13 shows results.

This system, in terms of energy efficiency, is most successful in meeting the demand, and is £3990 pa (61%) cheaper for fuel costs than the best economic system. However, because of the relatively high unit costs of heat pumps, the total cost is £2660 pa (14.3%) more

Fuel	Amount used (kWh/y)	Total cost (£/y)	Fuel cost (£/y)
Propane	28200	1070	1070
Diesel	53500	1830	1500
Hydro	223200	5560	0
Wind power	58100	3650	0
Solar	2700	170	0
Hydro-driven HP	-	8280	0*
Wind-driven HP	-	520	0*
Dies.-driven HP	-	160	0*
	365700	21240	2570

Energy shortfall = 5200 kWh/y
Notes: * = Fuel costs included in generator's costs

Table 6.2.13 Results of simulation 13

expensive than the best economic system. Within the limits imposed by practical equipment, few improvements are possible in second law efficiency, so this is chosen as the optimum thermodynamic system.

Simulations 14 and 15

All previous simulations were run using a simulation time step of one hour. However these are quite time consuming requiring about 1.5 hours CPU time, or 5.5 hours real time, each. To reduce this time, and to use a similar time step to that used by other modellers (see sub-section 4.1.3), simulations 14 and 15 used a daily and weekly (7 day) model time step respectively.

All hourly meteorological parameters and energy demands were averaged over the new time step. Demands and supplies were thus average rates, converted to total energy by multiplying by the number of hours per day or per week. All equipment was the same as for simulation 7.

Table 6.2.14 shows the results of both simulations. There are several points from these simulations, of which the most interesting is how they affect yearly system costs. A daily time step gives costs 26% higher than an hourly step, while a weekly step gives 13% higher costs.

	Simulation 14			Simulation 15		
Fuel	Amount used (kWh/y)	Tot. cost (£/y)	Fuel cost (£/y)	Amount used (kWh/y)	Tot. cost (£/y)	Fuel cost (£/y)
Propane	4700	200	200	1300	50	50
Wood	795300	12800	7160	838700	13680	7550
Diesel	6600	300	180	16100	570	450
Hydro	242500	7200	0	51700	1350	0
Wind	27100	1670	0	76500	5210	0
Solar	0	0	0	0	0	0
Hydro HP	-	20	0*	-	10	0*
Wind HP	-	60	0*	-	550	0*
Dies. HP	-	0	0	-	0	0
	1076200	22250	7540	984300	21420	8050

Energy shortfall = 0 kWh/y in all cases.
* = Fuel costs included in generator's costs

Table 6.2.14 Comparison of daily and weekly model time steps

Other points worth noting in comparison with simulation 7 are:

1) Total wind potential decreases with increasing time step. But the higher unit costs in simulation 15 change the cost of wind-powered heat pumps, giving higher total wind energy usage.

2) Hydro potential increases with increasing time step. The equation determining energy output (section 5.2) is of the form

$$P = kQ - cQ^{2.75} \qquad (6.2.1)$$

and the term $Q^{2.75}$ becomes comparatively smaller as the streamflow is averaged over longer periods, as this averaging reduces the higher short-term streamflow values. Despite this, hydro energy usage increases in simulation 14, but is much lower in simulation 15, being replaced by cheaper wind heat pump energy.

3) Solar energy, although not particularly economic in any simulation, is not used at all in the two longer time step runs.

It is concluded that there are considerable differences between the different time steps, both in energy potential and energy usage, and these differences are also not predictable in advance.

6.2.2 Thermodynamic results

Second law (exergy) efficiency and first law (energy) efficiency for 10 of the 15 systems described above are presented here, calculated using the energy quality against quantity diagrams discussed in section 4.2. The thermodynamic reasons for system changes are presented.

Energy supply and demand qualities are calculated by the equations of section 2.2. The energy demands are those shown in section 5.4, and the amounts of supply are those calculated by the simulation. These latter represent energy inputs to equipment, not outputs. Each simulation is the same as described above and in appendix 2.

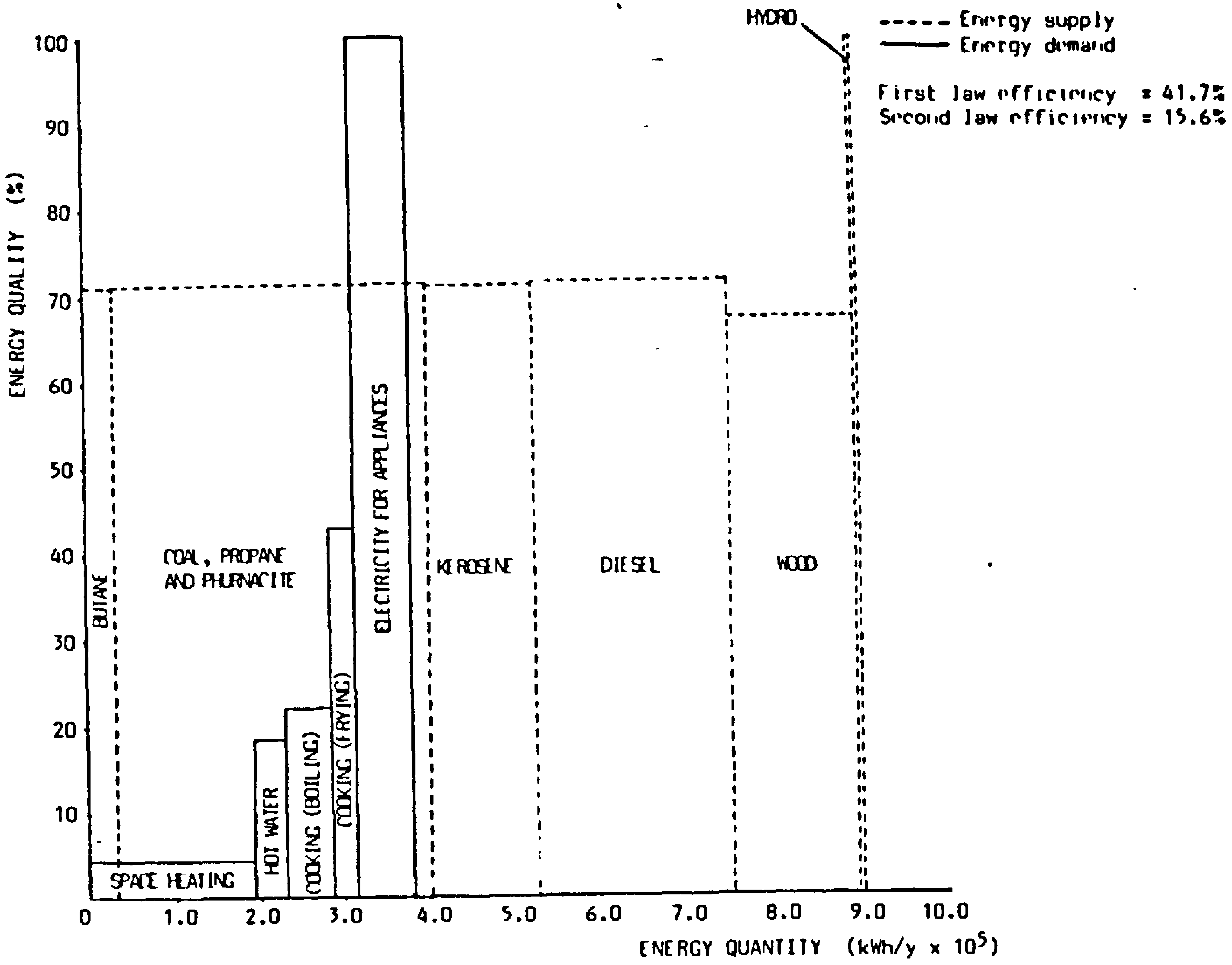
Exergy diagrams are drawn with various energy supplies centred over the demand they are approximately intended to meet. This helps show why system changes are made, and explains the efficiency values. First law efficiencies are obtained by dividing demand quantities by supply quantities (both from the x-axis). Second law efficiencies come from the demand area (its exergy) divided by the supply area.

Current Energy System on Eigg, and Simulation 1

Figure 6.2.1 shows results for the current energy supply system on the island (section 3.3) and fig. 6.2.2 shows results of simulating this system (simulation 1). Good agreement is seen for the two results between second law efficiencies (η_2), and reasonable agreement on first law efficiencies (η_1); η_2 for the simulation being slightly lower than from census results, because of its the greater amount of diesel usage.

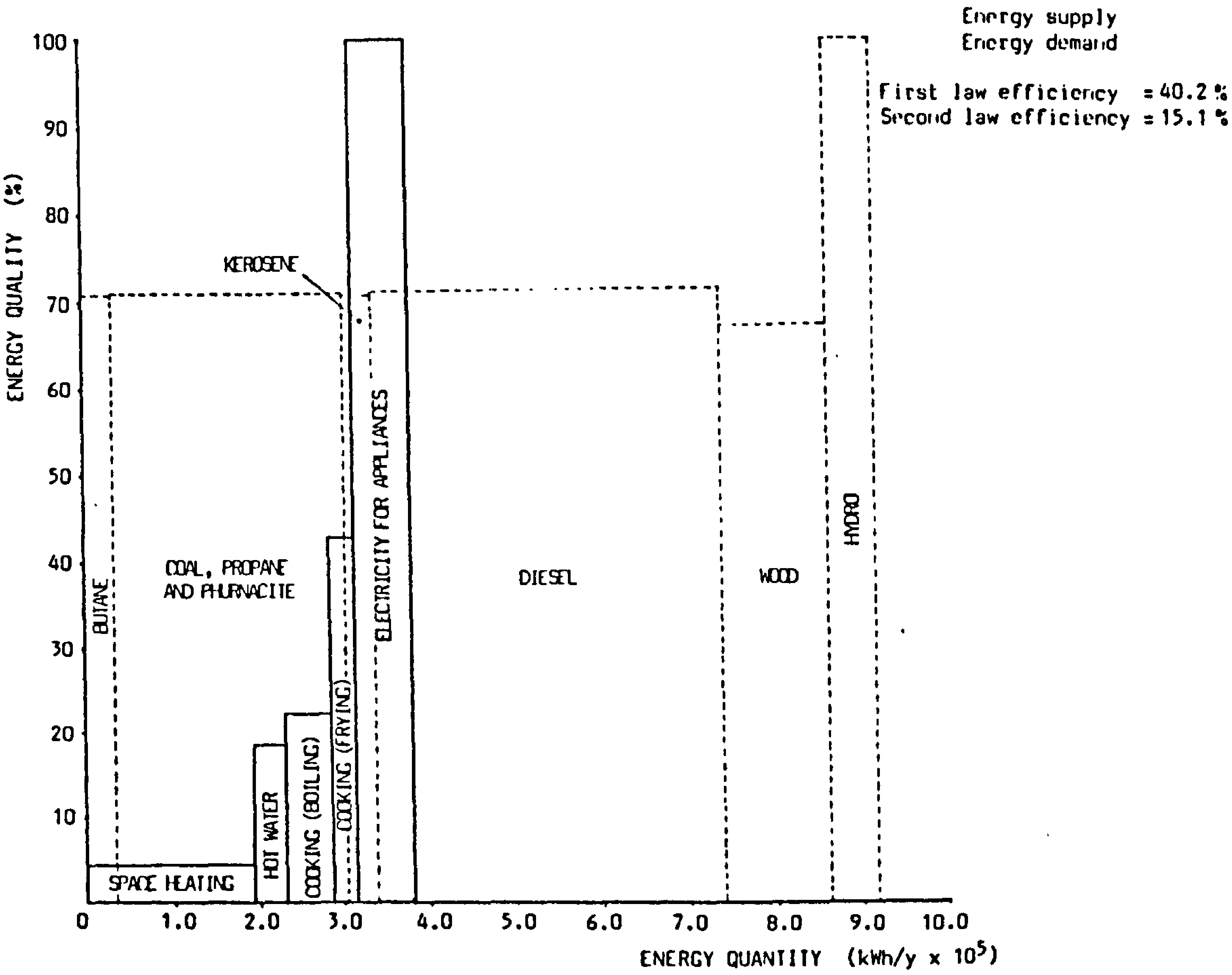
System changes

The reasons for the poor η_2 value are that (a) converting diesel fuel to electricity gives high energy losses and (b) using high quality fuels (gas, coal and kerosene) to supply low quality heat demands is exergy inefficient. So usage of hydro power to supply electricity is increased, and lower quality wood fuel substitutes for fossil fuels.



First law efficiency = 41.7%
Second law efficiency = 15.6%

FIGURE 6.2.1 Exergy Diagram for the Current Energy System on the Island of Eigg



First law efficiency = 40.2 %
Second law efficiency = 15.1 %

FIGURE 6.2.2 Exergy Diagram for Simulation 1

Simulation 2

Fig. 6.2.3 shows the results of this simulation. Both η_1 and η_2 have improved slightly, η_2 from 15.1% to 16.9%, η_1 from 40.2% to 45.4%. Improvements could still be made, but are not attempted because all further simulations use the higher energy demand level of section 5.4.

Simulation 3

Figure 6.2.4 (note the different x-axis scale) shows the exergy diagram for the system supplying the new level of demand (33% higher). Both η_1 and η_2 are lower than before, mainly owing to inefficient conversions of diesel fuel to electricity, and using combustible fuels to supply low quality heat demands.

System changes

Wood fired ranges and stoves have fairly high energy losses from their flues (this also lowers second law efficiency). High quality supplies (wind and hydro electricity) have no associated energy losses, so their use is increased. This also minimises the poor conversion of diesel fuel to electricity.

Simulation 4

This introduces the changes from simulation 3, the results being shown on figure 6.2.5. As expected both efficiencies have improved, η_1 by more than η_2. The former has improved from 44.3% to 67.2% (a 52% increase), while η_2 has improved from 12.6% to 17.6% (a 40% increase). Although η_1 might be considered quite acceptable, η_2 remains low.

System changes

There is a clear need to improve both the energy efficiency of the system, and the match between quality of supply and demand. Little is possible to improve energy efficiency, within the limitations of practical equipment, but exergy efficiency improvements are possible, by introducing low quality solar energy and electric heat pumps to replace the exergy-inefficient electricity to heat transformations.

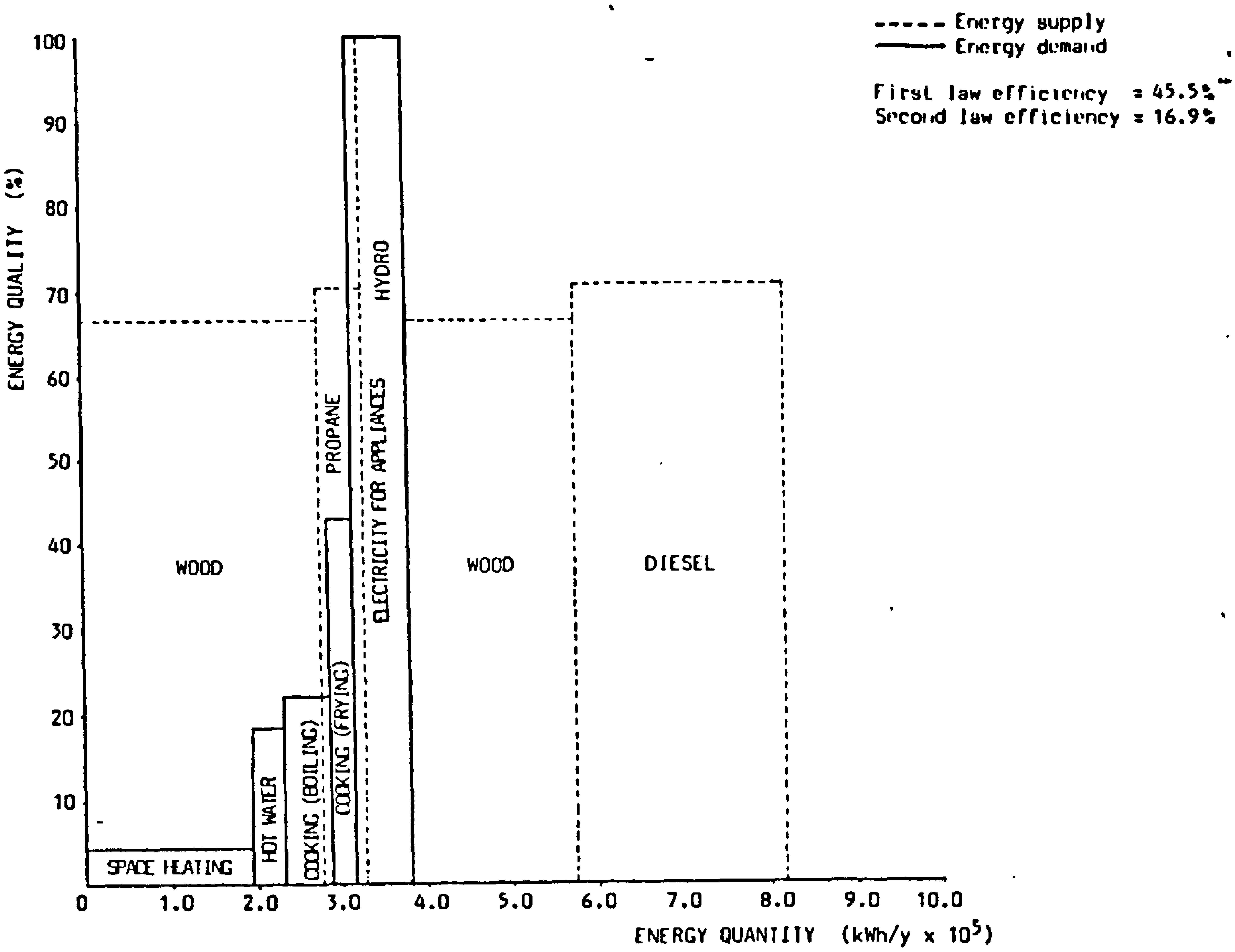


FIGURE 6.2.3 Exergy Diagram for Simulation 2

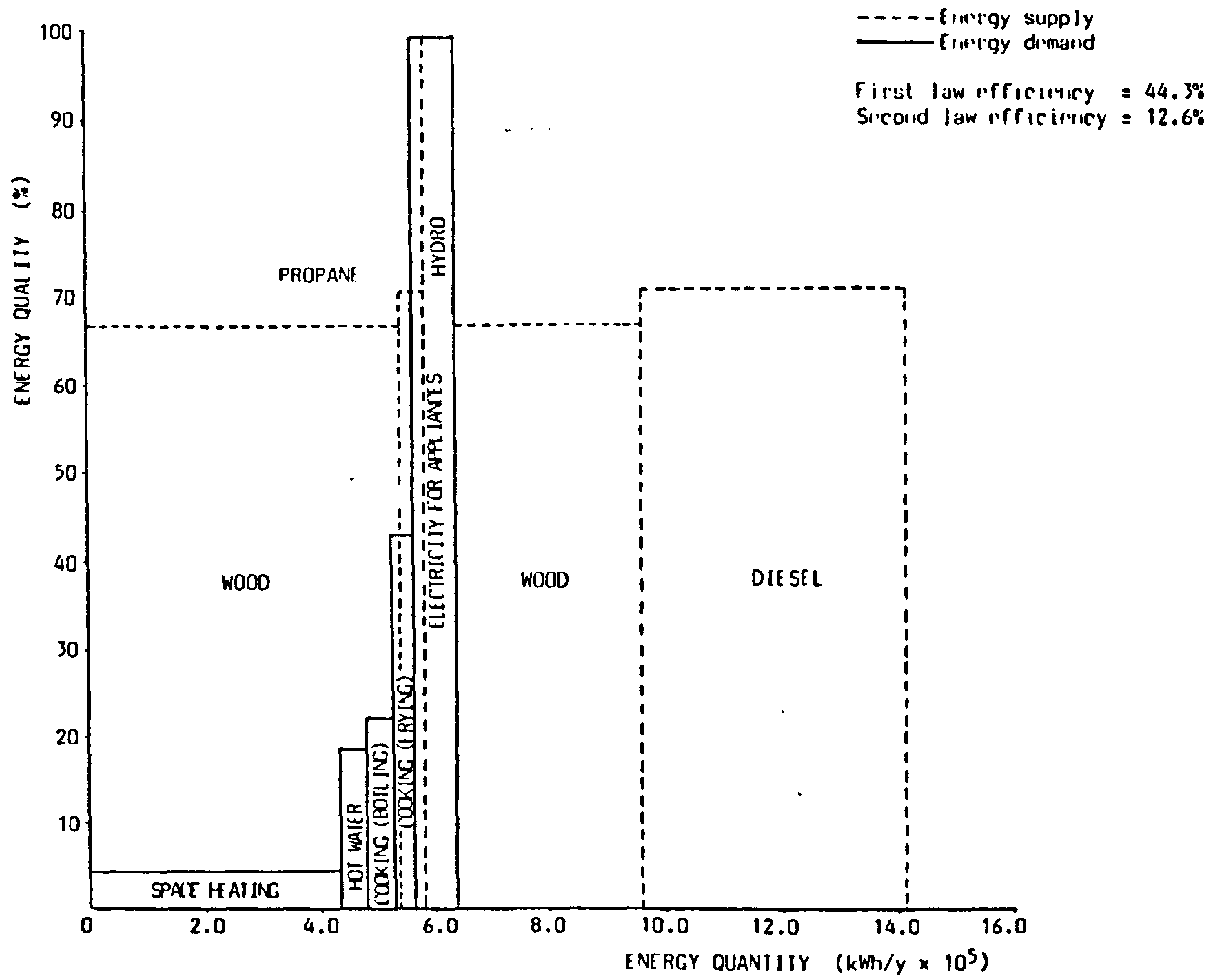


FIGURE 6.2.4 Exergy Diagram for Simulation 3

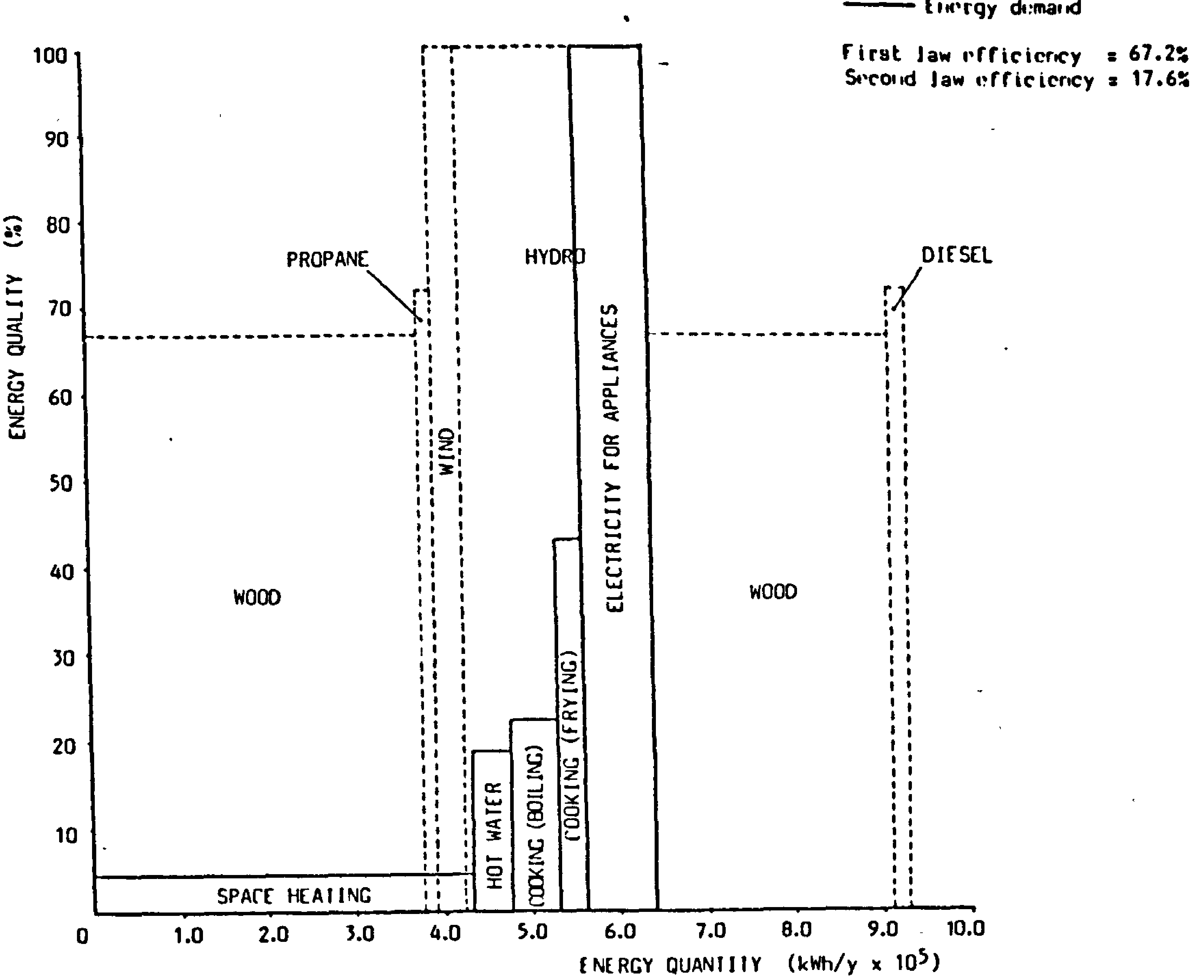


FIGURE 6.2.5 Exergy Diagram for Simulation 4

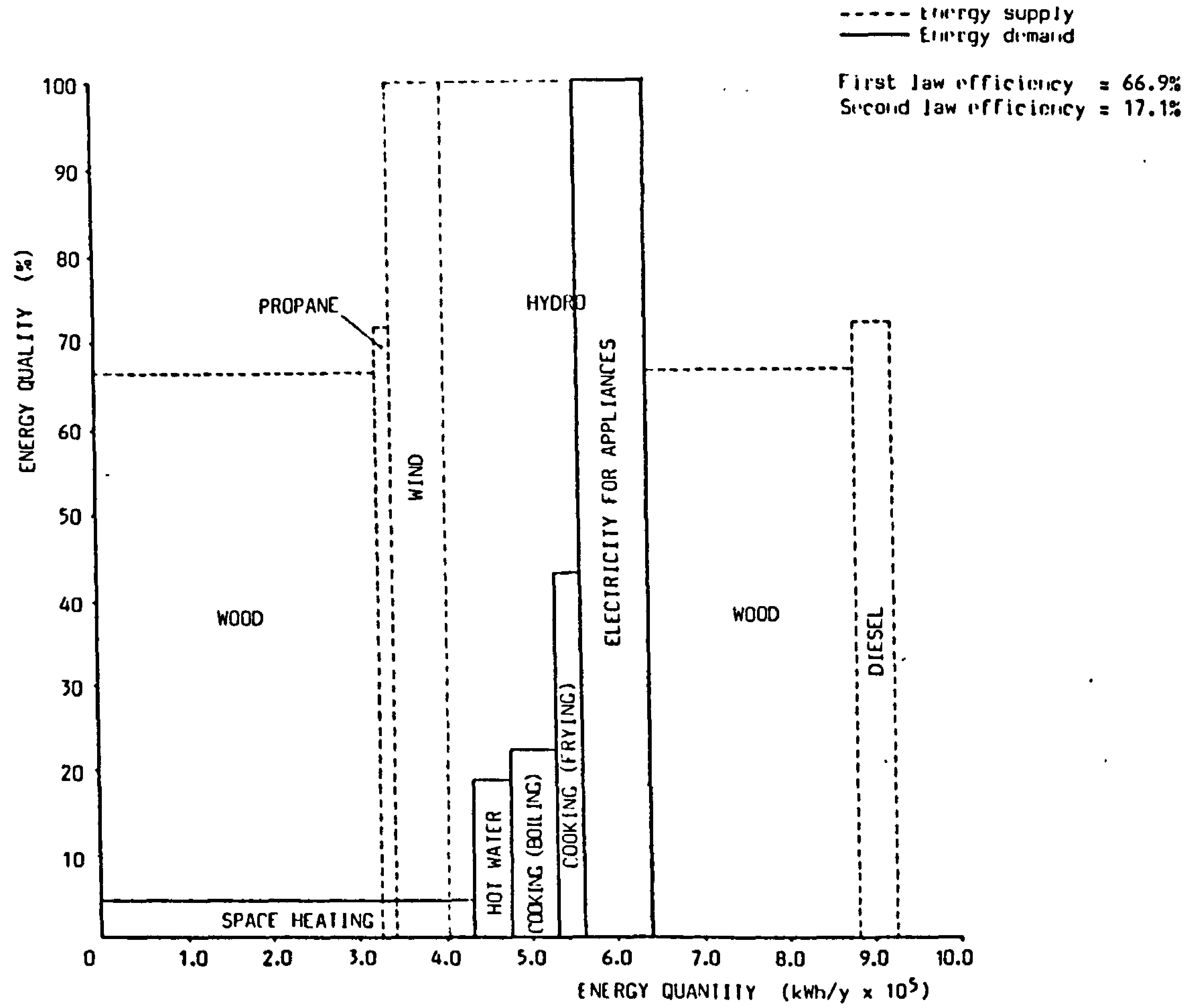


FIGURE 6.2.6 Exergy Diagram for Simulation 5

Simulations 5 and 6

Simulation 5 was an economic optimisation only, and in fact both η_1 and η_2 decreased slightly for this system (figure 6.2.6, previous page). Simulation 6 introduces low quality solar water heating, but its high cost prevented it having more than a small effect on thermodynamic performance (fig. 6.2.7). There are slight improvements compared with simulation 4: η_1 from 67.2% to 70.0%, η_2 from 17.6% to 17.9%.

Simulation 7

This simulation introduces heat pumps into the system, to (a) cut down the total energy needed to supply the demand (the heat pumps drawing energy from the environment) and (b) make the transformation high quality electricity to low quality heat more effective than by direct transformation. Figure 6.2.8 shows this system's exergy diagram.

Small improvements are seen in comparison with the previous best of simulation 6, this time higher for η_2 than η_1, the former improving from 17.9% to 18.5%, the latter from 70.0% to 71.4%. However, the cost of heat pumps makes them unfavourable compared with the direct combustion of wood, so they do not have as big an impact as hoped.

Simulation 8

This represents the optimum economic system. Small changes were made to simulation 7 to produce this system, whose results are shown on figure 6.2.9. There is a fall in efficiencies in comparison with simulation 7, η_2 from 18.5% to 17.9% and η_1 from 71.4% to 68.9%, these are largely due to a slight fall in heat pump usage, and a subsequent increase in wood consumption.

Simulation 12

Simulation 12 (fig. 6.2.10) is for the 'worst possible' year on Eigg, during which hydro potential, wind potential and wood fuel are limited by 25%, 20% and to 150000 kWh/y respectively. Interestingly these limitations make heat pumps cheaper, and their contribution

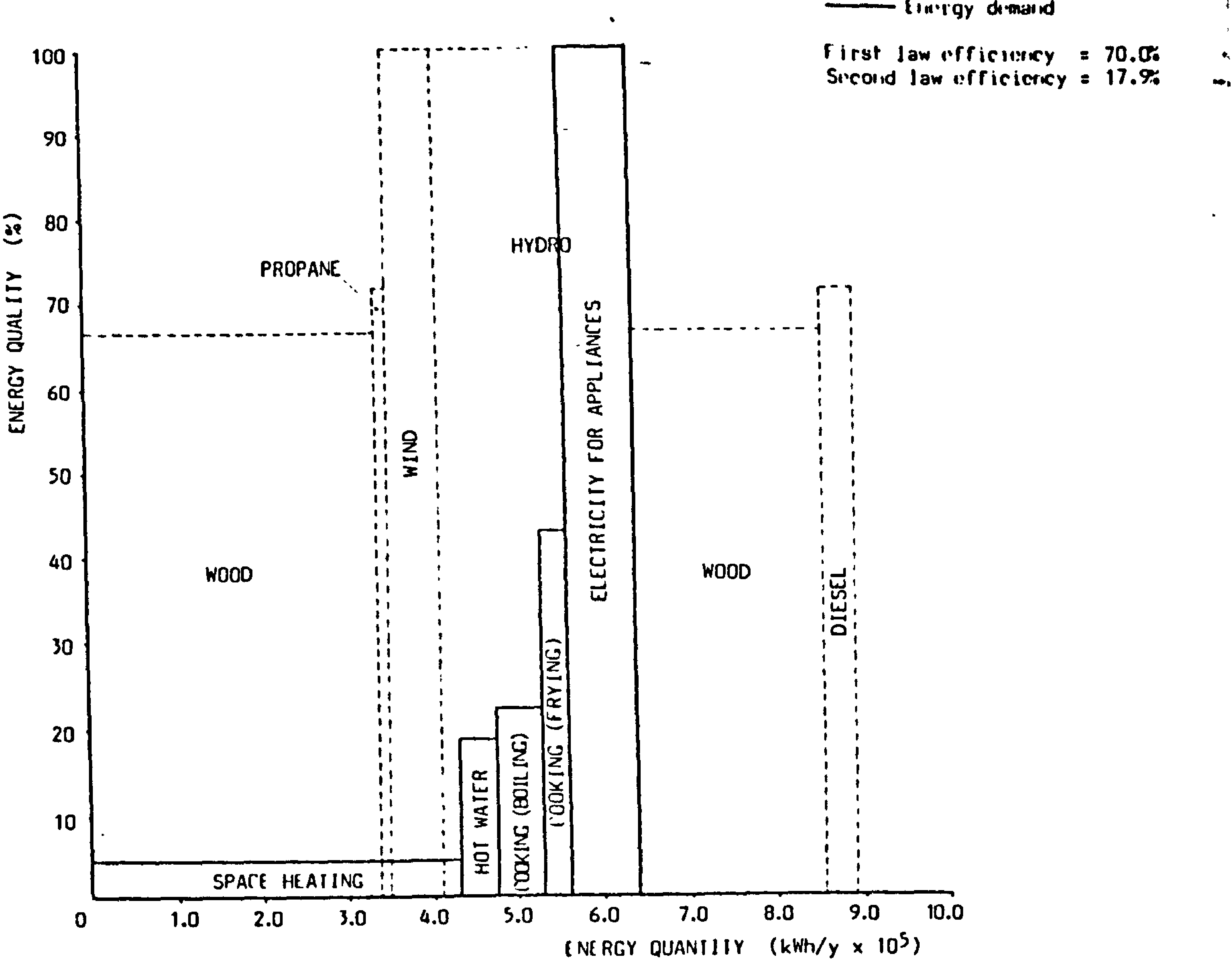


FIGURE 6.2.7 Exergy Diagram for Simulation 6

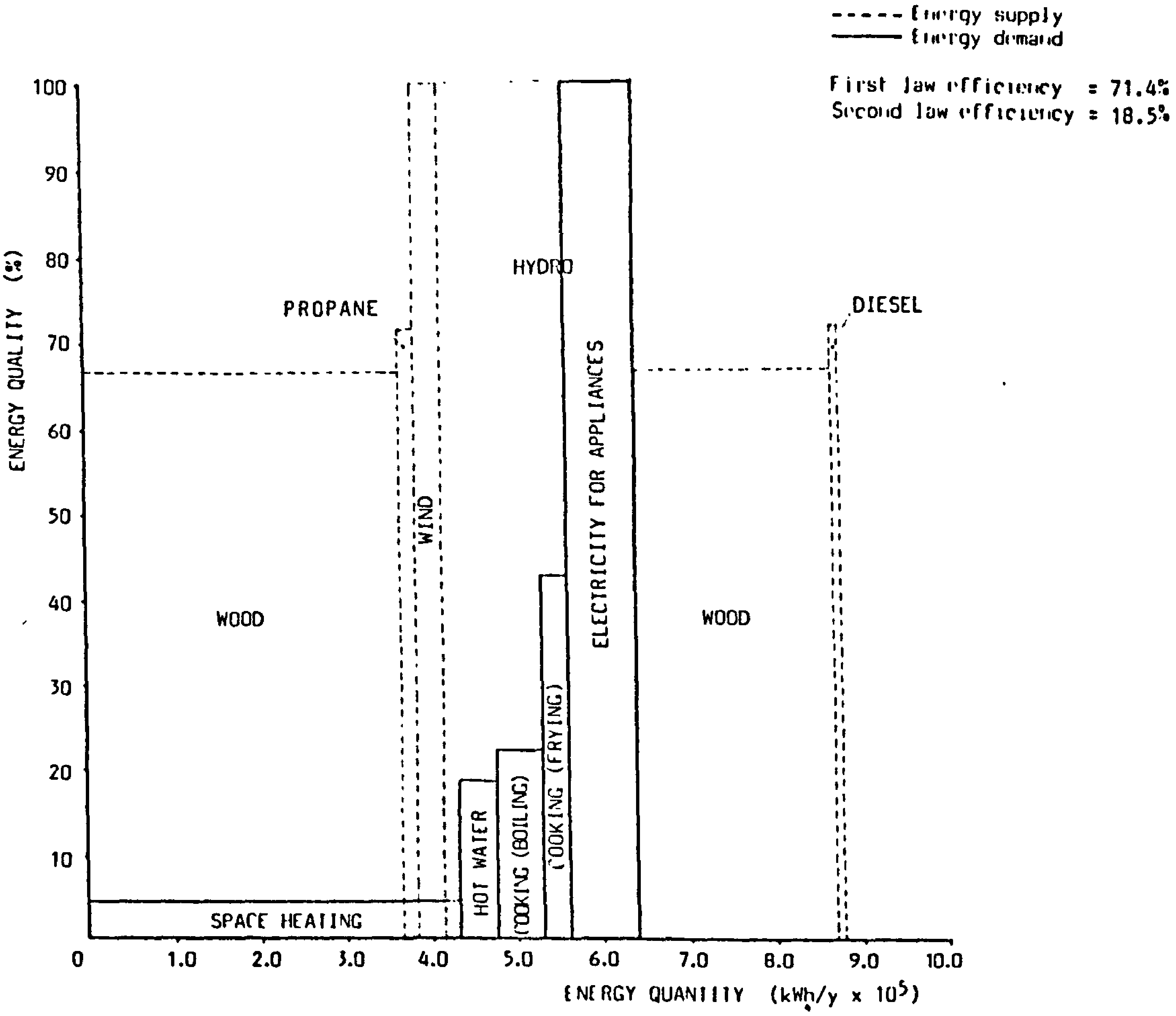


FIGURE 6.2.8 Exergy Diagram for Simulation 7

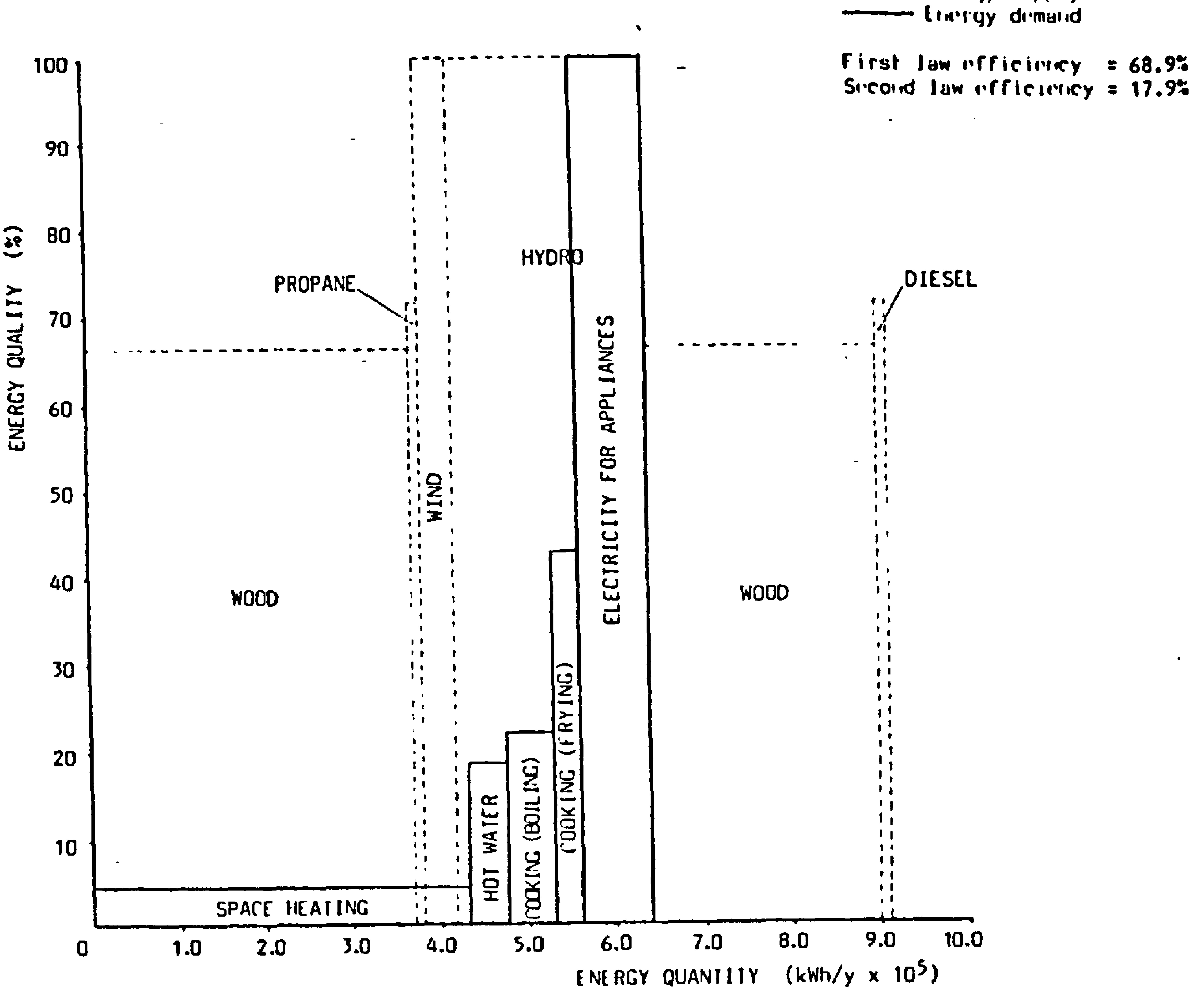


FIGURE 6.2.9 Exergy Diagram for Simulation 8

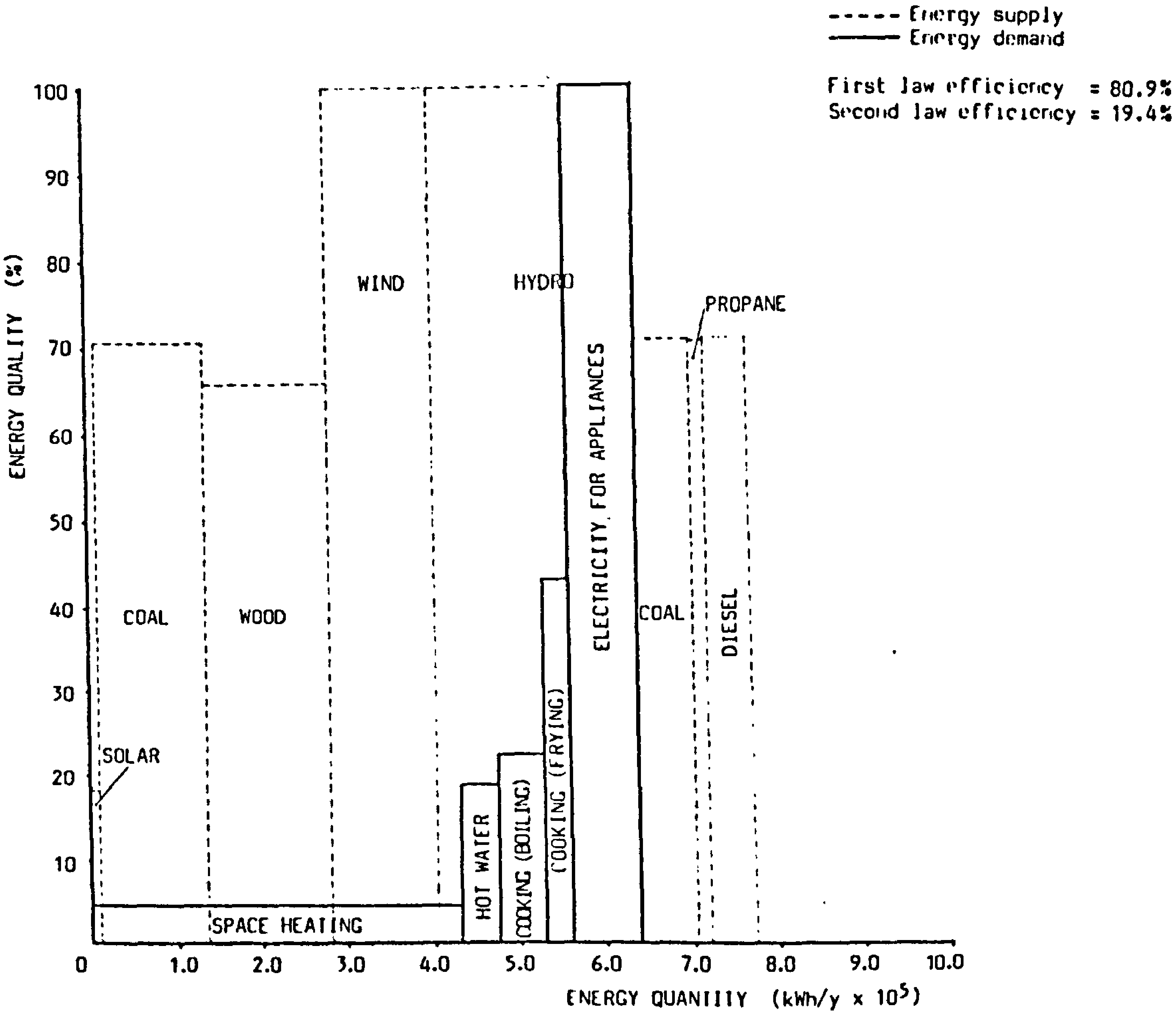


FIGURE 6.2.10 Exergy Diagram for Simulation 12

increases considerably. Solar energy contributes slightly more to this system than to others. There is a consequent increase both in η_1 to 80.9% and η_2 to 19.4%, these being higher than any previous simulation.

Nonetheless, the η_2 value remains very low, being limited by the simulation choosing equipment with preferential unit costs, rather than best thermodynamic performance. This is overcome in the simulation 13, in which the community is 'obliged' to make far more use of heat pumps.

Simulation 13

By removing all wood burning ranges and stoves, the system has to rely much more heavily on heat pumps. Figure 6.2.11 shows the results (note that energy supplies do not start at zero on the x-axis, having been centralised over the demands they cover), and a large improvement is seen in both first and second law efficiency.

Compared with the best economic system (simulation 8), the efficiency increases are: η_1 from 68.9% to 171.2% (a 148% improvement), and η_2 from 17.9% to 36.6% (a 104% increase). These come entirely from eliminating the exergy-inefficient wood fuel to heat transformation, and by increasing usage of the potential of high quality hydro and wind energy. Figure 6.2.12 helps to show these improvements, by presenting the energy at the output of each device. Therefore heat pumps give hot water at the mean temperature of 70°C (quality 18.4%).

The first law efficiency value of figure 6.2.11 shows how this can be misleading. The assumption is often that 100% is the maximum achievable, but this simulation shows that η_1 can have values well over 100%, so it is not possible to know with what optimum to compare them. Second law efficiency, on the other hand, can never exceed 100%. While a value of η_2 of 36.6% is higher than all other simulations, it still shows that thermodynamic improvements are possible, but it is unlikely that significant second law efficiency improvements could be made using practical, or economically-viable equipment.

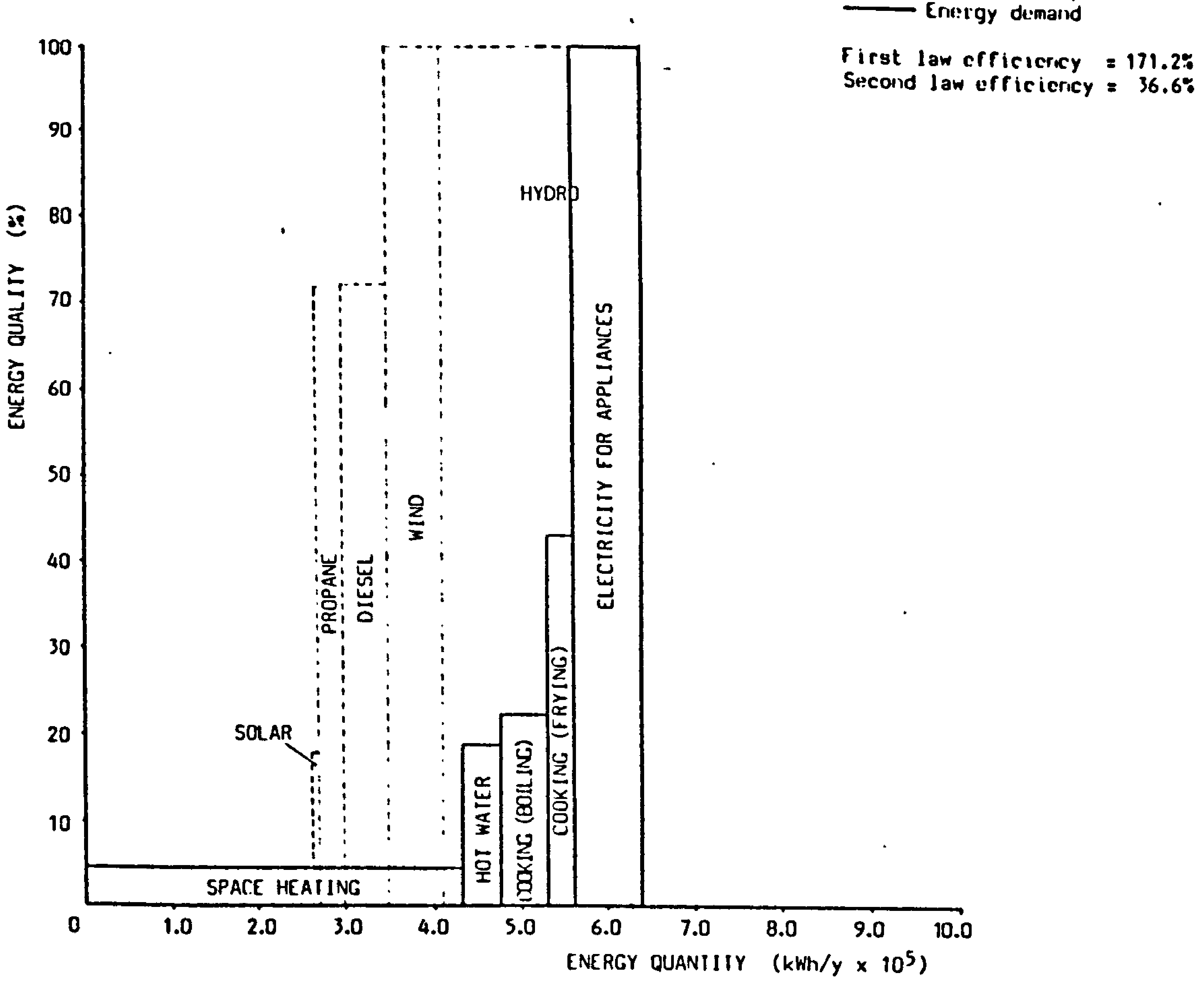


FIGURE 6.2.11 Exergy Diagram for Simulation 13

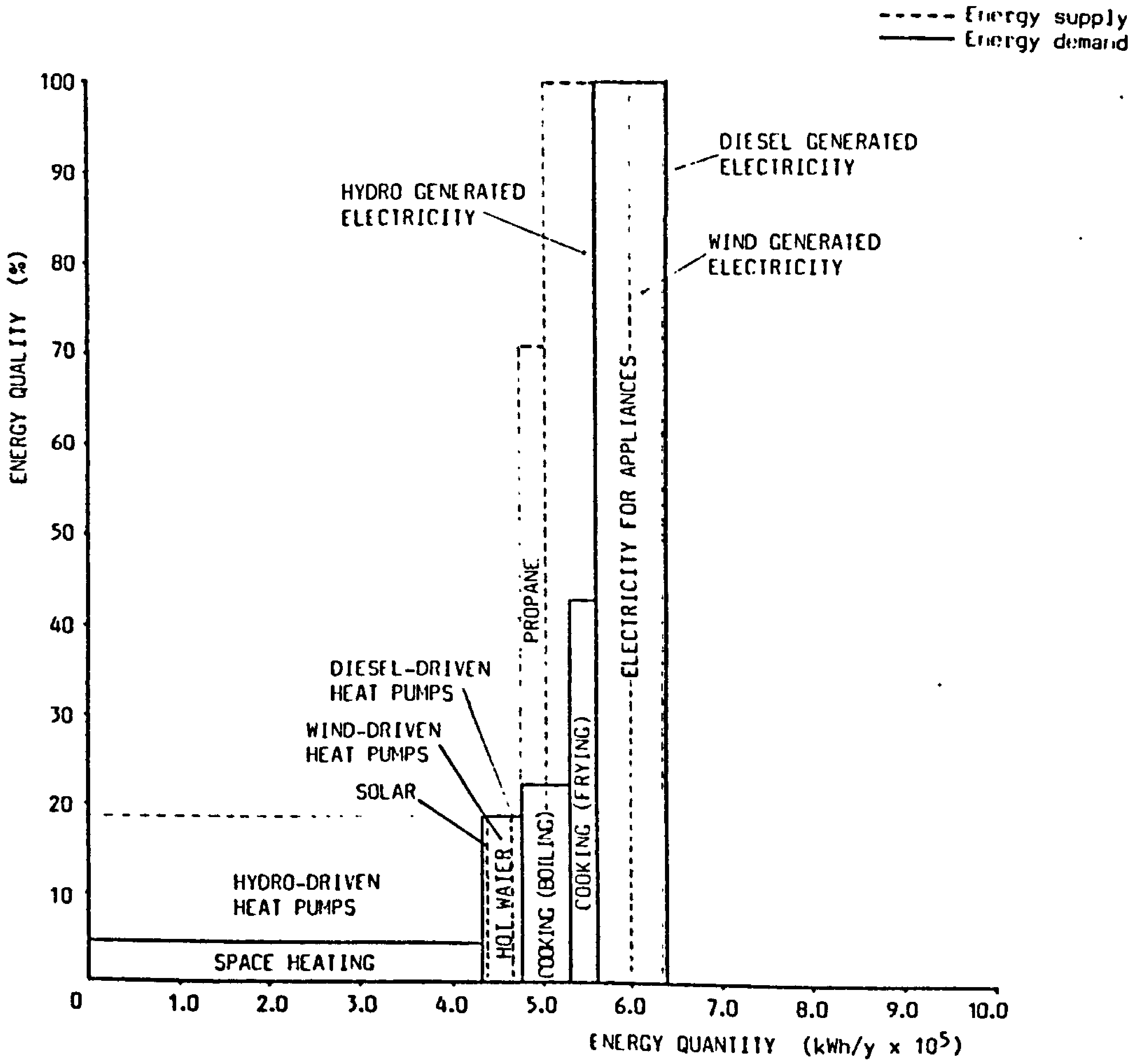


FIGURE 6.2.12 Exergy Diagram for Simulation 13, showing Outputs of Heat Pumps and Electricity Generators

6.2.3 Summary and comparison of economic and thermodynamic results, with discussion

The results of the 15 different simulations are discussed fully in the two preceding sections. Table 6.2.15 summarises the results from thermodynamic and economic analysis.

Simulation	Total cost (£/y)	Fuel cost (£/y)	First law efficiency (%)	Second law efficiency (%)
Eigg census	-	17900	41.7	15.6
1	21700	19000	40.2	15.1
2	17700	13300	45.4	16.9
3	28700	22200	44.3	12.6
4	16700	6800	67.2	17.6
5	21200	6900	66.9	17.1
6	20100	6700	70.0	17.9
7	18600	6200	71.4	18.5
8*	18600	6600	68.9	17.9
9	19800	6800	69.9	18.3
10	19200	6700	69.6	18.3
11	26400	5000	84.7	20.0
12	31000	6700	80.9	19.4
13	21200	2600	171.2	36.6
14	22300	7500	58.2	15.3
15	21400	8100	63.6	18.9

Notes: * = Optimum economic system
= Optimum thermodynamic system

Table 6.2.15 Summary of simulation results

Discussion

In general, economic optimisation and thermodynamic optimisation complement each other. Total costs fall from simulation 3 to 8, while there is a corresponding increase (although not great) in second law efficiency. The optimum thermodynamic system (simulation 13) is the cheapest system in terms of fuel cost only; it is only 14% more expensive than the best economic system on total costs. It would only require a relatively small increase in the unit cost of wood fuel (assuming other energy sources remained the same) for the optimum thermodynamic system to be the same as the optimum economic one.

Hydro energy, with zero fuel cost but high quality output, is both cheap and capable of supplying energy demands efficiently. Its use, therefore, optimises both costs and thermodynamic efficiency.

While attempting to maximise second law efficiency, the systems were still subject to the economic constraints of the economic planning model. Were this not the case, solar energy would make a far greater contribution than it does. Since solar energy, by the definition of this work, is relatively low quality, its greater use would improve thermodynamic performance further. Again if solar energy could be made cheaper, or other fuels became more expensive, the optimum economic system would again correspond to the optimum thermodynamic system.

Although sim. 8 appears to be slightly worse than sim. 7 in terms of fuel cost and efficiency, if the effects of load factors are included (see table 6.2.10), it in fact has lower total costs. These effects were not included in all simulations, as it was more important to correct equipment ratings first. For comparison, allowing for equipment load factors, the total cost of the best economic system (sim. 8) is about £39000 pa. For sims. 1 (the existing system) and 13 (the best thermodynamic system), total costs are about £29000 pa and £37000 pa respectively. This indicates that, per unit of energy delivered, sim. 13 becomes the economic optimum. The main cost increase is from poor usage of wind energy, and the contribution of wind to Eigg's energy system needs further study before any firm conclusions can be drawn. It seems likely that lower-rated wind turbines would be more suitable for the island, giving considerably lower system costs after accounting for equipment load factors.

Varying the simulation time step of the energy planning model, from one hour to one day or one week, shows considerable differences using the longer time steps. These differences were in general not predictable, and could not be assessed and accounted for in advance. It is concluded, therefore, that the choice of an hourly time step for the model is better than either a daily or weekly step, even allowing for the longer time needed to run the model.

6.3 CONCLUSIONS

The main conclusions relating to the methods of energy systems' analysis used in this work are that:

(a) Thermodynamic optimisation and economic optimisation in general complement each other, when applied to the type of energy supply system used on the island of Eigg.

(b) Thermodynamic performance is increased in two ways; replacing energy-inefficient transformations such as diesel fuel to electricity, and avoiding exergy-inefficient transformations such as high quality electricity direct to low temperature heat.

(c) Energy-inefficient transformations of combustible fuels can be successfully (both economically and thermodynamically) replaced by using high quality hydro and wind generated electricity.

(d) Exergy-inefficient transformations are improved either by using heat pumps, or by using lower quality supplies such as solar energy. The former are economically viable, the latter, in this study, is not.

(e) The combination of economic and thermodynamic analysis can help show where efforts should be made to make energy costs less in order to increase thermodynamic performance.

For the island of Eigg an economically-optimised energy supply system has been determined. This gives greater levels of energy usage and makes energy more easily available, at an average unit cost lower than that currently paid by the islanders. The thermodynamically-optimised system for Eigg gives much higher thermodynamic efficiency, but at a total cost 15% higher than the best economic system.

The analysis showed that if the costs of both solar energy and energy from heat pumps could be reduced, it is likely that the thermodynamically optimum system would also be the economically optimum one. This implies that work on these two would be worthwhile for systems of the sort proposed for Eigg.

CHAPTER 7 CONCLUSIONS

The main outcomes and conclusions from this work, all of which are discussed in more detail in this chapter, are:

1) The strategy for planning domestic energy supply systems is applicable to many small communities throughout the world. It shows which energy supply equipment (both renewable and non-renewable) should be used to best supply the energy demand in the community.

2) Meteorological data, potential renewable energy supplies and community energy demands, all needed for the planning strategy, can be determined using the methods suggested.

3) The two methods of energy systems' optimisation, economic and thermodynamic, both give valuable insight into how energy systems can be improved. Taken together, they show which energy supplies should be improved so that the thermodynamically-optimised system is the same as the economically-optimised one.

4) Applied specifically to the small Scottish island of Eigg, the planning strategy shows that significant improvements to the islanders' energy supply system are possible, improving energy usage (hence comfort levels) while decreasing the unit cost of the energy. Hydro-electric energy and wood fuel, in particular, are resources which are economically viable on the island, and should be developed.

7.1 The Energy Planning Strategy

This thesis presents a complete strategy for planning energy supply systems for small, remote communities. The strategy includes methods for (1) obtaining energy demand data, (2) obtaining meteorological data for assessing potential wind and solar energy, (3) predicting river flow rate to determine hydro-electric energy potential, (4) testing, by computer model, the economic performance of a proposed energy system, (5) assessing the thermodynamic performance of the system and (6) optimising the energy supply system on a thermodynamic or economic basis.

Energy Demands

Energy demands for small communities can be determined by energy census or survey, and this was done for Eigg. However, the results of such a census do not reflect realistic demand levels if energy prices are high, energy efficiency low, or insulation and energy conservation measures poor. It was concluded that the detail of the census for Eigg would only be worthwhile if the community already had satisfactory energy usage levels, and a simpler energy survey questionnaire was presented for other communities. The census did, however, give most useful personal experience of islanders' comfort levels, making the task of determining reasonable energy demands much easier.

Four types of energy demand were covered by the planning model: space heating, cooking, hot water and electricity for appliances. Cooking and hot water demands for Eigg were found adequately by the energy census. But for the reasons above this was not possible for space heating or electricity demands. Therefore other methods of assessing these demands were evaluated.

For space heat demand, three computer based models and an electric analoque circuit were applied to a typical (in terms of size, construction, etc.) house on Eigg. It was concluded that no model sufficiently accurate and easy to use could be found, but that the equivalent electrical circuit model, solved either analytically or by constructing the circuit (although not done by this work), might be a suitable method. Energy demands for the typical house were, however, calculated using the sophisticated simulation model known as ESP, and these were shown to be reasonable compared with census results. But this model is too complex for general energy planning work. Electricity demands were determined by assuming that, given cheaper and more available electricity supplies, they would be similar to those for a small community on the British national electricity grid.

Although there is little doubt that a community's energy usage would change if cheaper and more available supplies became available, the amount by which it would increase is unknown. Further study of communities, before and after improvements to their energy systems, is needed before the methods suggested can be validated. However, the methods allowed reasonable energy demands for Eigg to be determined, which otherwise could not have been easily obtained.

Meteorological Data and Renewable Energy Supplies

Renewable energy supplies have the advantages of making a community more energy self-sufficient, reducing costs and overcoming some of the problems of conventional energy sources. To assess renewable energy potential, meteorological (met.) data are needed.

For Eigg it was possible to use data from other recording stations in other areas in Scotland. An typical year, corresponding to average values extrapolated from the met. stations nearest to the island, was obtained. This method gave reasonable data for Eigg which could only otherwise have been determined by long-term monitoring.

For some communities, though, the above method might not be possible. So methods were investigated for simulating short term data from longer term averages: air temperature (controlling space heating demand), solar radiation (for calculating solar energy) and wind speed (for calculating wind energy potential). Although these methods were not used in the main planning model, they were used in the building space heating work, and were shown to be sufficiently accurate for general energy planning, eliminating the need for long-term data recording in the community being studied.

Hydro-electricity is a cheap, effective energy source worth developing if there is suitable potential. To assess this potential a simple hydrological model was developed, allowing daily river flow rates to be predicted, knowing only easily-recorded daily rainfall and air temperature and minimum information about the catchment area, and avoiding the need for costly and difficult direct measurement of river flows. The model was shown to be relatively insensitive to most parameters, and proved quite accurate (within 20%) at predicting hydro potential for small catchments in comparison with recorded results.

7.2 Energy Planning Methods

Two different methods were developed for assessing domestic energy supply systems for small, remote communities. A computer based model, used to test the economic performance of a particular energy system and suggest improvements to the system, was constructed, and tested for the island of Eigg. A method of assessing the thermodynamic performance of the same systems, using exergy diagrams, was also used to assess systems for Eigg. The two methods were shown to be, in general, complementary, with thermodynamic optimisations improving economic performance, and vice versa.

Economic Planning

The strategy of the economic planning model is to always make the best (cheapest) use of the different energy supplies in a simulation. The model bases its decision on the order in which to use energy sources by attempting to use the cheapest renewable energy source first to substitute for the most expensive non-renewable energies. Supplies are chosen on a unit energy cost (£/kWh) basis, and a sorting procedure determines the order in which they are used.

Unit costs in the model are determined by the well-established net present value analysis. The choice of money interest rate was shown to be important; low interest rates favouring renewable energy devices, while high rates favour non-renewables. This work used a yearly interest rate of 5% pa, representing the likely way in which energy projects might be funded on Eigg. It was shown that unit costs are determined independently of general inflation rates.

The calculation of unit costs depends on the amount of energy produced by each supply per year. Initial assumptions are made about energy output which can be modified after each simulation. Therefore the total yearly cost of a supply is the cost (£/y) independent of output. However, using unit energy costs allows direct comparison between different energy sources, which cannot be done if yearly costs (£/y) are used as the basis for choosing between sources. It is concluded that the method of this thesis is the most suitable method of ensuring minimum costs.

The economic planning model for most simulations used an hourly time step to simulate a year's system performance. However, two simulations were run using daily and weekly time steps, giving significantly different results compared with hourly simulations. The differences, additionally, were not predictable prior to the simulation. Therefore it was concluded that the choice of an hourly simulation step was better than the longer ones, even allowing for the increased running time of the model.

Thermodynamic Planning

An alternative method of assessing energy systems was developed, to allow systems' optimisation independent of economic factors. The function exergy was introduced; this being the amount of useful work extractable from an energy source. Exergy can be used to determine energy quality, defining quality as exergy divided by energy quantity. Second law efficiency was defined as being the exergy content of an energy demand or energy output divided by the exergy input to meet the demand or provide the output. This efficiency was the factor used to measure thermodynamic performance.

The methods of this thesis differed from those of other researchers, in that exergy was calculated after an initial transformation process chosen to represent the fundamental form of the energy source. Therefore the quality and exergy values used in this work more accurately represent practical processes, giving more realistic results than if a purely theoretical analysis had been used.

Energy quality against quantity diagrams were introduced, and these were shown to be useful for visualising exergy performance. Areas on these diagrams represent exergy, so demand areas divided by supply areas give second law efficiency. Since energy quantity is shown on the diagrams, energy efficiencies can also be seen. Studying the area representing supply exergy in comparison with the area representing demand exergy allows inefficiencies to be easily seen.

Thermodynamic system improvements were tested and simulated by the economic model, and therefore were only effective if they were economically viable. However, in one simulation the cheaper wood fuel sources were omitted, 'forcing' the simulation to increase its use of heat pumps. This was shown to result in the thermodynamic optimum (within practical limits imposed by cost and equipment) energy system.

7.3 Planning Results

The primary aim of this project was to develop a planning strategy and show how it could be applied to a community: this aim has been achieved. In addition, however, some useful recommendations for improving the energy system on the island of Eigg can be made. Although more work is needed to verify the assumptions made when choosing data, some general suggestions can be made for the island.

Comparison of Economic and Thermodynamic Results

Fifteen simulation results of different energy systems on Eigg, optimising both economic and thermodynamic performance, were compared by the criteria cost and second law efficiency. Hydro-electric energy, in particular, was shown to be most successful both economically and thermodynamically; its high quality output replaces less efficient energy transformations, and its low cost replaces much more expensive non-renewable sources. Wood fuel also proved very cost effective on Eigg. Its slightly lower quality than other combustible fuels make it more suitable for supplying lower quality heat demands, giving small improvements in second law efficiency.

Both wind and solar energy could give good thermodynamic improvements: low quality (defined by this work) solar energy being good for supplying low quality space heating, high quality wind energy replacing fossil fuels. However, their relatively high unit costs, compared with wood and hydro energy, limited their contribution to Eigg's energy supplies. Heat pumps also give excellent second law efficiency improvements, but again cost reduced their effectiveness.

The general conclusion of the comparison between economic and thermodynamic results is that, at least for the types of energy supplies studied by this thesis, the two types of optimisation are closely linked. It was shown that if heat pumps, solar collectors and wind turbines could be made cheaper or more efficient, or if other energy supplies became more expensive, the optimum economic energy supply system would be the same as the optimum thermodynamic one.

Results and Recommendations for the Island of Eigg

The general conclusions for improvements to Eigg's energy supply are:

1) There is good potential for the island to produce far more cheap wood fuel than at present, given proper management of wood plantations. The wood could be burnt in existing ranges and stoves, giving large cost savings by replacing coal and bottled gas.

2) Hydro power could be developed successfully on the island, giving energy supplies which are considerably cheaper and more available than the current diesel generators. To fully utilise hydro potential, electricity grids connecting all houses should be provided.

3) Most houses would benefit from the installation of central heating systems.

4) Active solar energy systems, and wind energy, need to be made cheaper before they can contribute more to Eigg's energy supplies. Heat pumps can make a small contribution to the island's energy system, but they also need to be made cheaper to have wider effect.

5) The above improvements would give greater energy usage (hence improvements in living standards) at a total yearly cost per unit less than that currently paid by the islanders. Fuel costs would be much lower, and the island would become much more energy self-sufficient, changing from 85% dependence on imported fuels from the mainland to only 3% dependence, although extra coal might be needed for some years.

The above suggestions clearly merit attention, and it is hoped that at least some of them could be implemented. The future of many small, remote communities depends to a certain extent on improved energy supplies, and the methods of this thesis are an excellent way of planning these improvements.

APPENDIX 1

Eigg Island Energy Census Questionnaires

The first questionnaire presented here is that used for personal interviews of householders on the island of Eigg during the energy census (see Chapter 3). Several of the sections of the questionnaire (including the plan of buildings) were not used, because of time constraints during each interview.

The second questionnaire is that developed for the postal census of householders who could not be personally interviewed. This is considered to be more suitable, in terms of the amount and detail of information it collects, for future energy surveys or censuses.

Both questionnaires are shown as they were filled in during the census on Eigg, using typical results. This helps show which questions were superfluous.

CODE NO. 12

Date 22 June 83

Time Evening

Weather conditions Overcast

Outside temperature ....

ENERGY SURVEY QUESTIONNAIRE

Information supplied for this survey will be kept strictly confidential.

Publication of results will be with prior permission only.

No connection will be made between named individual or groups and results.

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Tel. 041 552 4400

General Introduction Purpose of the survey

Section 1 Domestic Appliances

Type	Make and model	Rating	Age	Usage pattern Hrs/day		Total energy day (kWh/d)	
				Summer	Winter	Sum.	Win.
Deep freeze							
Fridge	Electrolux (gas)			All	All	5	5
Electric blanket							
Television	B + W Colour			3/week — 3/4	 3/4	0.05 0.58	0.05 0.58
Tape/radio	Radio - car	battery	from gen.	All	All	0.13	0.13
Toaster							
Other	Battery charger Tumble dryer	from gen.		4 0	4 5/week	0.13 0	0.13 2.14
		From tractor gen.		Hrs/week			
				Summer	Winter		
Washing machine	Top loader. Hot or cold bill			5	5	0.36	0.36
Iron				~	~		
Electric heater				2 hrs/week		1½	1½

welding + lights

Total/day	1.96 gen 1.36 trac.	1.96 gen 3.50 trac.
Total/year	720 gen. 890 trac.	

Do you plan to buy any new appliances in the next year? Yes/No
If so, which?

440 lights
1170 others

Section 2 Cooking Details

Cooker	Model			Rating	Age		Usage (hrs/day) (No. of rings, etc)	
	No. of rings	Oven	Grill				Weekdays	Weekends
Butane	4	1	1	r = 2.2 Gr = 3.6		Morning		
Propane						Lunchtime		
Coal	✓					Afternoon		
Wood	✓					Evening	1r × ½ hr Gr × 5 mins	
Oil								
Other								

Cooker type		How long does fuel last?	Energy used/day (kWh)	Energy used/year (kWh)
Butane	✓	13 kg / 4 wk winter 15 kg / 5 wk summer (lights + fridge)	Fuel used Sum 0.65 Win 1.12 Usage pattern W.H 0.48 0.48 Cooking 0.48 0.48	Fuel used 380 Usage pattern 350
Propane				
Coal		1 ton coal / year	63.3 WH 7.5 Cooking 12.7 S.H. 25.4 Flue loss 17.7	23110 WH 2740 Cooking 4620 S.H. 9280 Flue loss 6470
Wood		5 ton wood / year		
Oil		(including fire)		
Other				

Section 3 Water Heating (excluding kettles and pans)

Type	Normal temp. °C	Rating	T'stat setting	Energy (kWh) used/day		Usage Hrs/day		Tank cap. (1)
				Sum.	Win.	Sum.	Win.	
Cooker ✓								30 gall
Oil-fired								
Gas-fired								
Electric								
Other								

Water Used

		Bath	Dishes	Clothes washing	Cleaning	Shower	Other
Times /week	Summer	7	21	As washing	3		
	Winter	7	21	machine +1 HW/week	3		
Water used (1)	Summer	420	210	240	30		
	Winter	420	210	240	30		

Total energy used/day Summer ..7.50.. kWh Total energy used/year
Winter ..7.50.. kWh ..2740.. kWh

Storage tank insulation ..Jacket.. Total length of hot water pipe ......
Water pipe insulation ...No... Hot water pipe diameter ......

Kettle (water heated for cooking, drinking and washing)

Early morning	Breakfast	Mid-morning	Lunchtime	Afternoon	Supper	Evening	
1	1	1	1	1	1	1	Summer
1	1	1	1	1	1	1	Winter

Is the kettle/pan always full? ..4 pints.. Kettle/pan capacity ..4 pints..

Total water heated/day
Summer ....
Winter ....

Total energy used/day
Summer ..0.286.. kWh
Winter ..0.286.. kWh

Total energy used/year .... kWh

Section 4 Primary Fuel Supply

Fuel type	Supplier	How often delivered	Amount delivered Summer	Winter	How long lasting	Cost	kWh
Propane							
Butane	Estate		17 × 15kg	/year (inc. heater)			3492
Paraffin							
Diesel	Simpson / Johnston		5 gal/week 5 gal/7hrs 5 gal/week	2 tractors gen. on tractor Land Rover			12380 26530 12380
Petrol			2½ gal/week 2 gal/week ½ gal/week	digger for 2 bikes chain saw			6190 4720 1180
Heating oil							
Coal	Salen Coal Co.		1 ton /	year			7060
Wood			5 tons				20160
Peat							
Other							
					Total supplied (kWh)		94090

Fuel Bills (where available)

Time period	Supplier	Fuel	Amount	Cost	kWh supplied
		Propane			
		Butane			
		Paraffin			
		Diesel			
		Petrol			
		Heating oil			
		Coal			
		Wood			
		Peat			
		Other			
			Total supplied (kWh)		

Section 5 Generator

Type	Fuel type		Output rating (kW)	Estimated efficiency	Usage Hrs/day		Fuel used per day	kWh/d
Lister tractor	Diesel	✓	25 KVA	3.4 tractor	Morning			
	Other			17.6 gen.	Afternoon			
					Evening			
					Night	15/week	5 gal/7 hrs	

Do you share your generator? Please give details Yes. Gen. is number 10's

Section 6 Transport

Vehicle	Engine size (cc)	Fuel	Cost per week	Gallons per week	Distance per week	Miles/gall.	kWh/mile
Car							
Van							
Land Rover					75	15	
Boat							
Taxi							
M/cycle	250 110				50 for both	25 ea	
Bicycle ✓							
Tractor	2						
Other							

Frequency of Journey/Usage (including agricultural vehicles)

Vehicle		Reason	Destination or distance (miles)	Frequency
Car			To school	
Van				
Land Rover			To the harbour	
Boat				
Taxi			To the shops/ post office	
M/cycle				
Bicycle			Others	
Tractor				
Other				

Do you often travel to the mainland/other islands? Yes/No
If so, to where and how often? ....

Section 7 Building Details

Type				Days/year		Usage pattern	Week	W/end	Age			
				Summer	Winter							
Croft		Stone	✓	All	All	All day	✓	✓	New		Owned	
						Morning/evening			20 yrs			
Shop		Brick				Morning/lunch/			50 yrs		Rented	
						evening only			100 yr			
Chalet		Wooden				Other			Older	✓	Tied	✓
Other		Block										
House	✓	Other										

Loft/Roof

Roof type		Access	Insulation (roof)	Insulation (floor)	Dormer Windows		Ease of Insulation	
Slate	✓		No	No	Yes		Easy	
Tiles					No		Moderate	
Corrugated iron					5 skylights		Difficult	✓
Other								

Building Situation and Accessories

Situation		Shelter belt	Shutters	Conservatory	Porch	Other
	Front					
	Back					
	L. side					
	R. side					

External Building Photograph:

Floor Details

Floor level: Ground ☑ First ☐ Second ☐ Other ☐

Plan

Room number	1	2	3	4	5
Room type	Kitchen ✓ Bedroom	Living ✓ Other	Dining Other	Bedroom Store	Bathroom ✓ workshop
Usage (h/day) summer					
Usage (h/day) winter					
Windows (no.)					
Type					
Size (m)					
Curtain type					
Draught from windows Y/N?	Yes	Yes			Yes
Doors (no.)					
Type					
Size (m)					
Draught-proofing?					
Draught from doors Y/N?	Yes	Yes			Yes
Room temp. Winter °C					
Summer °C					

Room number	1	2	3	4	5
Dampness: None					
Moderate					
Bad					
Lights: Number	1 1 1	1			1 1
F'rescent					
I'descent	✓ ✓	✓			✓ ✓
Lantern					
Other	Gas				
Rating (W) 40					✓ ✓
60	✓ ✓	✓			
100					
Other					
Usage (h/day) summer	4 $\frac{1}{2}$ 0	4			4 4
Usage (h/day) winter	4 3 0	4			4 4
Space heating:					
Fuel and rating: Wood		(closed)			
Peat					
Propane					
Butane					
Oil					
Electric					
Other					
Usage (h/day) summer		0			
Usage (h/day) winter		Assume 7.5 kW input 3			
Ceiling type:					
Insulation					
Ease of insulation					
Floor type: Flags					
Wooden					
Other					
Carpet None					
Partial					
All over					
Walls: External thickness (m)					
Type: Stone					
Brick					
Wood					
Block					
Other					
Cavity					
Internal covering					

Room number		1	2	3	4	5
Internal thickness						
Type	Plasterboard					
	Plaster					
	Other					
Ease of insulation						
Heat/d (kWh)			0 summer 25.5 winter			
Light/d (kWh)		0.94	0.24			0.32

Section 8 General Details

Occupants		Male	Female	Children
Number		1	1	3
How do you spend your day?		Estate	Part-time shop + housewife	
How long have you lived on Eigg?	Always		✓	✓
	Other	7		
Did your parents live on Eigg/other island	Yes		✓	✓
	No	✓		
Working		✓	✓	
Retired				
Unemployed				
Energy related activities: insulation, etc.				

Section 9 Tourism

Is this property used for tourism? Yes/No ..No.....

Type	B + B	Letting	Caravan	Other
No. of rooms				
Usage pattern weeks/year				

Will your future plans for tourism, if any, affect the pattern of your energy usage? ....

Section 10 Additional Details

Do you own any animals? 5 dogs

What type of sewage system do you have? Septic tank

Do you collect seaweed or bracken? No

Do you produce your own meat/dairy produce? No

Do you have a vegetable plot? No

Do you have enough information about energy conservation? Can't afford anything, otherwise would insulate generally

If not, what information would you like?

Have you taken part, or plan to take part, in any energy conservation measures?

How do you see future progress on the island regarding population, industry and tourism? Static

How do you consider your future in the island? Semi-permanent

How do young people consider their future on the island?

Have you taken any steps, or plan to take steps, to obtain:

a) New industry (please specify)? Knitting machine

b) Better electricity supply? No

c) Increased tourism? No

d) More shops? No

e) Better roads? No

Are you satisfied with your existing comfort levels, regarding heating, transport and electricity supply? No

If not, what changes would you like to see? Electricity should be more readily available. Too cold in winter.

Energy Summary (All units are kWh. All results refer to energy inputs to each process. Energy for water and space heating may come from inputs to the range)

		From usage pattern	From fuel used
Energy for cooking/day..................	Summer...	18.59	18.28
	Winter...	18.59	18.75
Energy for domestic water heating/day... (inc. immersion heaters, exc. kettles)	Summer...	10.4	–
	Winter...	10.0	–
Energy for space heating/day............ (does not include free gains)	Summer...	–	35.3
	Winter...	58.9	58.9
Energy for electric appliances/day...... (inc. lights but not immersion)	Summer...	1.96 gen 1.36 tractor	
	Winter...	1.96 gen 3.50 tractor	
Energy for gas appliances/day........... (does not include heaters)	Summer...	5.2	–
	Winter...	6.2	–
Energy for transport/day................	Summer...	–	46.8
	Winter...	–	46.8
Energy for agriculture/day..............	Summer...		54.1
	Winter...		54.1
Diesel fuel for generators only/day.....	Summer...		40 tractor code 10 gen
	Winter...		100 tractor code 10 gen
	Total/day.....		

Energy for cooking/year.................	6670	6800
Energy for domestic water heating/year..	3810	–
Energy for space heating/year...........	17210	17210
Energy for electric appliances/year.....	720 gen. 890 tra.	–
Energy for gas appliances/year..........	1890	–
Energy for transport/year...............		17100
Energy for agriculture/year.............		19750
Diesel fuel for generator/year..........		26880 tra. gen. 4090 gen.

Total/year....

Cost (in this case, free gains are counted as useful energy)

Fuel	Cost per kWh delivered	Cost per useful kWh
Propane		
Butane	0.044	0.090
Diesel	0.028	0.159
Petrol	0.042	0.176
Heating oil		
Coal	0.014	0.019
Wood	0.009	0.010
Paraffin		
Other Diesel (tractor) Diesel (tractor generator)	0.028 0.028	0.112 0.824

CODE NO. 26

Date 16 Sept 83

Time ....

Weather conditions mild, drizzle

Outside temperature ....

ENERGY SURVEY QUESTIONNAIRE

Information supplied for this survey will be kept strictly confidential.

Publication of results will be with prior permission only.

No connection will be made between named individual or groups and results.

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GLASGOW G4 0NG.

Tel. 041 552 4400

Section 1 Domestic Appliances

Please complete this section if you have any of the following:

	How many hours per week is it used? (if the same as generators, put 'As gen.')	
	Summer	Winter
Deep freeze		
Fridge		
Television B & W or Colour?		
Washing machine		
Electric heater		
Other (Please specify) Radio + stereo cassette HP_2 batteries	21 hrs/week	31 hrs/week

Does the washing maching heat its own water when you use it? Yes/No

Do you have a gas fridge? Yes/[✓ No]
If so, how often is it run?
How long does a bottle of gas for the fridge last?

Section 2 Cooking Details

Do you have a cooking range? Yes/[✓ No]

If yes, what fuel does it use? Coal ☐ Wood ☐ Oil ☐ Coal & wood ☐

How many months is it running? Summer .... months Winter .... months

How much fuel does it use in a year?

Does this include fuel burnt in other stoves or fires? Yes/No

---

Do you use a gas cooker? [✓ Yes]/No

If yes, how long does a bottle of gas last? Summer..4..wks Winter..2..wks

What size gas bottles does the cooker use? 4.5 Kg ☐ 15 kg ☒ 47 kg ☐

Is the gas cylinder connected to any other appliances?
Lights [✓ Y]/N Fridge Y/N Water heater Y/N Space heater Y/N

Do you use any other sort of cooker? Yes/[✓ No]

If yes, please specify, and give details of amounts of fuel used per year.

Section 3 Water Heating (excluding water heated for cooking or drinks)

Which of the following methods do you use to heat your water:

Range Y/N Electric immersion Y/N Gas cooker [✓ Y/N] Gas heater Y/N

Is your water heated differently in the summer to the winter Yes/[✓ No]
If yes, please specify:

If you have a gas water heater, what size gas bottle do you use? ....kg

How long does a bottle last? Summer .... weeks Winter .... weeks

If you have an electric immersion, how many hours per week is it used?
Summer .... hours/week Winter .... hrs/week

If you heat water on the cooker, do you usually boil it? [✓ Yes]/No

Please say how often you use hot water for any of the following: (Do not put how much water you use, only the number of times per week, except where water is heated on the cooker, in which case please say how many gallons per week you use for each purpose)

		Bath	Washing dishes	Clothes washing	Shower	Personal cleaning	Household cleaning	Other
Times per week	Summer		every day 1 litre	1 per week 2 gallons		every day 2 litres		
	Winter		every day 1 litre	1 per week 2 gallons		every day 2 litres		

Do you have insulation on your hot water tank? Yes/No

Do you have insulation on your hot water pipes? Yes/No

Section 4 Diesel Generator

Do you use a diesel generator? Yes/[✓ No]

If yes, please give the following details:

Generator make and type	Output rating (kW)	Usage (hrs/day)		Fuel used per day or per year (Galls)		
		Summer	Winter		Sum.	Win.
				Per day		
				Per year		

Approximate cost of diesel maintenance per year £......

Section 5 Space Heating and Lighting

Please fill in the following details for each room of your house, even if a room has no heating or lighting Caravan

Room type			Kitchen	Living	Dining	Bathroom	Bedroom	Bedroom	Other	Other
Lighting: Fluorescent (number and rating)										
Incandescent (number and rating)										
Gas (number of mantles)			1	2						
Usage of lights (hrs/day) For example: Gas 1 light for 1h/d, 2 electric 2h/d each.										
Fluorescent		Summer								
		Winter								
Incandescent		Summer								
		Winter								
Gas		Summer	1hr/day	4 hr/day						
		Winter	2 "	7 "						
Lantern		Summer		4 candles a day						
		Winter		6 candles a day						
Space heating: Please give amount of fuel used per week or per year; how long a gas cylinder lasts; etc.										
Wood	Open fire	Summer	/	/						
		Winter	/	all day 70 kgs/week						
	Closed fire	Summer								
		Winter								
Gas		Summer								
		Winter								
Electric		Summer								
		Winter								
Coal	Open fire	Summer								
		Winter								
	Closed fire	Summer								
		Winter								

Section 6 Transport

Please give details of any of the following that you use:

	Engine size (cc)	Fuel type	Approx. fuel used per week or year	Distance travelled per week or year
Car				
Land Rover				
Tractor				
Bicycle	X			25 miles / week
Other (please specify)				

How often do you travel to the mainland or to other islands? ..6 times..

Section 7 Primary Fuel Supply

Pleas give details of total amounts of each fuel supplied per year, as far as possible for the year April 1982 to April 1983:
(note: if you buy fuel in other amounts than shown, please specify)

Propane	(47 kg)	No. of cylinders	....	Cost ....
Butane	(4.5 kg)	No. of cylinders	....	Cost ....
	(15 kg)	No. of cylinders	..16...	Cost ≈ £155
Diesel for generator	(45 gall)	No. of barrels	....	Cost ....
Diesel for transport or tractor	(45 gall)	No. of barrels	....	Cost ....
Petrol	(45 gall)	No. of barrels	....	Cost ....
Kerosene	(45 gall)	No. of drums	....	Cost ....
Coal		No. of tons	....	Cost ....
Wood		No. of tons	....	Cost ....
Other		Amount	....	Cost ....

Section 8 General Details

Number of permanent occupants: Male ..1.. Female ..1.. Children ....
Do you grow your own vegetables? [✓ Yes]/No
Do you produce your own meat or dairy produce? Yes/[✓ No]
Are you satisfied with your existing comfort levels, regarding heating, transport and electricity supply? Yes/[✓ No]
If not, what other changes would you like to see? better lighting system? (electricity generally) 12 volt battery powered by generator (waterfall or
Is there anything else for which you use energy, which has not been covered by the questionnaire? windmill for instance

APPENDIX 2

Energy Supply Equipment Data used in Energy Simulation of the Island of Eigg

This appendix gives details of the energy supply equipment used in the energy simulations of the island of Eigg described in chapter 6. Equipment costs, output rating, fuel costs and lifetimes are given, and which equipment is used by each house.

The information is given for each of the four programs making up the planning model: namely COSTCALCS, HOUSECOSTS, COSTSORT and COMSIM. These are described in section 4.1.

ENERGY PLANNING MODEL ENERGY EQUIPMENT DATA

Fifteen simulations were run, described fully in chapter 6. Some simulations use the same data, and where this is the case data are only listed once. Equipment efficiencies are those from table 3.2 (section 3.2). Equipment costs are from manufacturers or suppliers:

Ranges and stoves from the Solid Fuel Advisory Service, London and Glynwed Appliances Ltd., Ketley, Telford.

Hydro turbines from Water Power Engineering, Dursley, Gloucester, Swift Industrial Developments Ltd., Romsey, Hants and MacKellar Engineering Ltd., Grantown-on-Spey, Morayshire.

Wind turbines from a survey by Taylor (Taylor, J.R.M. & Twidell, J.W. 1985 An economic survey of wind generated electricity for heat pumps at a community school in the Western Isles. Proc. 7th British Wind Energy Association Conference (ed. A. Garrad), Mech. Eng. Publications Ltd., London).

Diesel generator prices from Bass (1985, personal communication).

Heat pumps from South of Scotland Electricity Board, Edinburgh, K.C. Heat Pumps, East Linton, Edinburgh and Myson Heat Pumps, Milton Keynes.

Solar water heating panels from Hanlon and Saluja & Robertson (Hanlon, M. 1982 Experience with domestic solar water heating. In Energy for Rural and Island Communities II (ed. J.W. Twidell), Pergamon Press, Oxford: Saluja, G. & Robertson, P. 1982 Active solar systems for higher latitudes. In E.R.I.C.II (ibid)).

Gas water heaters from Scottish Gas, Glasgow.

Wherever possible costs are those for the year 1983-84, chosen as the reference year. Capital cost values are those for new equipment: no account is taken of the fact that equipment might already be installed. The money discount rate used in all simulations (see section 2.1) is 5% per annum.

The simulations treat the 27 houses on Eigg in different orders, so each house is given a reference number (which remains constant).

Electricity demand levels are: 1) 0.276 kW mean, 2) 0.062 kW mean, 3) 0.817 kW mean, 4) 0.161 kW mean, 5) 0.563 kW mean and 6) zero demand. The zone types are: 1) bedrooms, 2) kitchen, 3) general purpose room and 4) living room (see section 5.3).

Simulation 1: Data for this are shown on tables A2.1 to A2.4.

Equipment	Type no.	Output rating (kW)	Capital cost (£)	Maint. cost (£/y)	Fuel cost (£/kWh)	Aver. eff. (%)	Life (y)
Hydro turb.	1	4.5	7000	0	0	90	40
Hydro turb.	2	4.0	6000	0	0	80	40
Dies. gen.	1	7.0	2450	25	0.028	20	15
Dies. gen.	2	3.5	1720	25	0.028	18	15
Dies. gen.	3	2.8	1440	25	0.028	15	15
Dies. gen.	4	10.5	2840	25	0.028	12	15
Dies. gen.	5	1.8	1030	25	0.028	14	15
Coal range	1	1.0	1500	0	0.014	50	30
Coal range	2	2.0	2000	0	0.021*	70	30
Coal range	3	1.0	1500	0	0.021*	70	30
Coal range	4	2.0	1900	0	0.014	70	30
Coal range	5	1.5	1750	0	0.014	60	30
Coal range	6	1.3	1600	0	0.014	70	30
Keros. range	1	1.8	1600	0	0.024	70	30
Wood range	1	2.0	1750	0	0.009	70	30
Wood range	2	2.5	1850	0	0.009	50	30
Coal stove	1	1.5	600	0	0.014	65	40
Wood stove	1	5.0	1500	0	0.009	60	40
Wood stove	2	1.5	600	0	0.009	55	40
Wood stove	3	2.0	800	0	0.009	55	40
Gas water heater	1	7.0	700	0	0.044	75	20

Notes: * Phurnacite.

Table A2.1 Data for COSTCALCS for simulation 1

Number of houses = 27
Number of electricity grids = 2

Grid	Supplying equipment	Capital cost (£)	Life (y)	Number of houses on grid
1	Diesel 1	100	20	2
2	Diesel 5	100	20	2

Central heating systems

Type	Capital cost (£)	Output rating (kW)	Life (y)
1	1000	3.0	15

Table A2.2 Data for HOUSECOSTS for simulation 1

							Equipment		
House ref no.	Simul. no.	Zone type	Supplied by CH?	Elec. demand level	Range	Stove	Coal fire	Wood fire	Gas cooker
2	1	2	no	2	C6	-	-	-	But.
		4	no		-	-	yes	-	
4	2	2	no	5	C5	-	-	-	Prop.
		4	no		-	W1	-	-	
11	3	2	no	4	W1	-	-	-	But.
		4	no		-	W1	-	-	
14	4	2	no	5	C1	-	-	-	But.
1	5	2	no	3	K1	-	-	-	Prop.
		4	no		-	W1	-	-	
		1	yes		-	-	-	-	
		1	yes		-	-	-	-	
		4	no		-	W2	-	-	
3	6	2	no	1	K1	-	-	-	Prop.
5	7	2	no	5	K1	-	-	-	But.
		4	no		-	-	-	yes	
6	8	2	no	1	C6	-	-	-	But.
7	9	2	no	6	C6	-	-	-	But.
		4	no		-	-	yes	-	
8	10	2	no	6	-	W3	-	-	But.
9	11	2	no	2	C5	-	-	-	But.
10	12	2	no	3	C2	-	-	-	Prop.
		2	no		-	-	yes	-	
12	13	4	no	6	-	-	yes	-	But.
13	14	2	no	6	K1	-	-	-	But.
15	15	2	no	2	K1	-	-	-	But.
16	16	2	no	3	C4	-	-	-	Prop.
		4	no		-	-	-	yes	
17	17	2	no	6	-	C1	-	-	But.
18	18	2	no	6	-	W3	-	-	But.
19	19	2	no	6	W2	-	-	-	-
20	20	2	no	6	-	-	-	-	But.
21	21	2	no	3	C3	-	-	-	But.
		4	no		-	-	yes	-	
22	22	4	no	6	-	-	yes	-	But.
23	23	2	no	6	C1	-	-	-	Prop.
24	24	2	no	1	K1	-	-	-	But.
		4	no		-	C1	-	-	
25	25	2	no	6	-	-	-	yes	But.
26	26	2	no	6	C1	-	-	-	But.
		4	no		-	W2	-	-	
27	27	2	no	5	C1	-	-	-	-

Table A2.3 Zone, equipment and electricity demand details for HOUSECOSTS, COSTSORT and COMSIN for simulation 1

House ref no.	Simul. no.	CH type	Elec. from	Range Type	Range HW via CH/dir	Stove Type	Stove HW via CH/dir	Gas water heater type
2	1	-	Grid 1	C6	Dir	-	-	-
4	2	-	Grid 1	C5	Dir	W1	-	-
11	3	-	Grid 2	W1	Dir	W1	-	-
14	4	-	Grid 2	C1	Dir	-	-	-
1	5	1	H1 & D1	K1	CH	W1 W2	CH -	-
3	6	-	Dies 2	K1	Dir	-	-	1
5	7	-	Dies 1	K1	Dir	-	-	-
6	8	-	Dies 2	C6	Dir	-	-	-
7	9	-	-	C6	Dir	-	-	-
8	10	-	-	-	-	W3	Dir	-
9	11	-	Dies 3	C5	Dir	-	-	-
10	12	-	Dies 4	C2	Dir	-	-	-
12	13	-	-	-	-	-	-	-
13	14	-	-	K1	Dir	-	-	-
15	15	-	Hydro 2	K1	Dir	-	-	1
16	16	-	Dies 5	C4	Dir	-	-	-
17	17	-	-	-	-	C1	Dir	-
18	18	-	-	-	-	W3	Dir	-
19	19	-	-	W2	-	-	-	-
20	20	-	-	-	-	-	-	-
21	21	-	Dies 2	C3	Dir	-	-	1
22	22	-	-	-	-	-	-	1
23	23	-	-	C1	Dir	-	-	-
24	24	-	Dies 3	K1	Dir	C1	-	-
25	25	-	-	-	-	-	-	-
26	26	-	-	C1	Dir	W2	-	-
27	27	-	Dies 1	C1	Dir	-	-	-

Table A2.4 Energy equipment for HOUSECOSTS for simulation 1

Simulation 2: Data for this are given on tables A2.5 to A2.8.

Equipment	Type no.	Output rating (kW)	Capital cost (£)	Maint. cost (£/y)	Fuel cost (£/kWh)	Aver. eff. (%)	Life (y)
Hydro turbines:		As simulation 1					
Dies. gen.	1	3.5	1720	25	0.028	18	15
Dies. gen.	2	0.5	340	25	0.028	18	15
Dies. gen	3	1.8	1030	25	0.028	14	15
Wood range	1	2.0	1750	0	0.009	70	30
Wood range	2	2.5	1850	0	0.009	50	30
Wood range	3	1.0	1500	0	0.009	50	30
Wood range	4	1.0	1500	0	0.009	70	30
Wood range	5	1.5	1750	0	0.009	60	30
Wood range	6	1.3	1600	0	0.009	70	30
Wood stoves:		As simulation 1					
Gas water heater:		As simulation 1					

Table A2.5 Data for COSTCALCS for simulation 2

Number of houses = 27
Number of electricity grids = 2

Grid	Supplying equipment	Capital cost (£)	Life (y)	Number of houses on grid
1	Diesel 1	100	20	2
2	Diesel 3	100	20	2

Central heating systems

Type	Capital cost (£)	Output rating (kW)	Life (y)
1	1000	3.0	15

Table A2.6 Data for HOUSECOSTS for simulation 2

Zone type and electricity demand levels are the same as for simulation 1.

All houses in simulation 2 have propane gas cooking except house 27.

				Range		Stove		
House ref no.	Simul. no.	CH type	Elec. from	Type	HW via CH/dir	Type	HW via CH/dir	Gas water heater type
2	1	-	Grid 1	W6	Dir	-	-	-
4	2	-	Grid 1	W5	Dir	W1	-	-
11	3	-	Grid 2	W1	Dir	W1	-	-
14	4	-	Grid 2	W3	Dir	-	-	-
1	5	1	H1 & D2	W4	CH	W1	CH	-
						W2	-	
3	6	-	Dies 3	W1	Dir	-	-	1
5	7	-	Dies 1	W1	Dir	-	-	-
6	8	-	Dies 3	W6	Dir	-	-	-
7	9	-	-	W6	Dir	-	-	-
8	10	-	-	-	-	W3	Dir	-
9	11	-	Dies 2	W5	Dir	-	-	-
10	12	-	Dies 1	W1	Dir	-	-	-
12	13	-	-	-	-	-	-	-
13	14	-	-	W1	-	-	-	-
15	15	-	Hydro 2	-	-	-	-	-
16	16	-	Dies 3	W1	-	-	-	-
17	17	-	-	-	-	W2	Dir	-
18	18	-	-	-	-	W3	Dir	-
19	19	-	-	W2	Dir	-	-	-
20	20	-	-	W5	Dir	-	-	-
21	21	-	Dies 3	W4	Dir	-	-	1
22	22	-	-	-	-	-	-	1
23	23	-	-	W5	Dir	-	-	-
24	24	-	Dies 3	W1	Dir	W2	-	-
25	25	-	-	W5	Dir	-	-	-
26	26	-	-	W3	Dir	W2	-	-
27	27	-	Dies 1	W3	Dir	-	-	-

Table A2.7 Energy equipment for HOUSECOSTS for simulation 2

House ref no.	Simul. no.	Zone type	Equipment		
			Range	Stove	Wood fire
2	1	2	W6	-	-
		4	-	-	yes
4	2	2	W5	-	-
		4	-	W1	-
11	3	2	W1	-	-
		4	-	W1	-
14	4	2	W3	-	-
1	5	2	W4	-	-
		4	-	W1	-
		1	-	-	-
		1	-	-	-
		4	-	W2	-
3	6	2	W1	-	-
5	7	2	W1	-	-
		4	-	-	yes
6	8	2	W6	-	-
7	9	2	W6	-	-
		4	-	-	yes
8	10	2	-	W3	-
9	11	2	W5	-	-
10	12	2	W1	-	-
		2	-	-	yes
12	13	4	-	-	yes
13	14	2	W1	-	-
15	15	2	-	-	-
16	16	2	W1	-	-
		4	-	-	yes
17	17	2	-	W2	-
18	18	2	-	W3	-
19	19	2	W2	-	-
20	20	2	W5	-	-
21	21	2	W4	-	-
		4	-	-	yes
22	22	4	-	-	yes
23	23	2	W5	-	-
24	24	2	W1	-	-
		4	-	W2	-
25	25	2	W5	-	-
26	26	2	W3	-	-
		4	-	W2	-
27	27	2	W3	-	-

Table A2.8 Zone and equipment details for HOUSECOSTS, COSTSORT and COMSIM for simulation 2. Other data as table A2.3

Simulation 3: Data for this are given on tables A2.9 to A2.12. Central heating systems and gas water heaters are the same as tables A2.6 and A2.7. All houses in simulation 3 have propane gas cooking. The CH system of house 1 supplies the same zones as on table A2.3.

Equipment	Type no.	Output rating (kW)	Capital cost (£)	Maint. cost (£/y)	Fuel cost (£/kWh)	Aver. eff. (%)	Life (y)
Hydro turb.	1	4.5	7000	0	0	90	40
Hydro turb.	2	4.0	6000	0	0	80	40
Dies. gen.	1	3.5	1720	25	0.028	18	15
Dies. gen.	2	0.5	340	25	0.028	18	15
Dies. gen.	3	1.9	1090	25	0.028	18	15
Dies. gen.	4	7.0	2450	25	0.028	18	15
Wood range	1	2.5	1850	0	0.009	70	30
Wood range	2	1.5	1750	0	0.009	70	30
Wood range	3	2.0	1750	0	0.009	70	30
Wood range	4	1.8	1750	0	0.009	70	30
Wood stove	1	1.5	600	0	0.009	55	40
Wood stove	2	2.0	800	0	0.009	55	40
Gas water heater	1	5.0	500	0	0.038	75	20

Table A2.9 Data for COSTCALCS for simulation 3

Number of houses = 27
Number of electricity grids = 5

Grid	Supplying equipment	Capital cost (£)	Life (y)	Number of houses on grid
1	Diesel 1	100	20	2
2	Diesel 3	100	20	2
3	Diesel 4	3000	20	2
4	Diesel 1	5000	20	2
5	Diesel 4	2000	20	2

Central heating systems

Type	Capital cost (£)	Output rating (kW)	Life (y)
1	1000	3	20

Table A2.10 Data for HOUSECOSTS for simulation 3

House ref no.	Simul. no.	Elec. from	Range		Stove		Electricity demand level for house
			Type	HW via CH/dir	Type	HW via CH/dir	
2	1	Grid 1	W4	Dir	W1	-	2
4	2	Grid 1	W3	Dir	W1	-	5
					W2	-	
11	3	Grid 2	W1	Dir	W1	-	4
					W2	-	
14	4	Grid 2	W2	Dir	W1	-	5
5	5	Grid 3	W1	Dir	W1	-	5
22	6	Grid 3	W1	Dir	W1	-	4
					W2	-	
6	7	Grid 4	W1	Dir	W1	-	1
					W2	-	
21	8	Grid 4	W2	Dir	W1	-	3
10	9	Grid 5	W1	Dir	W1	-	3
27	10	Grid 5	W2	Dir	W1	-	5
					W2	-	
1	11	Hydro 1	W4	CH	W1	-	3
					W2	CH	
3	12	Dies 3	W1	Dir	W1	-	1
					W2	-	
7	13	Dies 2	W4	Dir	W1	-	2
8	14	Dies 2	-	-	W2	Dir	2
9	15	Dies 2	W3	Dir	W1	-	2
12	16	Dies 2	-	-	W2	Dir	4
13	17	Dies 2	W1	Dir	W1	-	4
					W2	-	
15	18	Hydro 2	W1	Dir	W1	-	1
16	19	Dies 1	W1	Dir	W1	-	5
17	20	Dies 2	-	-	W1	-	2
					W2	Dir	
18	21	Dies 3	-	-	W1	-	1
					W2	Dir	
19	22	Dies 2	W1	Dir	W1	-	2
20	23	Dies 3	W3	Dir	W1	-	1
					W2	-	
23	24	Dies 3	W3	Dir	W1	-	1
					W2	-	
24	25	Dies 3	W1	Dir	W1	-	1
					W2	-	
25	26	Dies 2	W3	Dir	-	-	4
26	27	Dies 2	W2	Dir	W1	-	4

Table A2.11 Energy equipment for HOUSECOSTS, and electricity demands for COMSIM, for simulation 3

Ref no.	Simul. no.	Zone type	Range	Stove	Wood fire
2	1	2	W4	-	-
		4	-	-	yes
		1	-	W1	-
		3	-	W1	-
4	2	2	W3	-	-
		4	-	W2	-
		3	-	W1	-
		3	-	W1	-
		1	-	W1	-
11	3	2	W1	-	-
		4	-	W2	-
		1	-	W1	-
		1	-	W1	-
		3	-	W1	-
14	4	2	W2	-	-
		3	-	W1	-
		3	-	W1	-
5	5	2	W1	-	-
		4	-	-	yes
		1	-	W1	-
		1	-	W1	-
		3	-	W1	-
		3	-	W1	-
22	6	2	W1	-	-
		4	-	W2	-
		3	-	W1	-
6	7	2	W1	-	-
		4	-	W2	-
		1	-	W1	-
		3	-	W1	-
21	8	2	W2	-	-
		4	-	-	yes
		1	-	W1	-
		3	-	W1	-
10	9	2	W1	-	-
		4	-	-	yes
		1	-	W1	-
27	10	2	W2	-	-
		4	-	W2	-
		1	-	W1	-
		3	-	W1	-
1	11	2	W4	-	-
		4	-	W2	-
		1	-	W1	-
		1	-	W1	-
		1	-	W1	-
		3	-	W1	-
		3	-	W1	-
3	12	2	W1	-	-
		4	-	W2	-
3	12	1	-	W1	-
		3	-	W1	-
		3	-	W1	-
7	13	2	W4	-	-
		4	-	-	yes
		1	-	W1	-
		1	-	W1	-
		3	-	W1	-
8	14	2	-	W2	-
9	15	2	W3	-	-
		1	-	W1	-
		3	-	W1	-
		3	-	W1	-
12	16	2	-	W2	-
13	17	2	W1	-	-
		4	-	W2	-
		1	-	W1	-
15	18	2	W1	-	-
		1	-	W1	-
		3	-	W1	-
		3	-	W1	-
16	19	2	W1	-	-
		4	-	-	yes
		1	-	W1	-
		3	-	W1	-
17	20	2	-	W2	-
		3	-	W1	-
		3	-	W1	-
18	21	2	-	W2	-
		4	-	W1	-
		1	-	W1	-
		3	-	W1	-
19	22	2	W1	-	-
		3	-	W1	-
		3	-	W1	-
20	23	2	W3	-	-
		4	-	W2	-
		1	-	W1	-
		2	-	W1	-
23	24	2	W3	-	-
		4	-	W2	-
		1	-	W1	-
24	25	2	W1	-	-
		4	-	W2	-
		1	-	W1	-
		3	-	W1	-
25	26	2	W3	-	-
26	27	2	W2	-	-
		3	-	W1	-

Table A2.12 Zone and equipment data for HOUSECOSTS and COSTSORT for simulation 3

Simulation 4: Most equipment remains the same as for simulation 3, with a few changes. Only the changes are listed here, and the changed house order. Tables A2.13 to A2.15 give the data for this simulation.

Equipment	Type no.	Output rating (kW)	Capital cost (£)	Maint. cost (£/y)	Fuel cost (£/kWh)	Aver. eff. (%)	Life (y)
Hydro turb.	1	11.0	10000	0	0	90	40
Hydro turb.	2	8.0	8500	0	0	90	40
Hydro turb.	3	8.0	8500	0	0	90	40
Hydro turb.	4	8.0	8500	0	0	90	40
Hydro turb.	5	3.0	5500	0	0	90	40
Wind turbine	1*	60.0	58500	5000	0	-	25
Wind turbine	2†	40.0	31200	3000	0	-	25
Wind turbine	3‡	22.0	22000	2000	0	-	25

No gas water heaters.

Additional data (see section 5.2 and 5.4): Hydro 1, Laig catchment, static head = 30m, pipe length = 50m, pipe diameter = 0.25m; Hydro 2, Cleadale catchment, static head = 20m, pipe length = 50m, pipe diameter = 0.21m; Hydro 3, Lodge catchment, static head = 20m, pipe length = 100m, pipe diameter = 0.21; Hydro 4, Kildonan catchment, static head = 30m, pipe length = 300m, pipe diameter = 0.21m; Hydro 5, GPO catchment, static head = 20m, pipe length = 600m, pipe diameter = 0.20m.
* = I.R.D. 60/15 60kW. † = Polenko WPS11 40kW. ‡ = Windfoss 22kW turbine.

Table A2.13 Changed data for COSTCALCS for simulation 4. Other equipment data as table A2.9

Number of electricity grids = 3

Grid	Supplying equipment	Capital cost (£)	Life (y)	Number of houses on grid
1	H1, H2, W1, 2xD1, 2xD2, 5xD3.	67500	20	17
2	H3, W2, D1, D3.	35000	20	4
3	H4, H5, W3, D1, 2xD4.	50000	20	6

House order:

Ref no.	Simul. no	Ref no.	Simul. no	Ref no.	Simul. no
1	1	17	10	14	19
2	2	18	11	15	20
3	3	19	12	16	21
4	4	20	13	5	22
7	5	23	14	6	23
8	6	24	15	10	24
9	7	25	16	21	25
12	8	26	17	22	26
13	9	11	18	27	27

Grid 1: simul. nos 1 to 17. Grid 2: simul. nos 18 to 21.
Grid 3: simul. nos 22 to 27.

Table A2.14 Data for HOUSECOSTS for simulation 4

House ref no.	Simul. no.	Zone type	Range	Stove	Wood fire
1	1	2	W1	-	-
8	6	2	W2	-	-
12	8	2	W2	-	-
17	10	2	W2	-	-
18	11	2	W2	-	-

All ranges give direct hot water except house 1 range which supplies CH.

Table A2.15 Changed data for HOUSECOSTS for simulation 4. All other data for HOUSECOSTS, COSTSORT and COMSIM as tables A2.11 and A2.12

Simulation 5: All equipment data are the same as for simulation 4.

Table A2.16 lists the system changes.

Number of electricity grids = 3

Grid	Supplying equipment	Grid	Supplying equipment
1	H1, H2, W1, 2xD1, D3	2	H3, W2, D1, D3
3	H4, H5, W3, 2xD3		

Costs and lifetimes as before.

Central heating systems

No. of zones in house	System cost (£)	Output rating (kW)	Life (y)
3	600	1.4	15
4	700	1.8	15
5	800	2.2	15
6	900	2.6	15
7	1000	3.0	15

All ranges in 3 or more zoned houses supply CH system. A wood stove in the second zone also supplies CH system. All zones except the first two are supplied by the CH. Zones taken in the order of table A2.12. Stoves in houses with only two zones give direct hot water.

All other data the same as for simulation 4.

Table A2.16 Data for HOUSECOSTS for simulation 5

Simulation 6: Tables A2.17 and A2.18 show the modified data for COSTCALCS and HOUSECOSTS (all other data remaining the same). All ranges and stoves are only in the first two zones (all other zones being supplied by the CH), taking zones in the order of table A2.12. Table A2.18 lists only the first two zones of each house.

Solar panels supply the CH of houses with systems, giving space and water heating. Houses without CH receive only hot water from their panel.

Equipment	Type no.	Output rating (kW)	Capital cost (£)	Fuel cost (£/kWh)	Aver eff. (%)	Life (y)
Solar panel	1	2.5*	750	0	50	20
Solar panel	2	3.0*	900	0	50	20
Solar panel	3	3.6*	1080	0	50	20
Solar panel	4	4.1*	1230	0	50	20
Solar panel	5	4.6*	1380	0	50	20
Solar panel	6	5.2*	1560	0	50	20
Wood range	1	2.5	1850	0.009	70	30
Wood range	2	1.5	1750	0.009	70	30
Wood range	3	2.0	1750	0.009	70	30
Wood range	4	2.3	1800	0.009	70	30
Wood stove	1	1.5	600	0.009	55	40
Wood stove	2	2.0	800	0.009	55	40
Wood stove	3	2.5	900	0.009	55	40

* = Panel surface area (m^2). All maintenance costs 0 £/y.

Table A2.17 Additional data for COSTCALCS for simulation 6

House ref no	Simul. no.	Zone type	Range	Stove	Solar panel
1	1	2	W1	–	6
		4	–	W3	
2	2	2	W4	–	3
		4	–	W2	
3	3	2	W1	–	4
		4	–	W2	
4	4	2	W1	–	4
		4	–	W2	
7	5	2	W4	–	4
		4	–	W2	
8	6	2	W2	–	1
9	7	2	W1	–	3
		1	–	W2	
12	8	2	W2	–	1
13	9	2	W1	–	2
		4	–	W2	
17	10	2	W3	–	2
		3	–	W1	
18	11	2	W2	–	3
		4	–	W2	
19	12	2	W1	–	2
		3	–	W1	
20	13	2	W3	–	3
		4	–	W2	
23	14	2	W3	–	2
		4	–	W2	
24	15	2	W1	–	3
		4	–	W2	
25	16	2	W3	–	1
26	17	2	W4	–	1
		3	–	W1	
11	18	2	W1	–	4
		4	–	W3	
14	19	2	W3	–	2
		3	–	W1	
15	20	2	W1	–	3
		1	–	W1	
16	21	2	W1	–	3
		4	–	W2	
5	22	2	W1	–	5
		4	–	W3	
6	23	2	W1	–	3
		4	–	W2	
10	24	2	W1	–	2
		4	–	W2	
21	25	2	W3	–	3
		4	–	W2	
22	26	2	W1	–	2
		4	–	W2	
27	27	2	W3	–	3
		4	–	W2	

Table A2.18 Data for first two zones of houses in HOUSECOSTS for simulation 6

Simulation 7: All houses with 3 or more zones have electric heat pumps, supplying the CH system. Only houses with ref. numbers 1, 7, 11 and 5 retain solar panels. Small changes are made to the grids. Tables A2.19 and A2.20 list the modified data, all other data are as for simulation 6.

Houses which had solar panels type 4 in simulation 6 now have type 1, previous types 5 have type 2, and previous types 6 have type 3.

Equipment	Type no.	Output rating (kW)	Capital cost (£)	Maint. cost (£/y)	Fuel cost (£/kWh)	Aver. eff. (%)	Life (y)
Solar panel	1	4.1*	1230	0	0	50	20
Solar panel	2	4.6*	1380	0	0	50	20
Solar panel	3	5.2*	1560	0	0	50	20
Dies. gen.	1	3.5	1720	25	0.028	18	15
Dies. gen.	2	1.9	1090	25	0.028	18	15

* = Panel surface area (m^2)

Table A2.19 Changes to equipment data for COSTCALCS for simulation 7

Number of houses = 27
Number of electricity grids = 3

Grid	Supplying equipment	Grid	Supplying equipment
1	H1, H2, W1, 2xD1, D2	2	H3, W2, D1
3	H4, H5, W3, 2xD2		

Heat pumps

Number of zones in house	Heat pump type	Capital cost (£)	Output rating (kW)	COP	Life (y)
3 or 4	1	800	1.5	2.5	15
5	2	1000	3.0	3.0	15
6 or 7	3	1140	4.0	3.5	15

Table A2.20 Data for HOUSECOSTS for simulation 7

Simulations 9, 10, 11, 13 and 14 all use the same data as simulation 7, except that houses with ref. numbers 9, 10, 13, 14, 17, 19, 22, 23 and 24 no longer have heat pumps.

Simulation 8: Optimum Economic System

Tables A2.21 to A2.23 show the changes made to the system of the previous simulation, simulation 7. All solar panels are removed.

Equipment	Type no.	Output rating (kW)	Capital cost (£)	Maint. cost (£/y)	Fuel cost (/kWh)	Aver. eff. (%)	Life (y)
Dies. gen.	1	3.0	1560	25	0.028	18	15
Dies. gen.	2	1.6	960	25	0.028	18	15
No solar panels							
Wood stove	1	1.5	600	0	0.009	55	40
Wood stove	2	2.0	800	0	0.009	55	40
Wood stove	3	2.5	900	0	0.009	55	40
Wood stove	4	1.0	550	0	0.009	55	40

Table A2.21 Changes to equipment data for COSTCALCS for simulation 8

House ref no	Simul. no.	Zone type	Range	Stove	HP
1	1	2	W1	-	2
		4	-	W3	
2	2	2	W4	-	3
		4	-	W2	
3	3	2	W4	-	2
		4	-	W2	
4	4	2	W1	-	2
		4	-	W2	
7	5	2	W4	-	2
		4	-	W2	
8	6	2	W2	-	-
9	7	2	W1	-	-
		1	-	W4	
12	8	2	W2	-	-
13	9	2	W1	-	-
		4	-	W4	
17	10	2	W3	-	-
		3	-	-	
18	11	2	W2	-	3
		4	-	W2	
19	12	1	W1	-	-
		3	-	-	
20	13	2	W3	-	-
		4	-	W2	
23	14	2	W3	-	-
		4	-	W4	
24	15	2	W1	-	-
		4	-	W1	
25	16	2	W3	-	-
26	17	2	W4	-	-
		3	-	-	
11	18	2	W1	-	2
		4	-	W2	
14	19	2	W3	-	-
		3	-	W4	
15	20	2	W1	-	3
		4	-	W1	
16	21	2	W1	-	3
		4	-	W1	
5	22	2	W1	-	2
		4	-	W3	
6	23	2	W1	-	2
		4	-	W2	
10	24	2	W1	-	-
		4	-	W2	
21	25	2	W3	-	3
		4	-	W2	
22	26	2	W1	-	-
		4	-	W2	
27	27	2	W3	-	3
		4	-	W2	

Table A2.22 Modified data for first two zones of houses in HOUSECOSTS for simulation 8

Grid	Supplying equipment	Grid	Supplying equipment
1	H1, H2, W1, 2xD1	2	H3, W2, D1
3	H4, H5, W3, 2xD2		

Costs and lifetimes as before.

Heat pumps

Heat pump type	Capital cost (£)	Output rating (kW)	COP	Life (y)
1	800	1.5	2.5	15
2	900	2.0	2.5	15
3	700	1.0	2.5	15

Table A2.23 Changes to data for HOUSECOSTS for simulation 8

Simulation 12: All wood fired stoves and ranges are removed from thi simulation, and air-to-water heat pumps installed into all houses an uprated. Central heating systems are put into 1 and 2 zone houses, an systems in other house are extended to supply all zones. Other data ar the same as for simulation 7. Table A2.24 lists the heat pump types fo each house, and data on the additional central heating systems.

Heat pumps

House ref. number	Heat pump type	Capital cost (£)	Output rating (kW)	COP	Life (y)
8, 12, 25	1	800	1.5	2.5	15
14, 17, 19, 26	2	1000	3.0	3.0	15
9, 10, 13, 15, 22, 23	3	2000	5.5	3.5	15
2, 3, 4, 6, 16, 18, 21, 24, 27	4	3500	7.0	3.5	15
1, 5, 7, 11, 20	5	5000	11.5	3.5	15

Central heating systems

No. of zones in house	Capital cost (£)	Output rating (kW)	Life (y)
1	400	0.8	15
2	500	1.1	15

Table A2.24 Modified data for HOUSECOSTS for simulation 12

APPENDIX 3

The Electrically-Assisted Tricycle

An electrically-assisted pedal tricycle was lent to a family on the island of Eigg, from 1984 onwards. The purpose of this was to introduce the concept of alternative transport to the island, and to monitor the performance of the tricycle. Recharging of the tricycle also helped put a better load on the householder's diesel generator.

The tricycle was borrowed from the Open University Appropriate Technology Group, who had tested it on several families in Milton Keynes. Before sending it to Eigg, it was modified by the University of Strathclyde. Performance monitoring equipment was fitted, and attempts were made to make it both lighter and more rugged.

The tricycle was lent to a woman on Eigg who rode a normal, pedal powered, tricyle already. She has three young children, and the electric tricycle can carry two on the back, so it was a good substitution.

This appendix describes the tricycle and its monitoring system, and gives an interim report (after one year's use on Eigg). At present no data are available from the monitoring equipment.

DESCRIPTION

The tricycle is a standard model, built by Ken Rodgers of Hounslow, Middlesex (fig. A3.1). It has 20" wheels, with 1.375" tyres. It has a caliper brake on the front, and a disc brake on the back. A five speed derailleur gear block is used, with a range of 77.1" to 33.8" (a 40 tooth chainring driving a 14 to 32 tooth gear block). The gearing was deliberately lowered for the hilly and rough roads on Eigg.

Behind the seat, and between the wheels, a sheet-steel box is fitted, with two backward facing children's seats, and space for shopping, etc. The traction battery and instrumentation is fixed beneath these seats.

The drive motor, supplied by PedalPower of New Jersey, is in front of the steering column, and over the front wheel. It drives via a friction wheel rubbing directly onto the front tyre, and is controlled by two switches: an on-off switch, and the 'clutch', which pulls the motor down into contact with the wheel. This latter must be held all the time that the motor is driving. The motor was tested on a dynamometer at Strathclyde University, and found to have a maximum power output of 100 W. This is below that claimed by the manufacturer

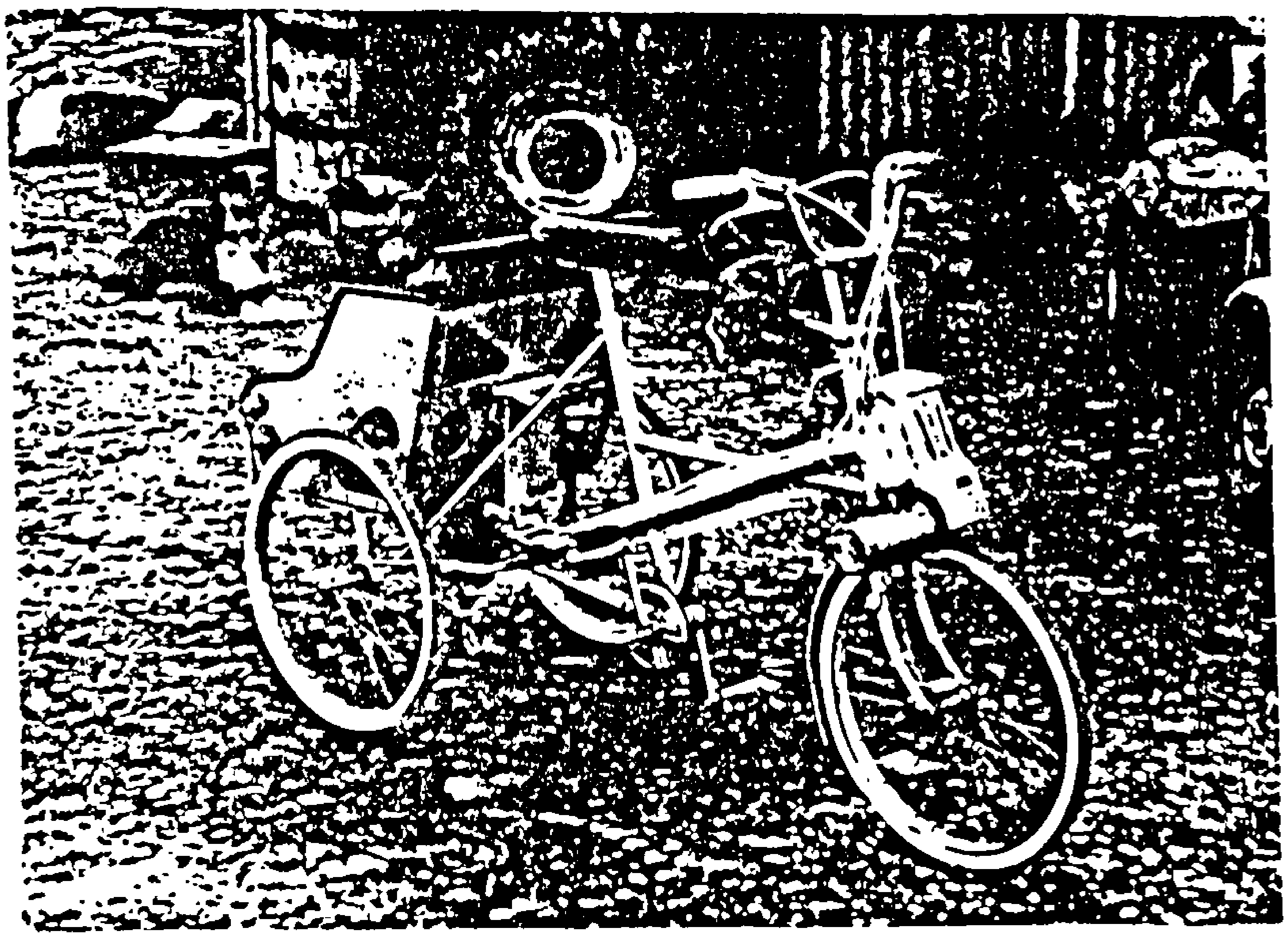

FIGURE A3.1 The Electrically-Assisted Tricycle

(250 W), but inside the legal limit for electrically-assisted (as opposed to electrically driven) vehicles, also 250 W. The lower output is probably a reflection of the motor's age.

During testing the tricycle was found to have a useful range of about 30 km if the motor is used in conjunction with pedalling. A range (untested) of 15 km is claimed using the motor alone, but this seems optimistic. It is, however, suspected that both the motor and battery are near the end of their useful lives. Its weight (of which the battery is the single heaviest item) limits top speed to about 22 km/h. Above this speed the motor is ineffectual, and a more realistic average speed is about 15 km/h.

Prior to modification with a view to saving weight, all items on the tricycle were weighed. Table A3.1 gives the results.

Item	Weight (kg)	Item	Weight (kg)
Battery	9.09	Main frame	5.47
3 wheels	4.09	Front forks	1.21
Rear box assy.	7.27	Motor	2.64
Pedals	1.64	Handlebars	1.36
Rear seats	1.73	Saddle	1.18
Lights	0.34	Mudguards	0.41
Cables	0.45	R.H. rear axle	0.36
Pedal shaft	0.18	Chain	0.39
Rear brake	0.30	TOTAL	38.08

Table A3.1 Weight of components on electric trike

Modifications were made to the tricycle, notably to the rear box and seat assembly, which reduced the weight by about 5 kg. Several other modifications, to make it more road worthy and easier to use, were made; the total cost of these being about £ 130.

Instrumentation

The tricycle was instrumented to allow charge/discharge efficiency to be measured. A mileometer was also fitted, allowing charge per kilometer to be calculated. To measure charge and discharge, two Radio Spares (R.S.) Miniature Elapsed Time Indicators were fitted, as shown in figure A3.2. These record charge by movement of a column of mercury whose length increases with passing charge. Movement of the columnn is given by

$$L = aQ \tag{A3.1}$$

where L = indicator movement in mm,
Q = charge, coulombs
and a = constant, value 0.677 mm/C.

A circuit was devised which would give full-scale movement of the indicator (16.5 mm) in about one year. The circuit was calibrated so that simply dividing the movement of the discharge indicator by that of the charging one gives the efficiency of the battery.

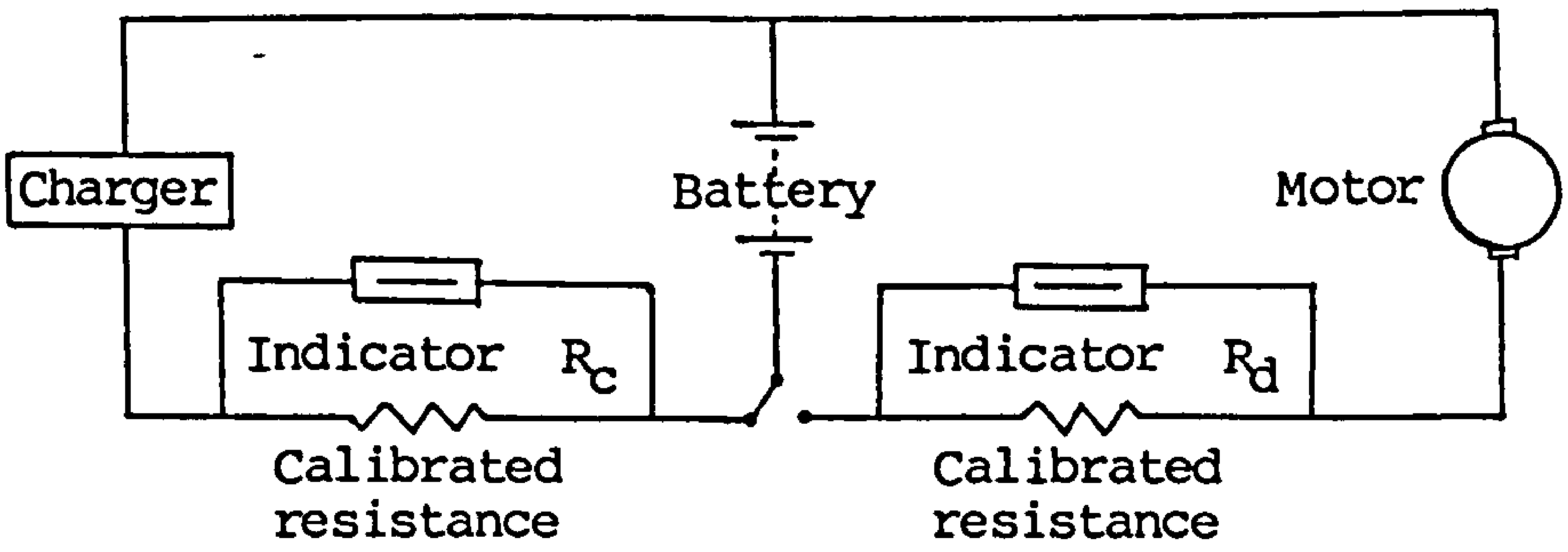

Figure A3.2 Tricycle charge/discharge monitoring circuit

PROGRESS REPORT

The tricycle was delivered to Eigg in April 1984. This report was made after 10 months of use.

In 10 months 203 miles had been covered, although more had been covered during the summer months. The only serious mechanical problem was a broken gear cable (probably caused by the relatively poor design of the derailleur system). This had been overcome by wiring the derailleur into 3rd gear, but almost certainly meant that the tricycle was too overgeared for the hills on Eigg.

Apart from that problem, the trike was in reasonable mechanical order. There was some rust on the rear box section, but this was not serious. Unfortunately the screws holding the lid of the box containing the instrumentation had corroded in place, so it was not possible to look at the indicators. These will be checked when the trike is returned in the summer of 1987.

The following are difficulties experienced by the tricycle's user. She feels that it is too heavy to pedal uphill when the battery is not fully charged. There are several sections of road on Eigg which are either too rough or too steep to ride, and it is heavy and awkward to push on these sections. This is the main reason why it has not been used more often. There is also a problem of keeping it charged in summer, when the diesel generator is only run intermittently. All of her children are now too big to use the rear seats, although the youngest was carried at first.

CONCLUSIONS

Much interest was shown in the tricycle, both by islanders and holiday makers. There is, therefore, a clear demand for such a vehicle, if it could be made more suitable for the island of Eigg.

It is felt that much of the power of the battery is used solely to move the battery and motor itself. A lighter tricycle would see more benefit, but might then not be strong enough for the island. If a lighter system could be developed, particularly with slightly longer range, it would be welcomed on the island.

The problem of charging in the summer might be overcome by using, for example, a small wind turbine, which could run unattended. Because of the high fuel consumptions of vehicles on Eigg, considerable fuel savings on the island could be achieved with such a system.

INTRODUCTION

In periods of very high general inflation rates such that the rate varies during the year, or when the annual inflation rate is not constant during all years of an investment project, the standard method for treating inflation shown in section 2.1 cannot be applied.

The standard, and well accepted net present value analysis used throughout this thesis assumes a fixed annual rate of inflation of 5%, and it was shown (equation 2.1.21) that this cancels out. For completeness though, this appendix presents a more formal approach to the treatment of inflation.

The analysis starts by reconsidering the standard treatment, whereby interest and cash flows occur at discrete times (usually at the start and end of each year), and with a fixed annual interest (or discount) rate. This analysis is extended to consider continuous compounding of interest, in which interest accrues instantaneously and continuously. Continuous compounding, although yet to be widely accepted, is conceptually more sound than discrete analysis.

The analysis is then extended to cover situations of non-constant general inflation rates, such as occur during periods of hyper-inflation. This is treated both discretely and continuously.

The methods presented in this appendix are taken mostly from Reisman, A. 1971 Managerial and Engineering Economics, Allyn and Bacon Inc., Boston, USA. This gives a very thorough treatment of the subject, and the reader is referred to this book for a fuller discussion than is presented here.

APPENDIX 4

The Effects of Inflation on Net Present Value Calculations

The treatment of inflation in net present value calculations presented in section 2.1 applies in most practical situations. However, it does not apply when either the annual inflation rate varies over the lifetime of an investment project, or when the inflation rate varies during a year itself. This appendix shows how these two circumstances can be accomodated, and expands the analysis to look at continuous compounding, a more conceptually sound way of treating inflation and net present value analysis

FORMAL ANALYSIS OF INFLATIONARY EFFECTS ON PRESENT VALUE ANALYSIS

This treatment starts by noting the difference between the discrete form of analysis (whereby income, expenditure, etc. occur at discrete times) used so far throughout this thesis, and continuous analysis, whereby interest accrues instantaneously and continuously.

In the examples used in section 2.1, if an amount C is invested at year zero in, for example, a bank giving an annual interest rate of r%, in N years time the equivalent amount (present value) V, using discrete analysis, is

$$V = C(1 + r)^N \qquad \text{(A4.1)}$$

If, however, the interest rate is now assumed to apply continuously, and the interest per small time period is q/m, where q is the nominal annual interest rate and m the number of compounding periods, equation A4.1 becomes

$$V = C(1 + q/m)^{mN} \qquad \text{(A4.2)}$$

In the limit, as m goes to infinity,

$$V = C(e^{qN}) \qquad \text{(A4.3)}$$

It follows from this that the nominal continuous interest rate is related to the effective discrete rate by

$$r = e^q - 1 \qquad \text{(A4.4)}$$

Different inflationary scenarios can now be formally analysed both discretely and continuously, starting with the situation already considered in section 2.1 of discrete, constant general inflation i and interest r. Table A4.1 overleaf shows the situation of investing an amount C at the start of a project, but does not consider returns (other than interest) on the investment.

Period (years)	Amount at start of period (£)	Interest during period (£)	Inflation during period (£)	Amount at end of period (£)
1	C	rC	iC	$C(1+r+i)$
2	$C(1+r+i)$	$rC(1+r+i)$	$iC(1+r+i)$	$C(1+r+i)^2$
3	$C(1+r+i)^2$	$rC(1+r+1)^2$	$iC(1+r+i)^2$	$C(1+r+i)^2$
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
N	$C(1+r+i)^{N-1}$	$rC(1+r+i)^{N-1}$	$iC(1+r+i)^{N-1}$	$C(1+r+i)^N$

Table A4.1 Effect of Interest and Inflation in Discrete Analysis

The present value at the end of k periods is therefore

$$V_k = C(1 + r + i)^k \tag{A4.5}$$

or

$$C = V_k(1 + r + i)^{-k} \tag{A4.6}$$

and since the present value is simply the sum of the discounted cash flows,

$$C = V_0 + \sum_{k=1}^{N} V_k(1 + r + i)^{-k} \tag{A4.7}$$

If continuous compounding is now assumed, eqn. A4.7 becomes

$$C = V_0 + \sum_{k=1}^{N} V_k e^{-(q + \ln(1+i))k} \tag{A4.8}$$

The analysis can now be extended to consider the situation where inflation rates do not remain constant from period to period, as in the case of hyper-inflation. In such circumstances, the term 'period' need not apply to a year, but could apply to much shorter periods.

The general inflation rate i is now not constant, but has values $i_1, i_2 \ldots i_k$ in each of the k periods. Looking first at discrete analysis, eqn. A4.5 becomes

$$V_k = C(1 + r + i_1)(1 + r + i^2) \ldots (1 + r + i^k) \tag{A4.9}$$

$$= C\prod_{x=1}^{k}(1 + r + i_x) \tag{A4.10}$$

Solving for present value, and summing over all periods, leads to

$$C = V_0 + \sum_{k=1}^{N} C_k[\prod_{x=1}^{k} (1 + r + i_x)]^{-1} \tag{A4.11}$$

If continuous compounding is now assumed, eqn. A4.11 becomes

$$C = V_0 + \sum_{k=1}^{N} C_k e^{-qk-\sum_{x=1}^{k}\ln(1-i_x)} \tag{A4.12}$$

The above analysis has considered only cases with continuous compounding of interest and discrete cash flow. Reisman (ibid) further extends the analysis to consider both continuous compounding of interest and continuous cash flow. He also looks at situations of differential inflation, such as when the energy inflation rate is higher than the general inflation rate. It is also fairly easy to see how the above analysis could be modified to account for non-constant interest (or discount) rates. The reader is referred to Reisman's very thorough treatment of inflationary effects for a more complete coverage of the subject.