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APPLICATIONS OF LINEAR MODELLING
IN ENERGY ANALYSIS

A thesis presented in partial fulfilment
of the requirements for
the Degree of Doctor of Philosophy
in Technology at
Massey University

MURRAY GRAHAM PATTERSON

1984

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ABSTRACT

The primary objective of this study was to explore the use of classical linear models in Energy Analysis; so as to resolve some of the methodological problems associated with Energy Analysis, and to extend the scope and potential of Energy Analysis as a scientific discipline. This was undertaken in the form of two separate yet related discourses.

The first discourse provided a basis for resolving the energy quality problem encountered in Energy Analysis. A general equation was hypothesized and tested:

$$m_1 \sum_{i=1}^{i=j} (Y_1)_i + m_2 \sum_{i=1}^{i=j} (Y_2)_i + \dots m_n \sum_{i=1}^{i=j} (Y_n)_i \\ = n_1 \sum_{i=1}^{i=j} (X_1)_i + n_2 \sum_{i=1}^{i=j} (X_2)_i + \dots n_n \sum_{i=1}^{i=j} (X_n)_i$$

where: y = effective energy output of an end-use class (ΔH output),
known

x = primary energy input (ΔH input), known

m = quality coefficient for an effective energy output (quality equivalents/ ΔH output), unknown

n = quality coefficient for a primary energy input (quality equivalents/ ΔH input), unknown

i = energy supply use pathways, j = number of pathways.

The matrix of simultaneous linear equations represented by this equation is usually overdetermined. Therefore, an appropriate solution method is a fitting procedure, such as regression. Further, in order to solve this general equation, one coefficient must arbitrarily be given a value equal to unity. Hence, all estimated coefficients are expressed in terms of multiples of that coefficient (termed quality equivalents).

The general equation was first tested for the 1976 New Zealand economy, so as to estimate 'actual' quality coefficients. Subsequently, the general equation was tested for a notional 'energy efficient' New Zealand economy, so as to estimate 'long run' quality coefficients, which reflected thermodynamic limits. Generally very accurate estimates of the coefficients were obtained. The solutions to the equations indicated that hydroelectricity was the highest quality

primary energy source, followed by natural gas, oil, coal and then wood.

The second discourse examined the 'optimal' use of primary energy resources in the New Zealand food system, using the formalism of Linear Programming. A preliminary discussion concluded that the concept of 'optimality' had greater potency than the concept of 'efficiency' in evaluating the use of energy resources, particularly in food systems. For each food sector (Production, Processing, Export-Import, Distribution, Catering and Household), coefficient matrices were assembled, drawing on literature data. Various combinations of constraints and objective functions were applied, in different Runs. The main objective functions used were minimising energy inputs for providing a nutritionally adequate diet, or maximising net energy gain from exporting agro-food products. The most critical constraints were found to be land area and market demand constraints.

Detailed results of the Linear Programming runs are presented and discussed. An energetically 'optimal' diet was found to consist of large amounts of cereals, significant amounts of fresh fruit and vegetables and dairy products, and a very small amount of meat. Such a diet provided the Recommended Daily Allowances, for all nutritional elements, for the New Zealand population. Meat, Fish and Dairy products were found to have a particularly important function as commodities to be traded for imports of oil and energy intensive goods.

A final discussion reviewed the use of Linear Models in Energy Analysis, and future directions for growth and development in Energy Analysis.

PREFACE

This thesis is part of two research programmes being undertaken in the Food Technology Research Centre. The first research programme began in the early 1970's, and has attempted to introduce quantitative techniques (principally Linear Programming and Extensions) to product development and diet planning. This has resulted in a number of PhD dissertations (Edwardson, 1974; Anderson, 1975; Chittaporn, 1977; Ngarmsak, 1983). The second research programme was initiated in 1977, and has attempted to quantify energy use in the food system, and to identify energy conservation measures particularly applicable to the food processing sector. This research has been funded by the New Zealand Energy Research and Development Committee. The material for this thesis has been drawn from the findings of Contract 3123 "Energy Requirements for Food Supply in New Zealand".

Much of the details of surveys undertaken for Contract 3123 and used in this thesis have been published by the N.Z.E.R.D.C., under the author's name. Readers are recommended to refer to these reports for further details:

- (1) Patterson, M.G. and Earle, M.D. 1982. Energy Use in the Catering Industry. N.Z.E.R.D.C. Report P66. (Appendix F).
- (2) Patterson, M.G. and Earle, M.D. 1982. Total Energy Requirements of Shopping for Food. N.Z.E.R.D.C. Report P67. (Appendix G).
- (3) Patterson, M.G. and Earle, M.D. 1982. Total Energy Requirements of the Wholesale Distribution of Foods. N.Z.E.R.D.C. Report P68. (Appendix H).
- (4) Patterson, M.G. and Earle, M.D. 1982. Total Energy Requirements of the Household Preparation and Storage of Foods. N.Z.E.R.D.C. Report P69. (Appendix I).
- (5) Patterson, M.G. and Earle, M.D. 1982. Total Energy Requirements of Food Retailing. N.Z.E.R.D.C. Report P70. (Appendix J).
- (6) Patterson, M.G. and Earle, M.D. 1984. Energy Use in the New Zealand Food System. N.Z.E.R.D.C. Report (In Press).

Another paper that summarises much of Part A of this thesis, has also been published: Patterson, M.G. 1983. Estimation of the Quality of Energy Sources and Uses. Energy Policy 11:4 346-359 (this paper appears in Appendix A).

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I also wish to acknowledge that my ability to present this thesis for examination, depended on funding provided by the New Zealand Energy Research and Development Committee to Massey University under contract 3123. Much of the data and information gained from work on this

contract, formed the basis of this thesis. I therefore wish to thank the NZERDC for providing me with the opportunity to undertake this research, and subsequently use it as the basis for this thesis.

I am also grateful for the information and assistance, given to me by literally hundreds of people in government agencies, and in various business establishments. The data provided by these people, during several surveys, were particularly valuable.

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- F. Energy Use in the Catering Industry (Copy of New Zealand Energy Research and Development Committee Report P66) (Microfiche).
- G. Total Energy Requirements of Shopping for Food (Copy of New Zealand Energy Research and Development Committee Report P67) (Microfiche).
- H. Total Energy Requirements of the Wholesale Distribution Foods

(Copy of New Zealand Energy Research and Development
Committee Report P68) (Microfiche).

- I. Total Energy Requirements of the Household Preparation and
Storage of Foods (Copy of New Zealand Energy Research and
Development Committee Report P69) (Microfiche).
- J. Total Energy Requirements of Food Retailing (Copy of New Zealand
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1 INTRODUCTION

1.1 Objectives and Approach

Classical Linear Modelling methods have been widely applied in Economics. However, despite the functional similarities between Energy Analysis and Economics, Linear Modelling methods have only gained limited application in Energy Analysis. Hence, the main purpose of this study was to explore the further use of Linear Modelling in Energy Analysis, with particular emphasis being placed on resolving the methodological problems encountered in Energy Analysis. The approach in this thesis was to firstly examine the use of Linear Models in Economics, and to review the methodological problems facing Energy Analysis. From this basis, the main foci of the study were two specific applications of Linear Regression and Linear Programming techniques. These two separate yet related discourses will:

- (1) apply the use of Linear Regression to resolving the Energy Quality Problem involved in Energy Analysis, using data for the New Zealand Economy.
- (2) apply the use of Linear Programming to investigate what constitutes the 'optimal' use of primary energy resources in the New Zealand food system.

This evaluation of 'optimality' fundamentally depends on the initial resolution of the energy quality problem. A final objective was to critically review these two applicative discourses, and to evaluate the further scope and potential for using Linear Modelling techniques in Energy Analysis.

1.2 Background

1.2.1 Energy Analysis and its Development

1.2.1.1 Definition

Energy Analysis (EA) can be defined as the discipline that is involved in the measurement and objective analysis of energy use in any process, system or economy; and in the application of such information so as to aid decision making. This is a somewhat broader definition of EA than that which is usually afforded to EA. Usually, definitions of EA (e.g. Carter, Peet and Baines, 1982; Slessor, 1978) only refer to the accounting procedure of identifying and measuring energy inputs (or

requirements) for a given product or system. However, the uses and applications of EA which are proposed and discussed in the literature (Gilliland, 1975; Pearson, 1977), go far beyond mere "energy accounting" which is implied in the above cited definitions of Energy Analysis. Therefore, it is considered correct and appropriate to indicate these uses and applications of EA, in the definition of EA. It should be noted, that the relationship between Energy Analysis and Energy Accounting, can be considered to be analogous to the relationship between Economics and Financial Accounting.

1.2.1.2 History and Origins of Energy Analysis

The term "Energy Analysis" was first coined in the early 1970's, mainly to describe the "energy accounting" procedure referred to above. Since, then the discipline has grown and developed, initially at quite a rapid rate and now at a steady rate, as evidenced by the amount of articles produced in the scientific literature. However, it should be recognised that many of the concepts and ideas that now form the basis of EA, had their origins well before EA first became recognised as a discipline.

Notably, Soddy (1912), a Nobel Prize winner, suggested as long ago as 1912, that energy was a more fundamental unit of account than money, which is a very similar notion to that suggested by Odum and Odum (1976). Similarly, Cottrell (1955) in his book "Energy in Society", identified the net energy concept, well before it gained wider currency. In the 1960's, a number of studies used EA techniques, to examine energy use in agricultural systems (Costes, 1964; Le Pori and Stapleton, 1967) and the Dow Chemical Company used EA techniques to determine the energy requirements of chemical products (Smith, 1968).

However, the early 1970's saw the real beginnings of EA as a discipline. Odum (1971) published his book "Environment, Power and Society", which is considered by many to have provided the earliest stimulus for the growth in EA which followed. Although it should be recognised that at about the same time other influential and seminal works appeared. For example, Georgescu-Roegen's (1971) book "The Entropy Laws and the Economic Process"; and Hirst's (1972) and Heredeen's (1973) works on Input-Output studies. From this point

onwards the growth of EA, was quite rapid. Many of the early studies (Duckham, 1973; Leach and Slessor, 1973; Lawton, 1973; Pimentel et al., 1973; Borgstrom, 1973 and Gifford and Millington, 1973) concentrated on energy analyses of food and agricultural systems. There was also an early growth in energy Input-Output studies (Wright, 1974; Herendeen and Bullard, 1974; Reardon, 1972) and thermodynamic studies (Berry and Fels, 1972). Much of this early growth was further stimulated by the oil price hike that occurred in late 1973, which consequently heightened public and scientific awareness of the vital role of energy in economic processes.

From this early work, emerged an obvious requirement to establish conventions, methods and techniques; and to standardise terminologies used in EA. In 1974, the I.F.I.A.S. (1974), held a workshop attended by many of the early workers in the field, which aimed to fulfill this requirement. This workshop recommended a set of conventions and methodologies, which have since been used quite widely, although far from universally. From this point onwards, EA studies continued to proliferate in the scientific literature. Many of the more influential articles were published in the journal "Energy Policy" (Chapman, 1974; Chapman, Leach and Slessor, 1974; Wright, 1974; Chapman, 1975; Berry, Long and Makino, 1975), with the entire issue of the December 1975 journal being devoted to EA. These papers covered a wide range of subjects including energy analyses of chemicals, materials and energy production, and addressed the methodological issues facing EA.

Other important articles, covered new areas such as the energy requirements of packaging (Boustead, 1974) and nuclear power stations (Chapman and Mortimer, 1974); as well as further studies of agro-food systems (Leach, 1976; Steinhart and Steinhart, 1974). In 1976, H.T. & E.C. Odum published their second book in this field, entitled "Energy Basis for Man and Nature". This book further expanded upon and clarified concepts first developed in 1971 (Odum and Odum, 1976). Although this book again had quite an influential effect on EA, the growth of EA consolidated from this point on; both in terms of the volume of literature produced, and in terms of the introduction of new concepts and methodologies. Furthermore, it should be noted that many of the original controversies over methodology and the application of EA, still exist and are yet to be resolved.

1.2.1.3 Methodological Approaches

Several methodological approaches have emerged over the last decade:

(1) Process Analysis This is probably the most commonly used method in EA. The main aim of the analysis is to calculate the total energy requirement for producing a product. The first stage is to identify all the inputs (direct and indirect) required to produce a product - this is sometimes done by way of using the flow diagram symbols recommended by the I.F.I.A.S. (1974). The second stage is to assign energy values to each input, so that they can be summed so as to determine the total energy requirement of the product. This method is generally accepted to be the most accurate method of determining the Energy Requirement of a product or process. However, the partitioning problem is often encountered when using Process Analysis. The partitioning problem refers to the problem of allocating one energy input, to several outputs of a process. Problems can be encountered in obtaining data which is representative of the processes involved - that is, a sampling problem is often encountered.

(2) Input-Output Analysis Input-Output (I-O) tables are used to determine the total energy requirements (MJ), per unit output (\$) of any sector in the economy. Since I-O tables are available in almost all countries, the method is widely applicable. However, there are many problems and limitations associated with I-O analysis: (a) There is quite a substantial time delay, from the time of the survey to the time the tables are published (often 5-10 years). During this time many technical and economic factors could have changed the coefficient in the I-O matrix. (b) The outputs (\$) of many sectors is often very heterogeneous, so therefore it is difficult to identify exactly what the output is, and attribute an energy requirement per unit of product. In reality there is often a quite substantial variation in the energy requirements of different products produced by the same industry, but I-O analysis assumes these energy requirements to be the same (c) Difficulties which are not insurmountable, are often encountered in dealing with imported commodities, as no energy coefficients are available for these. The main advantage of I-O analysis, is its systems approach, which makes it useful in macro-systems studies.

(3) Thermodynamic Analyses These sets of methods include Second Law Analysis (Connolly and Spraul, 1975), Availability Analysis (Sussman,

1977), and Exergy Analysis (Ahern, 1980). All these methods aim to examine the thermodynamic efficiencies and limits to processes. These analyses tend to focus on theoretical rather than actual energy requirements, and therefore often provide insights to future energy requirements and the development of technology. The major problem with these methods, is that they lack applicability to larger scale problems, and often because of the lack of data can only be applied to small scale, narrowly defined problems. Georgescu-Roegen (1971) has, nevertheless, provided theoretical thermodynamic constructs for larger scale systems, but they are as yet to be applied.

(4) Eco-Energetics This refers to the methodological approach used by Odum and Odum (1976). It is based on ecological systems modelling, which uses a circuit language to describe energy flows in systems. It is notably different from I-O and Process Analysis, in that it includes energy values for solar energy and labour; and it attempts to convert all forms of energy to common quality units (Fossil Fuel Equivalents). Some analysts from this school of thought, view eco-energetics as a replacement for conventional economics, and as the basis for an "energy theory of value". Understandably, this view has drawn much criticism from economists (Edwards, 1976), and those who practice the other methods of EA. The main advantage of Eco-energetics, is its systems approach which focuses on the interdependencies in and between natural and economic systems.

The first three approaches to EA are not mutually exclusive either in theory or in practice. Process analysis often utilizes I-O analyses to compute indirect inputs or at least some of the indirect inputs (Bullard et al., 1976). It should be noted that this method of analysis was used in the data collection phase of Section B of this thesis. Process Analysis, often involves elements of thermodynamic analysis, when comparing the actual with the theoretical energy requirements of a process. However, Eco-energetics has rarely, if ever, been combined with the other forms of EA and is often singled out as being "fundamentally" different to other forms of EA (e.g. Fluck and Baird, 1980).

1.2.1.4 Methodological Problems

The following methodological problems, which have been often used in criticism of EA, have been widely identified in the literature (I.F.I.A.S., 1974; Leach, 1975; Pearson, 1977):

(1) Boundary Problem The problem is one of what inputs (and sometimes outputs) should be included in the problem. Firstly, what energy inputs should be included? The I.F.I.A.S. (1974) recommended only including "non-renewable" resources, although this recommendation is far from universally accepted. Odum and Odum (1976), and others from the eco-energetics school of thought include renewable resources such as incident solar energy. Secondly, should labour inputs be included, and if so how? The I.F.I.A.S. (1974) recommended, that when considering industrial or developed systems, it was not necessary to include labour inputs, as they were not important. However, the I.F.I.A.S. (1974) did recommend that labour inputs be included in low intensity agricultural systems as in these systems they were considered to be important. The problem of what "energy value" to attribute to labour inputs, if they are included, is difficult to resolve. The following methods have been suggested: (a) muscular energy output of manual labour (Makhijani, 1975), (b) total energy content of food consumed, sometimes reduced for the proportion of man-hours worked per day (Newcombe, 1975; Pimentel, D., et al., 1973) (c) lifestyle support energy (Odum and Odum, 1976). This has the problem of double counting associated with it. (d) energy equivalent of labour, determined by examining labour energy substitutions (Echiburu, 1977). The third boundary problem which is considered in the literature is - how far back should a particular input be traced? For example, should the machines that make the machines be included in the analysis?

(2) Valuation Problem The problem here, is one of finding a unit of account (or numeraire). Different forms of energy have different qualities, different supply characteristics (some are flow resources, some are stock resources), different abilities to do work, different degrees of cleanliness and so on. Some means is required to equate these different energy sources, particularly one which takes account of energy quality (this is often referred to as the energy quality problem). The normal means of measuring energy, that is by enthalpy (ΔH) or heat measurements, does not take into account the quality or grade of the energy. Several techniques have been suggested for overcoming

the energy quality problem: Available Work Analysis, Exergy Analysis and the use of Fossil Fuel Equivalents (FFE). None of these techniques has gained anywhere near universal acceptance, and all of them have problems and limitations to their use. If EA is to gain acceptance as an evaluative technique, it is a fundamental requisite that this valuation problem be resolved, particularly the energy quality element of this problem.

(3) Partitioning Problem This refers to the problem of allocating one energy input to several (or multiple) outputs of a process or system. For example, a given amount of energy (MJ) is required to produce essentially 2 products from a sheep farm: wool (kg) and meat (kg). The problem arises, when the energy input (MJ) has to be allocated to the outputs (kg). The I.F.I.A.S., (1974), recommended 4 possible conventions for partitioning: (a) assign all energy requirements to the output of interest (b) assign energy requirements in proportion to financial value or payments (c) assign energy requirements in proportion to some physical parameter characterizing the system (e.g. weight, volume, energy content) (d) assign energy requirements in proportion to marginal energy savings which could be made if the good or service were not provided. All these conventions, are very arbitrary, and none of them has gained widespread acceptance. Regression analysis has provided a useful tool for overcoming this partitioning (or allocation) problem, where the outputs are produced in quantities not proportional to each other. For example, Cleland, Earle and Boag (1981), used regression analysis to allocate energy inputs to multiple products from food factories. When the outputs are proportional or near proportional to each other (e.g. in the case of meat and wool production from a sheep farm), the problem is said to be confounded or aliased, and cannot be solved by regression analysis. Regression analysis has also been used successfully by others (Jacobs, 1981; Rao et al., 1981). It should be noted that the partitioning problem is less evident in EA when a systems modelling technique is used, as systems equations can accommodate multiple inputs and multiple outputs. The partitioning problem only really arises when single products are examined (e.g. in Process Analysis).

Other methodological problems arising from both the theory and practice of EA have been identified in the literature (refer to Pearson, 1977). However, they are less serious, and present less

fundamental criticisms of EA.

1.2.1.5 Uses and Applications

Much debate on the uses and applications of EA has taken place in the literature, particularly in terms of EA's relationship with Economics (Webb and Pearce, 1975; Edwards, 1976).

However, there is a fairly wide consensus that EA has an important role to play in energy conservation. A systematic EA of a process or system can often identify areas of inefficient energy use, and identify areas of the greatest potential savings. This was found to be the case in the author's systematic study of the New Zealand food system (Patterson and Earle, 1984). Second law analyses can give a particular insight to the potential for energy conservation - the theoretical minimum energy requirements of a process can be compared with the actual energy requirements. These minimum energy requirements can be set as standards to attain both in terms of performance and design. Pearson (1977) also suggested that EA can provide consumer information, and therefore indirectly lead to energy conservation, as consumers alter their behaviour in response to this information.

As mentioned above, the greatest debate concerning EA's use and value has focused on its potential role in or in place of Economics, and its role in public policy formulation (Slessor, 1973; Gilliland, 1977; Webb and Ricketts, 1980). At one extreme, proponents view EA as a replacement for Economics, or at least in a role more important than Economics in public policy formulation (Odum and Odum, 1976). Energy is considered to be the primary resource which "drives" all natural and economic activities; and furthermore it is the only resource which is absolutely depletable. All other resources can be manufactured, or recycled out of existing or virgin materials, by using energy inputs. Whereas, energy is degraded when it is "used", and can only be up-graded by other energy inputs, which are in turn degraded (Second Law of Thermodynamics). From this basis, it is argued that energy is a more fundamentally important unit of account than money, and therefore EA is more fundamental in its basis than Economics. Proponents of this view have been accused of proposing an "Energy Theory of Value" by Economists (Webb and Ricketts, 1980).

A more moderate view of EA, considers that EA can be used to inject energetic variables into existing economic theory (Slessor, 1978). Economic models and theories do not recognise the fundamental and unique nature of energy. Labour, Land and Capital are afforded more importance in most economic models, and in many ways Energy should be afforded at least equal importance to these variables. For the most part Economists, have given "lipservice" to this view, and have continued to treat energy as any other input into the economic process, even in so called "energy modelling" exercises (e.g. refer to Vogely, 1974).

Another view is that EA is not a replacement for Economics, or a means of injecting energetic values into economic theory; but a complementary discipline to Economics (Carter, Peet and Baines, 1981). That is, EA can provide the policy-makers with data and information, which Economics cannot. In this way, it is considered to be one of the several disciplines that can provide useful inputs into the policy-making process. Commentators have various views on exactly what weight should be placed on the importance of the EA input into the policy making process.

Many of the more specific applications and uses of EA are outlined by Pearson (1977). Net energy analysis is considered by many to be one of the more important applications of EA. Energy production processes can be examined so as to ascertain if they produce net energy - and if so how much? It is considered important that a proposed energy technology actually produces more energy than it uses, particularly in an environment of impending energy shortages. Such analyses have been undertaken on Nuclear Power Stations (Chapman, 1975), and on Biological Energy Supply Processes (Slessor and Lewis, 1979). Net energy analysis has received some criticism in the literature (Leach, 1975; Huettner, 1976), particularly on those methodological grounds which are outlined in section 1.2.1.4.

1.2.2 Linear Modelling in Energy Analysis and Economics

1.2.2.1 Definition of Linear Models

A Linear Model is simply defined as a system of simultaneous

linear equations, represented by a matrix, and usually solved by using matrix algebra. Such matrices are usually solved using computer algorithms, because of the usual size and complexities of such matrices which precludes manual solution.

1.2.2.2 Typology of Linear Models in Economics

The use of linear models in Economics is widespread, and mainly outside the scope of this thesis. However, the following typology of linear models in Economics, provides a useful comparative basis and structure for describing the potential use of linear models in Energy Analysis.

Determined Matrix: Input-Output Model

In Economics, this represents the classical Input-Output analysis, pioneered by Leontief in the 1930's. The matrix in this problem type has an equal number of equations and unknowns - that is, the matrix is square. Such matrices only have one unique solution, and hence are said to be determined.

Such Input-Output models can be used to represent the interdependencies between sectors in the economy - that is, the flows of goods and services between different sectors in the economy. The Input-Output Model is formulated using a technical coefficients matrix (A). This matrix (A) consists of an identical set of columns and rows, with the inputs being represented by reading down the columns and the outputs being represented by reading across the rows. It is usual in Input-Output analysis to determine the total primary inputs for each unit of output which involves finding the inverse of the matrix (I-A), where I is the identity matrix - that is:

$$(I-A)^{-1} y = d = y + Ay + A^2y + A^3y + \dots$$

where: y = variable vector

d = is the final output vector

For further mathematical details of this method readers should refer to the Department of Statistics (1980c) or O'Connor and Henry (1975).

The fundamental assumptions of Input-Output analysis which limit its application are:

- (1) Each sector produces a single output with a single input structure, and there is no substitution between the outputs of the different sectors. This is known as the Homogeneity Assumption.
- (2) The inputs into each sector are simple proportions only of the level of output of that sector - that is, the amount of each kind of input absorbed by any particular sector goes up and down in direct proportion to the increase or decrease in that sector's total output. This is known as the Proportionality Assumption.
- (3) The total effect of carrying out production in several sectors is the sum of the separate effects. This is known as the Additivity Assumption.
- (4) No 'economies' or 'diseconomies' of scale are allowed - that is, inputs and outputs decrease and increase in linear proportions. This is known as the Linearity Assumption.

Despite these rather restrictive assumptions Input-Output analysis has been widely applied, with Input-Output matrices being constructed for almost all national economies. Input-Output analysis has also been widely applied in regional economics (Herfindahl and Kneese, 1974), and extended to include the Linear Programming case (refer to O'Connor and Henry, 1975), using the (I-A) matrix.

Overdetermined Matrix: Regression Model

The use of Regression models is widespread in Economics, as well as other applied disciplines such as Biometrics. In this problem type there are usually more equations than unknowns - that is, the matrix is said to be overdetermined. Such problems are usually solved by the least squares fitting method. The most popular form of regression is Linear Regression. The simplest Linear Regression case is represented by the following equation:

$$y = b_0 + b_1 x_1$$

where y = dependent variable (known)

b_0 = constant (unknown)

b_1 = coefficient (unknown)

x_1 = independent variable (known)

This simply involves fitting a straight line to a number of points. Multiple Linear Regression simply involves more than one variable and coefficient:

$$y = b_0 + b_1x_1 + b_2x_2 + \dots + b_nx_n.$$

It appears that the solution method was independently developed by Gauss (1797 - 1855) and Legendre (1752 - 1833) (refer to Draper and Smith, 1981).

Linear Regression analysis assumes that the x variables are independent of each other, and that the coefficients are linear.

In Economics, the use of Linear Regression (and Non-Linear Regression) is widespread. Its application is well suited to describing many of the statistical relationships which occur in economic systems. In this way Linear Regression has been widely used for forecasting and predictive purposes e.g. in Time Series Analysis.

Underdetermined Matrix: Linear Programming Model

Linear Programming problems are linear optimisation problems. Usually, there are more unknowns than equations (usually of the order of 2 - 3 times according to Murtagh, 1981). Danzig (1951) first developed the Simplex Method for solving such problems in the late 1940's, and subsequently more sophisticated solution methods have been developed (refer to Cooper and Steinburg, 1974).

Linear programming is used to maximise or minimise some function subject to a set of constraints or limitations. Mathematically, the linear programming problem can be expressed as:

$$\text{maximise/minimise: } c_1 x_1 + c_2 x_2 + \dots + c_m x_m$$

$$\begin{array}{l}
 \text{subject to: } a_{11}x_1 + a_{12}x_2 + \dots + a_{1m}x_m \leq b_1 \\
 \quad \quad \quad \cdot \quad \quad \quad \cdot \quad \quad \quad \cdot \\
 \quad \quad \quad \cdot \quad \quad \quad \cdot \quad \quad \quad \cdot \\
 \quad \quad \quad \cdot \quad \quad \quad \cdot \quad \quad \quad \cdot \\
 \quad \quad \quad a_{n1}x_1 + a_{n2}x_2 + \dots + a_{nm}x_m \leq b_n
 \end{array}$$

where: $x_1 \geq 0, x_2 \geq 0, \dots, x_n \geq 0$

(This non-negativity restriction applies in most but not all cases).

c = objective function coefficients (referred to "cost" or "profit" coefficients in economic jargon).

x = variables

b = constraints

In matrix notation this problem can be written more compactly:

$$\text{min/max: } Z = CX$$

$$\begin{array}{l}
 \text{subject to: } AX \leq B \\
 \quad \quad \quad X \geq 0
 \end{array}$$

Linear programming (and to a lesser extent non-linear programming), is widely used in Economics. As previously noted, in Macroeconomics, Linear Programming extensions of Input-Output Models have been extensively used. Other applications include: uses in natural resource economics, energy planning (particularly with respect to oil refinery operations), and numerous other microeconomic analyses. Obviously, the linearity assumption is the most restrictive assumption which applies in all cases. Further problems usually relate to the "time static" nature of the models - coefficients and indeed economic objectives change over time, which is difficult to allow for in the modelling process.

1.2.2.3 Uses and Applications of Linear Models in Energy Analysis

The use of Input-Output Models in Energy Analysis has been widespread, despite the comparative immaturity of the discipline. The first analysis was undertaken by Herendeen (1973) for the USA, and

subsequent studies have been undertaken for many developed nations (Chapman, 1975 for the United Kingdom; Denton, 1975 for the Federal Republic of Germany; James and Gilbert, 1982 for Australia and Carter et al. (1982) for New Zealand - to name just a few). The approach is determining the total primary energy requirement (usually in MJ) per unit of output (\$), is directly analogous to the method used in determining the total financial requirement (\$) per unit of output (\$). Essentially, the same set of assumptions also apply.

The use of the data (MJ/\$ for various sector outputs), is often important in estimating the indirect energy requirements of a process or system, although this method of estimation is not as accurate as the process method (refer to section 1.2.1.3). The cost (\$) of various indirect inputs is simply multiplied by the energy coefficient (MJ/\$) of the input, so to obtain an estimate of the total energy requirement (MJ) of that indirect input.

To date, Linear Regression and Linear Programming techniques have not been applied to Energy Analysis problems. This is despite, the obvious applicability of such methods of analysis, to systems studied in Energy Analysis.

PART A: A LINEAR REGRESSION APPROACH TO ENERGY QUALITY

2 METHODOLOGY

2.1 Introduction

2.1.1 Problem of Energy Quality in Energy Analysis

One of the main thrusts of criticism of Energy Analysis, since its beginnings in the early 1970's, has centred around the "energy quality problem" (Leach, 1975; Edwards, 1976; Webb and Ricketts, 1980 - to cite three of the literally hundreds of criticisms that could be made).

Different forms of energy have different qualities or grades, which are not taken into account by enthalpy (ΔH) measurements of energy. Enthalpy (ΔH) measurements only measure the heat content of energy forms, and do not necessarily make any distinction between low grade energy sources (such as incident solar energy) and higher grade energy sources (such as oil or natural gas). From this basis, it has consequently been argued that energy when measured in enthalpy (ΔH), cannot be "added-up", because it has different grades. This has variously been coined as the "oranges and lemons", "kippers and custards" and the "valuation" problem or dilemma of Energy Analysis (Leach, 1975). Finally, it has been argued that because energy measured in enthalpy (ΔH) terms, is not additive, Energy Analysis is without a numeraire, and therefore has no basis for its proposed evaluative role.

2.1.2 Previous Approaches to Energy Quality in Energy Analysis

Various approaches to overcoming the energy quality problem have been suggested and used in the literature:

(1) Available Work This was recommended as a possible measurement of the quality of a fuel by the I.F.I.A.S. (1974). In essence, this is a very similar measurement to Gibbs Free Energy (ΔG). Available work takes into account the pressure and temperature of the surroundings; whereas Gibbs Free Energy (ΔG) refers to a reference state. The fundamental problem with using these measurements in Energy Analysis, is that in any economy or system the end-uses or outputs are not only work. The outputs of an economy also include heat of various grades and other energetic outputs such as light. So, therefore, whilst it is

acknowledged that Available Work, and Gibbs Free Energy (ΔG) have great value in engineering and thermodynamic studies, they cannot be proposed as measurements that can deal with energy quality in larger economic systems.

(2) Exergy This is a widely recommended measurement of energy, which takes into account energy quality (Bejan and Bejan, 1982). However, unfortunately, although the concept is attractive, like Available Work and Gibbs Free Energy (ΔG), it seems so far to only have been successfully applied to rather narrowly defined problems (e.g. Mattarolo, 1982). Furthermore, as Slesser (1982) points out, a consensus view of how exergy should be measured has not yet emerged.

(3) Fossil Fuel Equivalents (F.F.E.) This approach is used by Odum and Odum (1976), and is sometimes used in official statistics (e.g. O.C.E.D. energy balances, 1973-79). Essentially, this approach determines how many units of one fossil fuel (measured in ΔH), is required to produce a given quantity of another form of energy. This is assumed to be a measure of the quality of the two forms of energy. For example, hydro-electricity is said to use four fossil fuel equivalents, because four units of a fossil fuel (say coal) are required to produce one unit of electricity. This approach is considered to be arbitrary in the way it equates lower quality energy forms (e.g. coal), with higher forms (e.g. electricity). The assumption is that lower quality forms of energy (e.g. coal) are ultimately converted to higher forms of energy (e.g. electricity), and therefore are equatable. In any system or economy, this is not necessarily the case - e.g. coal has more uses in an economy than just being converted into electricity (these usually include providing heat in industrial and household situations). Another criticism of the F.F.E. approach is that, the situation of converting one form of energy to another is somewhat contrived, as usually multiple forms of energy are required to produce another form of energy. For example, in converting coal to electricity, coal is the main requirement, but oil may be required to run the transport vehicles required, electricity may be required to run the drag lines, and indirect inputs of other forms of energy may be required.

The above approaches, have focused primarily on the energy quality of sources or inputs of energy. It should be noted that Lovins (1977, 1979), has extended the concept of energy quality to end-uses of

energy, and has proposed the end-use matching of energy sources and uses. Herein, lies another criticism of the above approaches - they do not take into consideration the end-uses of energy. That is, they essentially treat the concept of energy quality as a source or input related one, and not as one which is linked to the end-use of energy.

2.1.3 Reiteration and Statement of Objective for Part A

In reiteration, the "energy quality problem" is a fundamental point of criticism of EA, and therefore if EA is to be accepted as a valid evaluative tool a means of overcoming this problem needs to be established.

Previous approaches to the problem have drawn much criticism, and are limited in their applicability to macro-level systems. Herein, lies the origins of the objective for Part A; which is to develop a conceptual framework and logical way for resolving and clarifying the "energy quality problem", associated with the application and use of EA.

2.2 Proposed Methodology to Solve the Energy Quality Problem

2.2.1 Definitions

The concepts embodied in the following definitions formed the basis of the modelling procedure:

(1) Primary Energy Inputs Any given economy is considered to have a number of primary energy inputs. That is, energy inputs into the economy from exogenous sources such as from a natural resource base or from imports. All secondary or intermediary energies can be converted back to primary energy inputs. The primary energy inputs, as is normal practice, are in this study expressed in terms of their enthalpic values (ΔH).

(2) Effective Energy Outputs Any given economy is also considered to have a number of effective energy outputs. These outputs refer to effective or useful energies resulting from end-use processes in the economy. For example, in cooking this refers to energy absorbed by the cooking load, and it does not refer to the waste heat which is lost to the surrounding environment. In any specific analysis, it is important

that these effective energy outputs be clearly defined. In this study, the effective energy outputs are also expressed in terms of their enthalpic values (ΔH).

(3) Quality Equivalents These are common energy units to which all primary energy inputs (ΔH) and effective energy outputs (ΔH) can be converted (Abbreviated to Q in the text).

(4) Quality of Primary Energy Inputs This is defined as the relative efficiency at which a given primary energy input is converted to effective energy outputs. In this study, it is expressed in terms of common quality units per unit of enthalpy (ΔH), of primary energy input.

(5) Quality of Effective Energy Outputs This is defined as the Gross Energy Requirements (direct and indirect) of an effective energy output expressed in quality terms. In this study, it is expressed in terms of common quality units per unit of enthalpy (ΔH) of effective energy output.

2.2.2 Energy Accounting Procedures

The first step is to identify all primary energy inputs and all effective energy outputs of the economy or system. The second step is to link all primary energy inputs to all effective energy outputs, by constructing a number of pathway flow diagrams. These pathways should collectively cover all energy transformations and uses in the economy. However, there can be some degree of overlap between pathways - that is, the pathways need not be mutually exclusive. Each pathway can have multiple inputs and multiple outputs, which can overcome the partitioning problem often associated in such energy accounting procedures. The third step is to estimate the Gross Energy Requirements (G.E.R.) of each pathway. The G.E.R. includes the direct energy inputs and the indirect energy inputs of each pathway, expressed in enthalpic values (ΔH). As a general principle it is recommended that the I.F.I.A.S. conventions of energy accounting be used in determining the G.E.R. of each pathway (refer to I.F.I.A.S., 1974).

2.2.3 Regression Equations and Solutions

The supply and use of energy in any given economy can be

represented by the following set of linear equations.

$$\begin{aligned} m_1 \sum_{i=1}^{i=j} (Y_1)_i + m_2 \sum_{i=1}^{i=j} (Y_2)_i + \dots m_n \sum_{i=1}^{i=j} (Y_n)_i \\ = n_1 \sum_{i=1}^{i=j} (X_1)_i + n_2 \sum_{i=1}^{i=j} (X_2)_i + \dots n_n \sum_{i=1}^{i=j} (X_n)_i \end{aligned} \quad (2.1)$$

Where Y = effective energy output of an end-use class (ΔH_{output})

X = primary energy input (ΔH_{input})

m = quality coefficient for an effective energy output (quality equivalents/ ΔH_{output})

n = quality coefficient of a primary energy input (quality equivalents/ ΔH_{input})

i = energy supply-use pathways.

j = number of pathways.

The effective energy outputs ($Y_1 \dots Y_n$) and the primary energy inputs ($X_1 \dots X_n$) are known. The quality coefficients of the effective energy outputs ($m_1 \dots m_n$), and the quality coefficients of the primary energy inputs ($n_1 \dots n_n$) are not known. In almost all cases, the above set of simultaneous equations is overdetermined - that is, there are more equations than unknowns. Therefore, in practically all cases the only method for solving these equations is by regression analysis (refer to Johnson and Riess, 1977, p.61).

To determine these coefficients by multiple linear regression, one coefficient must arbitrarily be given a value equal to unity. For example, coefficient n can be given a value of 1, and then by rearrangement the general equation now reads:

$$\begin{aligned} \sum_{i=1}^{i=j} -(X_1)_i = n_2 \sum_{i=1}^{i=j} (X_2)_i + \dots n_n \sum_{i=1}^{i=j} (X_n)_i + \\ m_1 \sum_{i=1}^{i=j} -(Y_1)_i + m_2 \sum_{i=1}^{i=j} -(Y_2)_i + \\ \dots m_n \sum_{i=1}^{i=j} -(Y_n)_i \end{aligned} \quad (2.2)$$

where $n_1 = 1$

This equation is now in a form that can be solved by multiple linear regression. The left-hand-side expression is equivalent to the 'Y' variable used in conventional regression equations, and the right-hand-side expressions are equivalent to the 'X' variables used in conventional regression equations.

The coefficients which result from the solution of this regression equation, only have meaning relative to $n_1 = 1$. That is, they are expressed in multiples of n_1 . In this study such multiples are termed "quality equivalents". It is recommended that the regression equation be solved several times by in turn assigning values of unity to each coefficient ($m_1 \dots m_n, n_1 \dots n_n$). In this way the general robustness of the model, and the validity of this procedure can be tested.

As a general principle, it is advisable that as many pathways as possible be used in the regression procedure. This should increase the variability in the data set, and hence lead to more accurate solutions of regression. In particular it is advisable that if at all possible, each primary energy input class be linked to each effective energy output class by one pathway each (that is, $X_n \times Y_n$ pathways should result from this).

2.2.4 Statistical Analysis of Solutions

To test the statistical validity of any given set of solutions (i.e. a particular model), generated by this technique, a number of statistical tests should be undertaken. For a more complete range of statistical tests of regression models readers should refer to the appropriate literature (Draper, N.R. and Smith, H. 1981):

(1) F Test Usually in regression analysis this is the most important test, as it indicates the overall statistical validity of the model. That is, how adequately the solutions to the regression equation "fit" the actual data set. The F ratio for a model is calculated by most programme packages used in regression analysis. The level of significance (p) can be calculated by using standard F distribution tables.

(2) T Test of Coefficients The t ratios for each coefficient are also

calculated by most programme packages used in regression analysis. The t ratio of a coefficient is simply the estimated coefficient divided by its standard deviation. The level of significance (p) of each t ratio, and hence the statistical accuracy of each coefficient estimate, can be calculated by using standard t distribution tables.

(3) Examination of Residuals An examination of the residuals for each pathway should be undertaken. Those pathways which have the highest standardised residuals least conform to the regression model. If at all possible, it is advisable that the model be reconstructed to eliminate such pathways. Various residual plots are outlined in statistical texts and are outputted by most programme packages used in regression analysis.

(4) Other Statistics Various other statistics and statistical tests can be undertaken to test a model. For example, the Durbin-Watson Statistic can be calculated so as to test the model for auto-correlation. It may also be useful to calculate partial F ratios for each coefficient, so as to estimate their contributions to the overall level of significance of the model.

2.2.5 Recommended Methods of Model Selection and Improvement

It is recommended that the maximum number of models be generated by giving in turn each coefficient a value of unity. These basic models should form the basis of the model selection and improvement procedures.

The simplest approach is to choose the basic model which has the highest F ratio, provided the model makes good physical sense. For example, it is meaningless to use a model where a coefficient is negative, as this is a physical impossibility.

A more complicated and instructive approach is to "experiment" with the models so as to maximise the level of significance (p) of the model. The aggregation and where possible, the disaggregation of variable classes ($X_1 \dots X_N, Y_1 \dots Y_N$) should form the basis of this "experimentation". The original classifications may not necessarily be the "best" way of classifying the inputs ($X_1 \dots X_N$) and outputs ($Y_1 \dots Y_N$), in terms of their energy qualities. It not only is more statistically valid to maximise p, but it can also be more instructive

to the analyst. This is because such reclassification may give some insight as to the physical and technical reasons why it is best to classify inputs and outputs in a particular way.

When aggregating various inputs ($X_1 \dots X_n$) or outputs ($Y_1 \dots Y_n$), it is recommended that those classes with the lowest t ratios for their coefficients be added together first. By doing this the more insignificant coefficients can be eliminated from the model, while also increasing the likelihood of increasing the F ratio of the model. Eventually, an optimum aggregation of inputs ($X_1 \dots X_n$) and outputs ($Y_1 \dots Y_n$) should be reached, where the level of significance (p) of the model cannot be improved upon. This model, in a statistical sense, best explains the use of energy in the economy or system, in terms of energy quality. This model should also make good physical and technical sense.

2.2.6 Central Hypothesis and Model Building

The central hypothesis that is being tested by this regression technique, is that for a given economy or system all inputs ($X_1 \dots X_n$) and all outputs ($Y_1 \dots Y_n$) have intrinsic quality coefficients.

This hypothesis will hold true in any system or economy where the amount of outputs is proportional to the amount of inputs. Evidence and experience strongly indicates that this hypothesis holds true in all economic systems.

Time series data and international comparisons strongly indicate that dollar outputs (\$) are linearly proportional to primary energy inputs in economic systems. Therefore it is not so much a matter of proving this central hypothesis, but a matter of building a model which best explains this central hypothesis.

To elaborate with an example, the simplest way to model an economy, is to set up a model where all inputs are classified into one class. Although this model may be statistically significant, it may not be the "best" model in terms of maximising its statistical validity and in terms of its instructiveness. The problem for the analyst is to disaggregate these two classes, so as to obtain this "best" model.

This requires a good understanding and knowledge of the statistical testing procedures, and a good understanding of the nature of the system being modelled.

2.2.7 Post Regression Analysis of Pathways

In conventional regression analysis the examination of the individual equation residuals, forms an important part of the modelling process. Essentially, each equation is tested for conformity to the regression model, by comparing the predicted value ($\hat{Y}$) against the actual value (Y), with difference between the two values being the residual ($Y - \hat{Y}$).

In this particular application of regression modelling, the conformity of each pathway (equation) to the model can similarly be assessed by calculating:

(1) Relative Net Energy Yield This is numerically equivalent to the residual. For a pathway which perfectly conforms to the models (i.e. has an "average" net energy yield), the relative net energy yield is zero. Those pathways that use more energy (in quality equivalent terms, Q) than predicted have a negative relative net energy yield. Conversely, those pathways that use less energy (Q) than predicted have a positive relative net energy yield.

(2) Relative Efficiency This is the sum of Outputs (OQ) divided by the sum of Inputs (IQ), where these sums are measured in quality equivalent terms. Those pathways which have a Relative Efficiency equal to unity, exactly conform to the model. Whereas, those pathways which have a Relative Efficiency greater than unity are more efficient; and those pathways which have a Relative Efficiency less than unity are less efficient. The Relative Efficiency (Q) is related to the Residual (Q) by the following equation:

$$\text{Relative Efficiency } (Q) = \frac{\text{Residual } (Q) + IQ}{IQ}$$

It should be noted that both the Relative Net Energy Yield and the Relative Efficiency, are relative not absolute measurements. For a

perfectly fitted model, the Relative Net Energy Yield would equal zero for all equations, and the Relative Efficiency would equal unity.

2.3 Conclusion

In this Chapter, the "energy quality problem" associated with the application and use of EA, has been discussed and previous approaches to solving the problem have been detailed and criticised. A methodology was proposed for resolving the "energy quality problem", based on the concept of quality equivalents, and a general equation for converting enthalpy (ΔH) units to quality equivalents.

Data for two systems will be fitted to this general equation, and statistically tested in Chapters 3 (N.Z. Economy, 1976) and 4 (Efficient N.Z. Economy). It is considered to be of fundamental importance in testing the validity of the methodology, that data can be accurately fitted to the general equation. Hence the emphasis placed on statistical analyses in Chapters 3 and 4. In Chapter 5, the proposed methodology is reviewed in view of these statistical results, and the applications and uses of data derived from the proposed methodology are discussed.

3 AN APPLICATION TO THE NEW ZEALAND ECONOMY, 1976

3.1 Data Sources

Data were obtained from a wide variety of sources (for details refer to Appendix B). The main sources of data were:

- (1) The New Zealand Yearbook (1977), and the energy flow diagram contained in the Ministry of Energy's (1978) publication "Goals and Guidelines".
- (2) Energy Data files published by the Ministry of Energy (1978), particularly for end-use efficiencies.
- (3) Carter, Peet and Baines (1981) Input-Output analysis of energy use in the New Zealand economy, particularly for indirect energy requirements.

3.2 Inputs and Outputs Considered

The primary energy inputs considered in this example are:

- (1) Hydro-electricity (X_1). This refers to hydro-electricity at the point of generation, before transmission.
- (2) Natural Gas (X_2). This refers to natural gas as it lies in the gas well.
- (3) Oil (X_3). This refers to oil products as they are imported in their various degrees of refinement, or indigenous oil as it lies in the oil well.
- (4) Coal (X_4). This refers to coal as it lies in the ground.
- (5) Wood (X_5). This refers to wood as it leaves the forest.

The effective energy outputs considered in this example are:

- (1) Electrical Output (Y_1). This class includes all energy use in all end-use processes where there is an absolute requirement for the direct use of electricity. The system boundary ends at the point where electrical energy is delivered to the end-use appliance. This is because the mean end-use efficiency of end-uses in this class is very difficult to estimate accurately. Other energy sources can only be used directly, after they have been up-graded to electricity. These end-use processes include the operating of electronic equipment such as

computers and various electrical appliances and machines such as electrically powered refrigeration units.

(2) High Grade Transport (Y_2). This refers to the use of energy by relatively long range, route flexible and high powered road vehicles (that is, the modern automobile which is an important end-use of energy in the New Zealand economy). This does not include other forms of road transport which are more limited in their range, route flexibility and/or power output. High grade transport directly uses high grade fuels such as gasoline, methanol, hydrogen and diesel.

(3) Industrial Heat (Y_3). This refers to the use of energy in industrial situations in producing medium to high temperature heat.

(4) Water Heating (Y_4). This refers to the use of energy in heating water to medium temperatures, primarily in the household situation.

(5) Space Heating (Y_5). This refers to the use of energy in heating space to medium temperatures, primarily in the household situation.

(6) Cooking (Y_6). This refers to the use of energy in heating food, primarily in the household situation.

3.3 Pathways Considered

The following pathways collectively describe the main energy flows in the New Zealand economy. (Because of the lack of reliable data not all primary energy inputs (e.g. geothermal energy) and not all effective energy outputs (e.g. sea and air transport) were considered. It should be noted that these inputs and outputs are relatively small, and their inclusion in the model should not significantly affect the results :

1. Coal -> Electricity -> Electrical Output.
2. Natural Gas -> Electricity -> Electrical Output.
3. Oil -> Electricity -> Electrical Output.
4. Hydrogenerated Electricity -> Electrical Output.
5. Oil -> High Grade Transport.
6. Coal -> Industrial Heat.
7. Oil -> Industrial Heat.
8. Natural Gas -> Industrial Heat.
9. Wood -> Industrial Heat.
10. Hydrogenerated Electricity -> Industrial Heat.
11. Coal -> Electricity -> Industrial Heat.
12. Natural Gas -> Electricity -> Industrial Heat.

13. Oil -> Electricity -> Industrial Heat.
14. Hydrogenerated Electricity -> Water Heating.
15. Coal -> Electricity -> Water Heating.
16. Natural Gas -> Electricity -> Water Heating.
17. Oil -> Electricity -> Water Heating.
18. Gas -> Water Heating.
19. Coal -> Space Heating.
20. Natural Gas -> Space Heating.
21. Oil -> Space Heating.
22. Wood -> Space Heating.
23. Coal -> Electricity -> Space Heating.
24. Natural Gas -> Electricity -> Space Heating.
25. Oil -> Electricity -> Space Heating.
26. Hydrogenerated Electricity -> Space Heating.
27. Coal -> Electricity -> Cooking.
28. Oil -> Electricity -> Cooking.
29. Natural Gas -> Electricity -> Cooking.
30. Hydrogenerated Electricity -> Cooking.
31. Natural Gas -> Cooking.

The technologies used in these pathways, and the assumed operational efficiencies of the supply, distribution and end-use stages are detailed in Table 3.1.

3.4 Data Set and Regression Equations

The G.E.R. (Gross Energy Requirements) of each of the above pathways was calculated, using data obtained from the sources described in section 3.1 and detailed in the Appendix B. For example, the G.E.R. of pathway one is:

0.06 PJ (Hydro) + 0.02 PJ (N. Gas) + 0.19 PJ (Oil) + 8.80 PJ (Coal) is required for 1.93 PJ (Electrical Output).

This represents the following equation, when written in terms of the mathematics detailed in the methodology section:

$$n_1 0.06X_1 + n_2 0.02X_2 + n_3 0.19X_3 + n_4 8.80X_4 = m_1 1.93Y_1$$

Similar equations can be written for each pathway, and these are summarised in Table 3.2

The data set was then normalised so that the effective output of

TABLE 3.1 Actual New Zealand Energy Economy (1976): Technologies and Operational Efficiencies

Pathway	Supply Technology	Efficiency ^a (%)	Distribution Technology	Efficiency ^a (%)	End-Use Technology	Efficiency ^a (%)
1. Coal → Elect. → Electrical Output	Conventional Power Station	26	Transmission System	90	Electrical and electronic technology	b
2. Gas → Elect. → Electrical Output	Conventional Power Station	30	Transmission System	90	Electrical and electronic technology	b
3. Oil → Elect. → Electrical Output	Conventional Power Station	32	Transmission System	90	Electrical and electronic technology	b
4. Hydro → Elect. → Electrical Output	Hydro-electrical generation (Dam; Water Turbine)	b	Transmission System	90	Electrical and electronic technology	b
5. Oil → High Grade Transport	Oil Refinery	92	Tanker delivery	100	Internal combustion engine	25
6. Coal → Industrial Heat	Coal mining technology	b	Rail-Road Distribution	100	Industrial boilers and furnaces	70
7. Oil → Industrial Heat	Oil Refinery	92	Tanker delivery	100	Industrial boilers and furnaces	75
8. Gas → Industrial Heat	Gas well technology	b	Pipeline	90	Industrial boilers and furnaces	75
9. Wood → Industrial Heat	Residues from forestry industry	b	On site distribution, truck delivery to other sites	100	Industrial boilers and furnaces	33
10. Hydro → Elect. → Industrial Heat	Hydro-electrical generation (Dam; Water Turbine)	b	Transmission System	90	Resistance Heaters	100
11. Coal → Elect. → Industrial Heat	Conventional Power Station	26	Transmission System	90	Resistance Heaters	100
12. Gas → Elect. → Industrial Heat	Conventional Power Station	30	Transmission System	90	Resistance Heaters	100
13. Oil → Elect. → Industrial Heat	Conventional Power Station	32	Transmission System	90	Resistance Heaters	100
14. Hydro → Elect. → Water Heating	Hydro-electrical generation (Dam; Water Turbine)	b	Transmission System	90	Water heating cylinder, with resistance heater	100
15. Coal → Elect. → Water Heating	Conventional Power Station	26	Transmission System	90	Water heating cylinder, with resistance heater	100
16. Gas → Elect. → Water Heating	Conventional Power Station	30	Transmission System	90	Water heating cylinder, with resistance heater	100
17. Oil → Elect. → Water Heating	Conventional Power Station	32	Transmission System	90	Water heating cylinder, with resistance heater	100
18. Gas → Water Heating	Gas well technology	b	Pipeline	90	Gas Heating Cylinder	65
19. Coal → Space Heating	Coal mining technology	b	Rail-Road Distribution	100	Enclosed burners and open fires	49
20. Gas → Space Heating	Gas well technology	b	Pipeline	90	Enclosed burner	64
21. Oil → Space Heating	Oil Refinery	90	Tanker Delivery	100	Enclosed burner	57
22. Wood → Space Heating	Residues from Forestry Industries	b	Truck Delivery	100	Enclosed burner and open fires	35
23. Coal → Elect. → Space Heating	Conventional Power Station	26	Transmission System	90	Resistance Heater	100
24. Gas → Elect. → Space Heating	Conventional Power Station	30	Transmission System	90	Resistance Heater	100
25. Oil → Elect. → Space Heating	Conventional Power Station	32	Transmission System	90	Resistance Heater	100
26. Hydro → Elect. → Space Heating	Hydro-electrical generation (Dam; Water Turbine)	b	Transmission System	90	Electric Range	44
27. Coal → Elect. → Cooking	Conventional Power Station	26	Transmission System	90	Electric Range	44
28. Oil → Elect. → Cooking	Conventional Power Station	30	Transmission System	90	Electric Range	44
29. Gas → Elect. → Cooking	Conventional Power Station	32	Transmission System	90	Electric Range	44
30. Hydro → Cooking	Hydro-electrical generation (Dam; Water Turbine)	b	Transmission System	90	Electric Range	44
31. Gas → Cooking	Gas well technology	b	Pipeline	100	Gas Range	23

NOTE:

- a. Enthalpy (ΔH) efficiency of direct energy flows. Enthalpic (ΔH) efficiencies are also implied in indirect energy flows.
b. Either input or output is outside study boundary. Therefore, no enthalpic (ΔH) efficiency can be calculated.

TABLE 3.2 Data Set: Gross Energy Requirements of Energy Supply-Use Pathways in the New Zealand Energy Economy, 1976

Pathway	Primary Energy Inputs (PJ) ^a					Effective Energy Outputs (PJ) ^a					
	X ₁ Hydro	X ₂ Gas	X ₃ Oil	X ₄ Coal	X ₅ Wood	Y ₁ Electrical Output	Y ₂ High Grade Transport	Y ₄ Industrial Heat	Y ₅ Water Heating	Y ₆ Space Heating	Y ₇ Cooking
1 Coal → Elect → Electrical Output	0.06	0.02	0.19	8.80	0.00	1.93	0.00	0.00	0.00	0.00	0.00
2 Gas → Elect → Electrical Output	0.13	12.40	0.55	0.13	0.00	3.23	0.00	0.00	0.00	0.00	0.00
3 Oil → Elect → Electrical Output	0.09	0.07	8.77	0.71	0.00	2.29	0.00	0.00	0.00	0.00	0.00
4 Hydro → Elect → Electrical Output	31.36	0.28	2.20	1.10	0.00	27.51	0.00	0.00	0.00	0.00	0.00
5 Oil → High Grade Transport	9.25	4.37	144.95	15.42	0.00	0.00	25.70	0.00	0.00	0.00	0.00
6 Coal → Industrial Heat	0.75	0.19	1.32	28.38	0.00	0.00	0.00	18.80	0.00	0.00	0.00
7 Oil → Industrial Heat	0.55	0.55	40.98	3.55	0.00	0.00	0.00	27.32	0.00	0.00	0.00
8 Gas → Industrial Heat	0.20	10.33	0.40	0.13	0.00	0.00	0.00	6.58	0.00	0.00	0.00
9 Wood → Industrial Heat	0.21	0.10	0.68	0.16	5.27	0.00	0.00	1.74	0.00	0.00	0.00
10 Hydro → Elect → Industrial Heat	5.79	0.05	0.41	0.20	0.00	0.00	0.00	5.08	0.00	0.00	0.00
11 Coal → Elect → Industrial Heat	0.01	0.00	0.04	1.64	0.00	0.00	0.00	0.36	0.00	0.00	0.00
12 Gas → Elect → Industrial Heat	0.02	2.30	0.10	0.02	0.00	0.00	0.00	0.60	0.00	0.00	0.00
13 Oil → Elect → Industrial Heat	0.02	0.01	1.61	0.13	0.00	0.00	0.00	0.42	0.00	0.00	0.00
14 Hydro → Elect → Water Heating	10.80	0.09	0.76	0.38	0.00	0.00	0.00	0.00	9.47	0.00	0.00
15 Coal → Elect → Water Heating	0.02	0.01	0.07	3.01	0.00	0.00	0.00	0.00	0.66	0.00	0.00
16 Gas → Elect → Water Heating	0.04	4.26	0.19	0.04	0.00	0.00	0.00	0.00	1.11	0.00	0.00
17 Oil → Elect → Water Heating	0.03	0.02	3.03	0.25	0.00	0.00	0.00	0.00	0.79	0.00	0.00
18 Gas → Water Heating	0.01	0.87	0.03	0.01	0.00	0.00	0.00	0.00	0.48	0.00	0.00
19 Coal → Space Heating	0.03	0.16	0.26	5.68	0.00	0.00	0.00	0.00	0.00	2.63	0.00
20 Gas → Space Heating	0.05	2.12	0.08	0.02	0.00	0.00	0.00	0.00	0.00	1.15	0.00
21 Oil → Space Heating	0.23	0.23	15.21	1.31	0.00	0.00	0.00	0.00	0.00	7.72	0.00
22 Wood → Space Heating	0.17	0.09	0.54	0.13	4.17	0.00	0.00	0.00	0.00	0.50	0.00
23 Coal → Elect → Space Heating	0.02	0.01	0.05	2.33	0.00	0.00	0.00	0.00	0.00	0.51	0.00
24 Gas → Elect → Space Heating	0.03	3.26	0.14	0.03	0.00	0.00	0.00	0.00	0.00	0.85	0.00
25 Oil → Elect → Space Heating	0.02	0.02	2.30	0.19	0.00	0.00	0.00	0.00	0.00	0.60	0.00
26 Hydro → Elect → Space Heating	8.25	0.07	0.48	0.29	0.00	0.00	0.00	0.00	0.00	7.24	0.00
27 Coal → Elect → Cooking	0.01	0.00	0.02	0.94	0.00	0.00	0.00	0.00	0.00	0.00	0.09
28 Oil → Elect → Cooking	0.01	0.01	0.97	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.11
29 Gas → Elect → Cooking	0.01	1.41	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.16
30 Hydro → Cooking	2.78	0.05	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	1.33
31 Gas → Cooking	0.02	0.77	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.15

NOTE: a. Expressed in enthalpy (ΔH) terms; 1kWhr = 3.6 MJ.

each pathway equalled unity. This normalisation process had the effect of improving the versatility of the data set - i.e. in such data sets, it was unimportant which variable was used as the equivalencing unit. Furthermore, data sets that had been normalised, also were found to have greater statistical validity - that is, the statistical indicators (e.g. t ratios, F ratios) were generally found to be more satisfactory in models generated from normalised data sets. Moreover, models generated from normalised data sets, were generally found to make greater technical and physical sense. For example, in some cases of models generated from non-normalised data sets, the coefficients were negative, which is a physical impossibility.

3.5 Computer Analysis of Data Set

The data were analysed by using the "Minitab" statistical programme package on Massey University's Prime 750 computer. The following set of commands were used:

READ 'DATA' C1-C12	The data sets (see Table 3.2) were read into the programme package, from a file created elsewhere in the computing system. The data is in the form of general equation 2.1.
MULT. C6, -1, C13	This arithmetic re-arranges the data set so that all effective energy outputs are negative. That is, all effective energy outputs are taken to the same side of the general equation as the primary energy inputs - refer to general equation 2.2.
MULT. C7, -1, C14	
MULT. C8, -1, C15	
MULT. C9, -1, C16	
MULT. C10, -1, C17	
MULT. C11, -1, C18	
MULT. C12, -1, C19	

This step is repeated by, in turn, assigning values of unity to each coefficient.

MULT. C1, -1, C21	In this example, column 1 (hydro-electricity) is given an arbitrary value of 1. The value is "-1", so that in effect it is taken to the other side of the equation - see general equation 2.2.

NO CONSTANT	This indicates that there is no constant in the

regression equations - see methodology section.

BRIEF 7 This indicates that the fullest statistical analysis output is required.

REGRESS C21, 10, C2-C5,

C13-C19

This indicates to the computer that Column 21 is to be regressed, against 10 variables in columns C2 to C5 and C13 to C19. Because most regression problems are formatted in the $y = m_1x_1 \dots m_nx_n + C$ format, C21 is considered to be the "Y" variable and the other variables the "X" variables. This is mere convention, and makes little sense in terms of this problem. Nevertheless, this point should be recognised when interpreting the results from this and other programme packages.

3.6 Statistical Analysis of Solutions to the Regression Equations

A series of models were generated, by in turn using each variable, as the equivalencing unit - that is:

- $n_1 = 1$, hydro-electrical equivalents
- $n_2 = 1$, natural gas equivalents
- $n_3 = 1$, oil equivalents
- $n_4 = 1$, coal equivalents
- $n_5 = 1$, wood equivalents
- $m_1 = 1$, electrical output equivalents
- $m_2 = 1$, high grade transport equivalents
- $m_3 = 1$, industrial heat equivalents
- $m_4 = 1$, water heating equivalents
- $m_5 = 1$, space heating equivalents
- $m_6 = 1$, cooking equivalents.

A detailed statistical analysis of each of these models was undertaken.

3.6.1 Detailed Results

The following set of statistical results were obtained for each one of the above mentioned models. The "Minitab" computer programme package, routinely produces a more detailed set of results than can be included here. An example of this computer print-out is included at 3.6.2 for the model $n_1 = 1$.

$n_1 = 1$ (Hydro-electric equivalents)

	Estimate of Co-efficient	Standard Deviation	t Ratio	Level of Significance (2P)
n_2 (natural gas)	0.22	0.04	6.06	<0.001
n_3 (oil)	0.19	0.04	5.31	<0.001
n_4 (coal)	0.17	0.03	5.58	<0.0005
n_5 (wood)	0.03	0.04	0.77	<0.50>0.20
m_1 (electrical output)	0.94	0.18	5.16	<0.001
m_2 (high grade transport)	1.58	0.38	4.11	<0.001
m_3 (industrial heat)	0.64	0.13	4.89	<0.001
m_4 (water heating)	0.85	0.17	5.12	<0.001
m_5 (space heating)	0.75	0.14	5.22	<0.001
m_6 (cooking)	1.88	0.24	7.73	<0.001

F Ratio = 7.62 (df, $V_1=10$, $V_2=21$), significant at the $p=0.001$ level.

$n_2 = 1$ (Natural gas equivalents)

	Estimate of Co-efficient	Standard Deviation	t Ratio	Level of Significance (2P)
n_1 (hydro electricity)	2.84	0.47	6.06	<0.0005
n_3 (oil)	0.71	0.12	5.93	<0.001
n_4 (coal)	0.64	0.10	6.33	<0.001
n_5 (wood)	0.14	0.14	1.01	<0.50>0.20
m_1 (electrical output)	3.40	0.64	5.31	<0.001
m_2 (high grade transport)	5.60	1.37	4.07	<0.001
m_3 (industrial heat)	2.36	0.45	5.23	<0.001
m_4 (water heating)	3.11	0.56	5.54	<0.001
m_5 (space heating)	2.75	0.48	5.67	<0.001
m_6 (cooking)	7.06	0.72	9.73	<0.001

F Ratio = 11.30 (df, $V_1=10$, $V_2=21$) significant at the $p=0.001$ level.

n₃=1 (Oil equivalents)

	Estimate of Co-efficient	Standard Deviation	t Ratio	Level of Significance (2P)
n ₁ (hydro electricity)	3.00	0.56	5.31	<0.001
n ₂ (natural gas)	0.88	0.15	5.93	<0.001
n ₄ (coal)	0.67	0.13	5.24	<0.001
n ₅ (wood)	0.13	0.15	0.83	<0.50 >0.20
m ₁ (electrical output)	3.66	0.74	4.94	<0.001
m ₂ (high grade transport)	7.27	1.29	5.64	<0.001
m ₃ (industrial heat)	2.54	0.52	4.88	<0.001
m ₄ (water heating)	3.28	0.67	4.90	<0.001
m ₅ (space heating)	2.96	0.56	5.27	<0.001
m ₆ (cooking)	7.39	0.99	7.49	<0.001

F Ratio = 8.96 (df, V₁=10, V₂=21), significant at the p=0.001 level.

n₄=1 (Coal equivalents)

	Estimate of Co-efficient	Standard Deviation	t Ratio	Level of Significance (2P)
n ₁ (hydro electricity)	3.46	0.62	5.58	<0.001
n ₂ (natural gas)	1.02	0.16	6.33	<0.001
n ₃ (coal)	0.85	0.17	5.24	<0.001
n ₅ (wood)	0.17	0.17	1.01	<0.50>0.20
m ₁ (electrical output)	4.20	0.82	5.09	<0.001
m ₂ (high grade transport)	6.82	1.77	3.86	<0.001
m ₃ (industrial heat)	2.90	1.58	4.99	<0.001
m ₄ (water heating)	3.76	0.74	5.06	<0.001
m ₅ (space heating)	3.39	0.63	5.42	<0.001
m ₆ (cooking)	8.49	1.07	7.96	<0.001

F Ratio = 7.79 (df, V₁=10, V₂=21), significant at the p=0.01 level.

n₅=1 (Wood equivalents)

	Estimate of Co-efficient	Standard Deviation	t Ratio	Level of Significance (2P)
n ₁ (hydro electricity)	0.92	1.19	0.77	<0.50>0.20
n ₂ (natural gas)	0.33	0.33	1.01	<0.50>0.20
n ₃ (oil)	0.25	0.30	0.83	<0.50>0.20
n ₄ (coal)	0.27	0.26	1.01	<0.50>0.20
m ₁ (electrical output)	1.20	1.50	0.80	<0.50>0.20
m ₂ (high grade transport)	1.94	2.82	0.69	<0.50>0.20
m ₃ (industrial heat)	1.19	1.03	1.16	<0.50>0.20
m ₄ (water heating)	1.09	1.35	0.81	<0.50>0.20
m ₅ (space heating)	1.96	1.12	1.75	<0.10>0.05
m ₆ (cooking)	2.48	2.59	0.96	<0.50>0.20

F Ratio = 0.43 (df, V₁=10, V₂=21), not significant at the p=0.10 level.

m₁=1 (Electrical output equivalents)

		Estimate of Co-efficient	Standard Deviation	t Ratio	Level of Significance (2P)
n ₁	(hydro electricity)	0.59	0.11	5.16	0.001
n ₂	(natural gas)	0.17	0.03	5.31	0.001
n ₃	(oil)	0.15	0.03	4.94	0.001
n ₄	(coal)	0.13	0.03	5.09	0.001
n ₅	(wood)	0.02	0.02	0.80	0.50 0.20
m ₂	(high grade transport)	1.15	0.32	3.55	0.01 0.001
m ₃	(industrial heat)	0.46	0.11	4.00	0.001
m ₄	(water heating)	0.60	0.15	4.10	0.001
m ₅	(space heating)	0.53	0.13	4.25	0.001
m ₆	(cooking)	1.35	0.24	5.66	0.001

F Ratio = 4.17 (df, V₁=10, V₂=21), significant at the p=0.005 level.

m₂=1 (High grade transport equivalents)

		Estimate of Co-efficient	Standard Deviation	t Ratio	Level of Significance (2P)
n ₁	(hydro electricity)	0.28	0.07	4.11	<0.001
n ₂	(natural gas)	0.08	0.02	4.07	<0.001
n ₃	(oil)	0.08	0.01	5.64	<0.001
n ₄	(coal)	0.06	0.02	3.86	<0.001
n ₅	(wood)	0.01	0.02	0.69	<0.50>0.20
m ₁	(electrical output)	0.33	0.09	3.55	<0.01>0.001
m ₃	(industrial heat)	0.23	0.06	3.50	<0.01>0.001
m ₄	(water heating)	0.29	0.08	3.54	<0.01>0.001
m ₅	(space heating)	0.26	0.07	3.70	<0.01>0.001
m ₆	(cooking)	0.66	0.14	4.65	<0.001

F Ratio = 3.41 (df, V₁=10, V₂=21), significant at the p=0.01 level.

m₃=1 (Industrial heat equivalents)

		Estimate of Co-efficient	Standard Deviation	t Ratio	Level of Significance (2P)
n ₁	(hydro electricity)	0.83	0.17	4.89	<0.001
n ₂	(natural gas)	0.24	0.05	5.23	<0.001
n ₃	(oil)	0.21	0.04	4.88	<0.001
n ₄	(coal)	0.19	0.04	4.99	<0.001
n ₅	(wood)	0.05	0.04	1.16	<0.50>0.20
m ₁	(electrical output)	0.94	0.24	4.00	<0.001
m ₂	(high grade transport)	1.63	0.47	3.50	<0.01>0.001
m ₄	(water heating)	0.77	0.18	4.32	<0.001
m ₅	(space heating)	0.77	0.18	4.32	<0.001
m ₆	(cooking)	1.91	0.35	5.51	<0.001

F Ratio = 4.00 (df, V₁=10, V₂=21), significant at the p=0.005 level.

$m_4=1$ (Water heating equivalents)

		Estimate of Co-efficient	Standard Deviation	t Ratio	Level of Significance (2P)
n_1	(hydro electricity)	0.66	0.13	5.12	<0.001
n_2	(natural gas)	0.19	0.03	5.54	<0.001
n_3	(oil)	0.16	0.03	4.90	<0.001
n_4	(coal)	0.15	0.03	5.06	<0.001
n_5	(wood)	0.03	0.03	0.81	<0.50>0.20
m_1	(electrical output)	0.74	0.18	4.10	<0.001
m_2	(high grade transport)	1.27	0.36	3.54	<0.01>0.001
m_3	(industrial heat)	0.51	0.13	4.01	<0.001
m_5	(space heating)	0.59	0.14	4.26	<0.001
m_6	(cooking)	1.50	0.26	5.72	<0.001

F Ratio = 4.24 (df, $V_1=10$, $V_2=21$), significant at the $p=0.005$ level.

 $m_5=1$ (Space heating equivalents)

		Estimate of Co-efficient	Standard Deviation	t Ratio	Level of Significance (2P)
n_1	(hydro electricity)	0.76	0.15	5.22	<0.001
n_2	(natural gas)	0.22	0.04	5.67	<0.001
n_3	(oil)	0.19	0.04	5.27	<0.001
n_4	(coal)	0.17	0.03	5.42	<0.001
n_5	(wood)	0.07	0.03	1.75	<0.10>0.05
m_1	(electrical output)	0.86	0.20	4.25	<0.001
m_2	(high grade transport)	1.50	0.40	3.70	<0.01>0.001
m_3	(industrial heat)	0.61	0.14	4.32	<0.001
m_4	(water heating)	0.77	0.18	4.26	<0.001
m_6	(cooking)	1.75	0.29	6.01	<0.001

F Ratio = 5.66 (df, $V_1=10$, $V_2=21$), significant at the $p=0.001$ level.

 $m_6=1$ (Cooking equivalents)

		Estimate of Co-efficient	Standard Deviation	t Ratio	Level of Significance (2P)
n_1	(hydro electricity)	0.39	0.05	7.73	<0.001
n_2	(natural gas)	0.12	0.01	9.73	<0.001
n_3	(oil)	0.10	0.01	7.49	<0.001
n_4	(coal)	0.09	0.01	7.96	<0.001
n_5	(wood)	0.02	0.02	0.96	<0.50>0.20
m_1	(electrical output)	0.45	0.08	5.66	<0.001
m_2	(high grade transport)	0.77	0.17	4.65	<0.001
m_3	(industrial heat)	0.31	0.06	5.51	<0.001
m_4	(water heating)	0.40	0.07	5.72	<0.001
m_5	(space heating)	0.36	0.06	6.01	<0.001

F Ratio = 21.52 (df, $V_1=10$, $V_2=21$), significant at the $p=0.001$ level.

3.6.2 An Example of the Computer Printout for Model $n_1 = 1$

An example of the computer printout for the model $n_1 = 1$, is included below.

THE REGRESSION EQUATION IS

$$C21 = 0.224 C2 + 0.191 C3 + 0.173 C4 + 0.0300 C5 + 0.944 C7 + 1.58 C8 + 0.642 C10 + 0.846 C11 + 0.746 C12 + 1.88 C13$$

COLUMN	COEFFICIENT	ST. DEV. OF COEF	T-RATIO - COEF/S
NOCONSTANT			
C2	0.22407	0.03696	6.05
C3	0.19170	0.03603	5.31
C4	0.17382	0.03076	5.65
C5	0.02996	0.03875	0.77
C7	0.9442	0.1826	5.16
C8	1.5807	0.3843	4.11
C10	0.6423	0.1313	4.89
C11	0.8458	0.1452	5.82
C12	0.7463	0.1429	5.22
C13	1.8847	0.2437	7.73

S = 0.3187

ANALYSIS OF VARIANCE

DUE TO	DF	SS	MS=SS/DF
REGRESSION	10	7.7398	0.7740
RESIDUAL	21	2.1335	0.1016
TOTAL	31	9.8733	

FURTHER ANALYSIS OF VARIANCE

SS EXPLAINED BY EACH VARIABLE WHEN ENTERED IN THE ORDER GIVEN

DUE TO	DF	SS
REGRESSION	10	7.7398
C2	1	0.0325
C3	1	0.1155
C4	1	0.0117
C5	1	0.1023
C7	1	0.3082
C8	1	0.0851
C10	1	0.2203
C11	1	0.3747
C12	1	0.4136
C13	1	6.0758

ROW	C2	Y C21	PRED. Y VALUE	ST. DEV. PRED. Y	RESIDUAL	ST. RES
1	0.01	-0.0300	-0.1348	0.1817	0.1048	0.40
2	3.84	-0.0400	-0.0443	0.1811	0.0043	0.02
3	0.03	-0.0400	-0.1512	0.1813	0.1112	0.41
4	0.01	-1.1400	-0.9197	0.1811	-0.2203	-0.84
5	0.17	-0.3600	-0.3600	0.3187	0.0000	0.00
6	0.01	-0.0400	-0.3657	0.1179	0.3257	1.10
7	0.02	-0.0200	-0.3284	0.1196	0.3084	1.04
8	1.57	-0.0300	-0.2755	0.1192	0.2455	0.83
9	0.06	-0.1200	-0.4479	0.1555	0.3279	1.18
10	0.01	-1.1400	-0.6178	0.1296	-0.5272	-1.79
11	0.01	-0.0300	0.1671	0.1479	-0.1971	-0.70
12	3.84	-0.0400	0.2576	0.1494	-0.2976	-1.06
13	0.03	-0.0400	0.1507	0.1490	-0.1907	-0.68
14	0.01	-1.1400	-0.8214	0.1635	-0.3186	-1.16
15	0.01	-0.0300	-0.0364	0.1702	0.0064	0.02
16	3.84	-0.0400	0.0541	0.1644	-0.0941	-0.34
17	0.03	-0.0400	-0.0529	0.1698	0.0129	0.05
18	1.81	-0.0300	-0.4234	0.1480	0.3934	1.39
19	0.06	-0.0100	-0.3404	0.1273	0.3304	1.13
20	1.84	-0.0400	-0.3171	0.1272	0.2771	0.95
21	0.03	-0.0300	-0.3333	0.1278	0.3033	1.04
22	0.17	-0.3300	-0.2107	0.3022	-0.1193	-0.43
23	0.01	-0.0300	0.0631	0.1508	-0.0931	-0.33
24	3.84	-0.0400	0.1536	0.1502	-0.1936	-0.67
25	0.03	-0.0400	0.0467	0.1498	-0.0867	-0.31
26	0.01	-1.1400	-0.7218	0.1410	-0.4182	-1.46
27	0.02	-0.0700	-0.0286	0.2563	-0.0414	-0.22
28	0.07	-0.0900	-0.0610	0.2566	-0.0290	-0.15
29	8.81	-0.0900	0.1796	0.2306	-0.2696	-1.23
30	0.04	-2.0900	-1.8495	0.2397	-0.2405	-1.14
31	5.16	-0.1000	-0.6805	0.1697	0.5805	2.15

It should be noted on this print-out that:

$C1 = X_1, C2 = X_2, C3 = X_3, C4 = X_4, C5 = X_5, C7 = Y_1, C8 = Y_2,$
 $C10 = Y_3, C11 = Y_4, C12 = Y_5, C13 = Y_6.$

3.6.3 Interpretation of Results

3.6.3.1 Estimates of Coefficients and t Ratios

Irrespective of what variable was chosen as the equivalencing variable, the same pattern of estimates of the coefficients results. That is, hydro-electricity was found to be the highest quality energy input (highest estimates of coefficient), followed by natural gas, oil, coal and finally by wood. Similarly the cooking output was always found to have the highest estimates for its coefficient, indicating that it was the highest quality energy output. Cooking was then followed by the other outputs - high grade transport, electrical output, water heating, space heating and finally industrial heat.

It should be noted that these estimates of the co-efficients appear to make good technical and physical sense. That is, the recognised higher quality energy sources, such as electricity, have larger coefficients than the recognised lower quality energy sources. Similarly, the often referred to lower grade (quality) uses (outputs) are also predicted by the modelling process, with water heating, space heating and industrial heating having the lowest coefficients.

The t ratios measure the degree of accuracy of the estimates of the coefficients. For all models (except $n_5 = 1$ and $m_2 = 1$), the coefficients were all significant at the $2p = 0.001$ level (except n_5 and m_2). The exceptions are due to the error associated with the n_5 (wood) and m_2 (high grade transport) coefficients. However it should be noted that acceptable estimates for the m_2 coefficient were obtained for the models: $n_1 = 1, n_2 = 1, n_3 = 1, n_4 = 1$ and $m_6 = 1$.

This general high level of significance of the t Ratios, means

that very accurate estimates were obtained for the quality coefficients. This, in turn, means that the quality coefficients can be used with some degree of confidence in further analyses.

3.6.3.2 F Ratios

The F Ratios indicated that all the models, except $n_5 = 1$ (wood equivalents) model, were statistically highly significant. This indicates, at least in this case, that it is unimportant which variable is used as the equivalencing unit. Therefore, at least in this case, the modelling procedure of choosing an arbitrary variable as the equivalencing unit, is valid and flexible in its application.

The most significant model was:

$m_6 = 1$ (Cooking equivalents), F Ratio = 21.52, followed by the following models in decreasing order:

$n_2 = 1$ (gas equivalents), F Ratio = 11.30,

$n_3 = 1$ (oil equivalents), F Ratio = 8.96

$n_4 = 1$ (coal equivalents), F Ratio = 7.79

$n_1 = 1$ (hydroelectric equivalents), F Ratio = 7.62

$m_5 = 1$ (space heating equivalents), F Ratio = 5.66

$m_4 = 1$ (water heating equivalents), F Ratio = 4.24

$m_1 = 1$ (electrical output equivalents), F Ratio = 4.24

$m_3 = 1$ (industrial heat equivalents), F Ratio = 4.17

$m_2 = 1$ (high grade transport equivalents), F Ratio = 3.41

$n_5 = 1$ (wood equivalents), F Ratio = 0.43

The first six models ($m_6 = 1$, $n_2 = 1$, $n_3 = 1$, $n_4 = 1$, $n_1 = 1$, $m_5 = 1$) were significant at the $p = 0.001$ level, the next three models ($m_4 = 1$, $m_1 = 1$, $m_3 = 1$) were significant at the $p = 0.005$ level, and the last model ($n_5 = 1$) was not significant at the $p = 0.10$ level.

The wood equivalents model ($n_5 = 1$) was insignificant because of the error associated with the X_5 variable. This error is due to there being only two data points for the X_5 variable, and the inaccuracy associated with these two data points (as is indicated by the low t ratios of the n_5 coefficients obtained in other models). Similarly, the high grade transport model ($m_2 = 1$) was less significant than the other models, as there was only one data point for the Y_2 variable. However, in this case, there was not so much inaccuracy associated with the Y_2

variable (as indicated by the relatively high t ratios of the m_2 coefficients obtained in the other models). Therefore, this offsets the effect of there only being one data point for the Y_2 variable.

3.6.4 Model Selection and Improvement

The "best" model appears to be $m = 1$ (cooking equivalents), as it has the highest F ratio and it makes good physical and technical sense. However, as it is conceptually difficult to refer to cooking equivalents, it is recommended that the coefficients in this model be converted to hydro-electricity equivalents - this can be done by dividing each coefficient by 0.39269

	Cooking equivalents	Hydro-electric equivalents
n_1 (hydro-electricity)	0.39269	1.0000
n_2 (natural gas)	0.11600	0.2954
n_3 (oil)	0.09839	0.2506
n_4 (coal)	0.08844	0.2252
n_5 (wood)	0.01690	0.0430
m_1 (electrical output)	0.44779	1.1403
m_2 (high grade transport)	0.7691	1.9585
m_3 (industrial heat)	0.30886	0.7865
m_4 (water heating)	0.40431	1.0296
m_5 (space heating)	0.36029	0.9175
m_6 (cooking)	1.0000	2.5465

It is recommended that this be referred to the $n_1(m_6)$ model, indicating that the coefficients are expressed in terms of n_1 multiples (hydro-electricity equivalents), but the model was originally determined by equating m_6 to unity.

3.7 Post Regression Analysis of Pathways, for the M_6 Model

Conventionally, in regression analysis the examination of the residuals of the equations forms an important part of the modelling process (Draper and Smith, 1981). Similar, post regression examination and analysis of the pathways (equations), can also provide the analyst with extra information and insight to the nature of the model.

3.7.1 Residuals of Pathways (Relative Net Energy Yield)

Table 3.3 details the analysis of the residuals for the M_6 model. Conventionally, the data presented in Table 3.3 is plotted in various ways (referred to as residual plots). In fact, residual plots are routinely produced by regression programme packages. Often this can act as a diagnostic as to where "errors" are occurring in the model, and therefore can lead to a more accurate reformulation of the model. In this case, the residual plot (Fig. 3.1) is satisfactory as the residuals appear to be randomly distributed around the origin. Therefore, there is no need to modify the general equation used in the model.

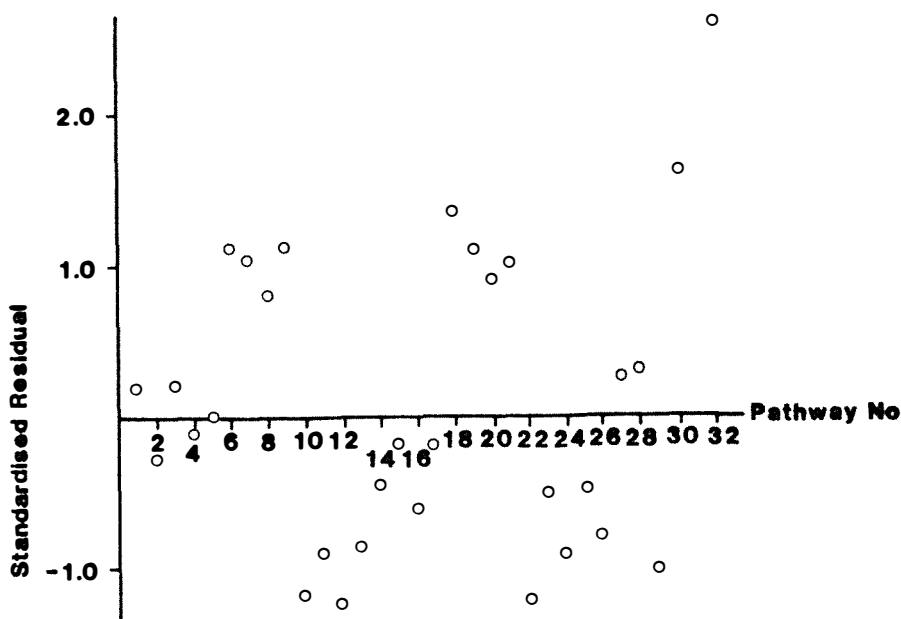


Fig. 3.1: Residual Plot: Standardised Residual vs Pathways for M_6 Model of New Zealand Economy, 1976.

It should be noted, that a higher positive residual, does not necessarily imply a higher relative efficiency (Q) of the pathway. This would only be the case if the inputs (IQ) were numerically the same sum for each pathway. The relationship between the relative efficiency (Q) and the residual (Q) or the relative net energy yield (Q) is given by the following equation:

$$\text{Relative efficiency } (Q) = \frac{\text{Residual } (Q) + IQ}{IQ} \quad (3.1)$$

It should also be noted that an analysis of the residuals similar to that detailed by Table 3.3, is routinely produced by most regression programme packages. Therefore, although as previously mentioned, the examination of the residuals is not so important in this application;

Table 3.3: Analysis of Residuals, for Cooking Equivalents (M_6) for the New Zealand Economy, 1976

Pathway	Actual $-X_1$ ($-Y_6$)	Predicted $-X_1$ ($-Y_6$)	Standard Deviation of $-Y_6$	Residual {($-Y_6$)-($-Y_6$)}	Standardised Residual
1. Coal → Elect. → Electrical Output	0.0000	-0.0217	0.0835	0.0217	0.18
2. Gas → Elect. → Electrical Output	0.0000	0.0336	0.0823	-0.0336	-0.28
3. Oil → Elect. → Electrical Output	0.0000	-0.0243	0.0833	0.0243	0.20
4. Hydro → Elect. → Electrical Output	0.0000	0.0124	0.0855	-0.0124	-0.11
5. Oil → High Grade Transport	0.0000	0.0000	0.1455	0.0000	0.00
6. Coal → Industrial Heat	0.0000	-0.1516	0.0543	0.1516	1.12
7. Oil → Industrial Heat	0.0000	-0.1396	0.0547	0.1396	1.04
8. Gas → Industrial Heat	0.0000	-0.1073	0.0549	0.1073	0.80
9. Wood → Industrial Heat	0.0000	-0.1572	0.0702	0.1572	1.23
10. Hydro → Elect. → Industrial Heat	0.0000	0.1514	0.0715	-0.1514	-1.19
11. Coal → Elect. → Industrial Heat	0.0000	0.1172	0.0665	-0.1172	-0.91
12. Gas → Elect. → Industrial Heat	0.0000	0.1726	0.0641	-0.1726	-1.32
13. Oil → Elect. → Industrial Heat	0.0000	0.1146	0.0660	-0.1146	-0.88
14. Hydro → Elect. → Water Heating	0.0000	0.0559	0.0802	-0.0559	-0.46
15. Coal → Elect. → Water Heating	0.0000	0.0217	0.0776	-0.0217	-0.18
16. Gas → Elect. → Water Heating	0.0000	0.0771	0.0737	-0.0771	-0.61
17. Oil → Elect. → Water Heating	0.0000	0.0191	0.0774	-0.191	-0.16
18. Gas → Water Heating	0.0000	-0.1739	0.0682	0.1739	1.35
19. Coal → Space Heating	0.0000	-0.1485	0.0584	0.1485	1.11
20. Gas → Space Heating	0.0000	-0.1225	0.0584	0.1225	0.92
21. Oil → Space Heating	0.0000	-0.1362	0.0586	0.1362	1.02
22. Wood → Space Heating	0.0000	0.0572	0.1379	-0.0572	-1.23
23. Coal → Elect. → Space Heating	0.0000	0.0658	0.0679	-0.0658	-0.51
24. Gas → Elect. → Space Heating	0.0000	0.1211	0.0661	-0.1211	-0.93
25. Oil → Elect. → Space Heating	0.0000	0.0632	0.0676	-0.0633	-0.49
26. Hydro → Elect. → Space Heating	0.0000	0.0999	0.0735	-0.0999	-0.80
27. Coal → Elect. → Cooking	1.0000	0.9775	0.1169	0.0225	0.26
28. Oil → Elect. → Cooking	1.0000	0.9731	0.1170	-0.0269	0.31
29. Gas → Elect. → Cooking	1.0000	1.1036	0.1062	-0.1036	-1.04
30. Hydro → Cooking	1.0000	0.8388	0.1063	0.1612	1.62
31. Gas → Cooking	1.0000	0.6624	0.0626	0.3376	2.57

Table 3.4: Numerical Calculations for Pathways of the $n_1(m_c)$ Model of the New Zealand Economy, 1976

Pathways	Outputs (OQ)	Inputs (IQ)	Outputs (OH)	Inputs (IH)	Relative Efficiency (Q) (OQ/IQ)	Efficiency (H) (OH/IH)	Quality of Inputs (IQ/IH)	Quality of Outputs (OQ/OH)	Relative Net Energy Yield (OQ-IQ)
1. Coal → Elect. → Electrical Output	1.1403	1.0849	1.0000	4.7000	1.0510	0.2128	0.2328	1.1403	0.0554
2. Gas → Elect. → Electrical Output	1.1403	1.2260	1.0000	4.0900	0.9301	0.2445	0.3530	1.1403	-0.0857
3. Oil → Elect. → Electrical Output	1.1403	1.0785	1.0000	4.2100	1.0573	0.2375	0.2568	1.1403	0.0618
4. Hydro → Elect. → Electrical Output	1.1403	1.1720	1.0000	1.2700	1.0278	0.7874	0.9268	1.1403	-0.0317
5. Oil → Elect. → Electrical Output	1.9585	1.9587	1.0000	6.7700	0.9999	0.1477	0.2910	1.9585	-0.0002
6. Coal → Industrial Heat	0.7865	0.4005	1.0000	1.6300	1.9636	0.6135	0.2478	0.7865	0.3860
7. Oil → Industrial Heat	0.7865	0.4311	1.0000	1.6700	1.8245	0.5988	0.2591	0.7865	0.3554
8. Gas → Industrial Heat	0.7865	0.5133	1.0000	1.6800	1.5322	0.5952	0.3586	0.7865	0.2732
9. Wood → Industrial Heat	0.7865	0.3860	1.0000	3.6900	2.0374	0.2710	0.1104	0.7865	0.4005
10. Hydro → Elect. → Industrial Heat	0.7865	1.1720	1.0000	1.2700	0.6712	0.7874	0.9236	0.7865	-0.3855
11. Coal → Elect. → Industrial Heat	0.7865	1.0849	1.0000	4.7000	0.7249	0.2128	0.2328	0.7865	-0.2984
12. Gas → Elect. → Industrial Heat	0.7865	1.2260	1.0000	4.0900	0.6415	0.2445	0.3530	0.7865	-0.4395
13. Oil → Elect. → Industrial Heat	0.7865	1.0785	1.0000	4.2100	0.7293	0.2375	0.2568	0.7865	-0.2920
14. Hydro → Elect. → Water Heating	1.0296	1.1720	1.0000	1.2700	0.8785	0.7874	0.9234	1.0296	-0.1424
15. Coal → Elect. → Water Heating	1.0296	1.0849	1.0000	4.7000	0.9490	0.2128	0.2328	1.0296	-0.1964
16. Gas → Elect. → Water Heating	1.0296	1.2266	1.0000	4.0900	0.8398	0.2445	0.3530	1.0296	-0.1964
17. Oil → Elect. → Water Heating	1.0296	1.0785	1.0000	4.2100	0.9547	0.2375	0.2568	1.0296	-0.0489
18. Gas → Water Heating	1.0296	0.5867	1.0000	1.9300	1.7549	0.5181	0.3572	1.0296	0.4429
19. Coal → Space Heating	0.9175	0.5392	1.0000	2.3300	1.7015	0.4292	0.2346	1.0296	0.3783
20. Gas → Space Heating	0.9175	0.6056	1.0000	1.9700	1.5151	0.5076	0.3604	0.9175	0.3119
21. Oil → Space Heating	0.9175	0.5708	1.0000	2.2000	1.6087	0.4545	0.2605	0.9175	0.3469
22. Wood → Space Heating	0.9175	1.0629	1.0000	10.1500	0.8632	0.0985	0.1105	0.9175	-0.1454
23. Coal → Elect. → Space Heating	0.9175	1.0849	1.0000	4.7000	0.8457	0.2127	0.2328	0.9175	-0.1674
24. Gas → Elect. → Space Heating	0.9175	1.2260	1.0000	4.0900	0.7484	0.2445	0.3530	0.9175	-0.3085
25. Oil → Elect. → Space Heating	0.9175	1.0785	1.0000	4.2100	0.5141	0.2375	0.2568	0.9175	-0.1610
26. Hydro → Elect. → Space Heating	0.9175	1.1720	1.0000	1.2700	0.7828	0.7874	0.9234	0.9175	-0.2545
27. Coal → Elect. → Cooking	2.5465	2.4891	1.0000	10.7800	1.0230	0.0928	0.2329	2.5465	0.0574
28. Oil → Elect. → Cooking	2.5465	2.4784	1.0000	9.6800	1.0275	0.1033	0.2567	2.5465	0.0681
29. Gas → Elect. → Cooking	2.5465	2.8105	1.0000	9.3800	0.9061	0.1066	0.3529	2.5465	-0.264
30. Hydro → Cooking	2.5465	2.1361	1.0000	2.2700	1.1921	0.4405	0.9421	2.5465	0.4104
31. Gas → Cooking	2.5465	1.6869	1.0000	5.5300	1.509	0.1808	0.3581	2.5465	0.8596

it can provide an easily accessible starting point for a preliminary analysis of the relative efficiencies (Q) of each equation (pathway).

3.7.2 Relative Efficiency of Pathways

The relative efficiency (Q) of each pathway is the Outputs (Q) divided by the Inputs (Q). It can also be calculated by using equation 3.1.

For a perfectly fitted model, all equations should have a relative efficiency (Q) equal to unity. Therefore, the model (m_6) indicates that pathways (2, 4, 10, 11, 12, 13, 14, 15, 16, 18, 22, 23, 24, 25, 26, 29) are relatively inefficient (Q), as they have efficiencies (Q) less than 1 (refer to table 3.4. Whereas, the model (m_6) indicates that the pathways (1, 3, 5, 6, 7, 8, 9, 17, 19, 20, 21, 27, 28, 30, 31) are relatively efficient (Q), as they have efficiencies (Q) greater than 1.

The model (m_6) predicts that the pathways (6, 7, 8, 9, 18, 19, 20, 21, 31) are inefficient (Q) compared with the pathways (11, 12, 13, 15, 16, 17, 23, 24, 25, 29), because the former pathways convert primary fuels to electricity which is subsequently used as a heat source. Whereas, the latter pathways directly use the primary fuels, which has been widely cited in the literature as a thermodynamically more efficient use of fuels (Peet et al., 1978). Similarly, the model (m_6) predicts that the pathways (10, 14, 26) are comparatively inefficient because they use hydro-electricity as a low grade heat source. Again it has been widely argued that it is thermodynamically more efficient or appropriate to use lower quality (grade) energy sources (fuels) for the purposes of providing low quality (grade) heat (Lovins, 1977), or alternatively use heat pump technology powered by electricity to provide low grade heat (Odum and Odum, 1979).

The model (m_6) also predicts that the Gas $\rightarrow$ Electricity $\rightarrow$ Electrical Output pathway, in relative terms, is slightly inefficient (Q). This is because gas has a similar enthalpic conversion efficiency for Gas to Consumer Electricity (30%), as Oil to Consumer Electricity (32%), and Coal to Consumer Electricity (26%). In relative terms, this is "inefficient" as according to the energy quality coefficients

(IQ/IH) predicted by the model, these differences should be greater. Put simply, gas has more efficient alternative uses than being the main primary energy source for producing electrical output. A similar reason exists why the pathway wood $\rightarrow$ space heating is relatively inefficient (Q). The wood $\rightarrow$ industrial heat, which is the only other pathway with wood in the model, is more efficient (Q) in relative terms than the wood $\rightarrow$ space heating pathway.

3.8 Central Hypothesis: Relationship Between Quality of Inputs, Quality of Outputs and Enthalpic Efficiency

These plots (Figs 3.2-3.7) demonstrate the relationship between three important variables, implicit in the Central Hypothesis:

- (1) Quality of Inputs (IQ/IH), on the Y axis.
- (2) Enthalpic Efficiency (OH/IH), on the X axis.
- (3) Quality of Outputs (OQ/OH), gradient.

Firstly the plots demonstrate that there is a statistical linear relationship between the quality of inputs (IQ/IH) and the enthalpic efficiency (OH/IH) of the pathway. The higher the quality of inputs (IQ/IH), the higher the enthalpic efficiency (OH/IH) of the pathway. Statistically, this relationship holds true (i.e. is statistically significant) irrespective of the actual inputs and outputs of the pathway.

Secondly, the plots demonstrate that in a statistical sense each output has a fixed energy requirement (in quality equivalent terms). If this relationship was perfect, all points would fall on the plotted lines. Again, this relationship is significant irrespective of the actual mix of inputs and the output.

3.9 Discussion

3.9.1 Adequateness of the Models and Modelling Procedure

Generally, adequate models of energy use in the N.Z. Economy 1976 were generated by the modelling procedure, the exception being where wood (n_5) was used as the equivalencing unit. This was because there was the greatest error in the wood (X_5) variable. Furthermore, the

Electrical Output, $w_1 = 1.20n_1$

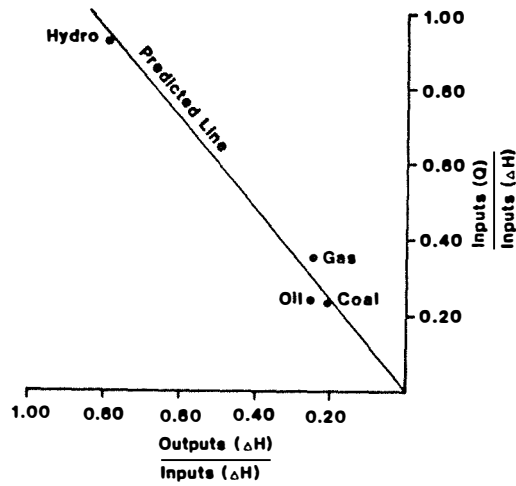


Fig. 3.2 Quality of Inputs vs Enthalpic Efficiency for Pathways 1-4, n_1 Model of N.Z. Economy, 1976.

High Grade Transport $w_2 = 1.97n_1$

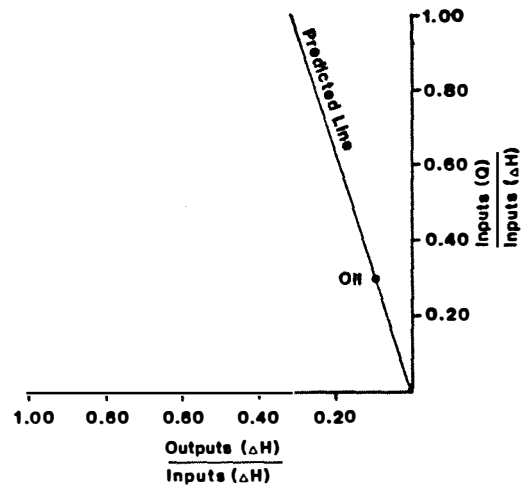


Fig. 3.3 Quality of Inputs vs Enthalpic Efficiency for Pathways n_1 Model of N.Z. Economy 1976.

Industrial Heat $w_3 = 0.83n_1$

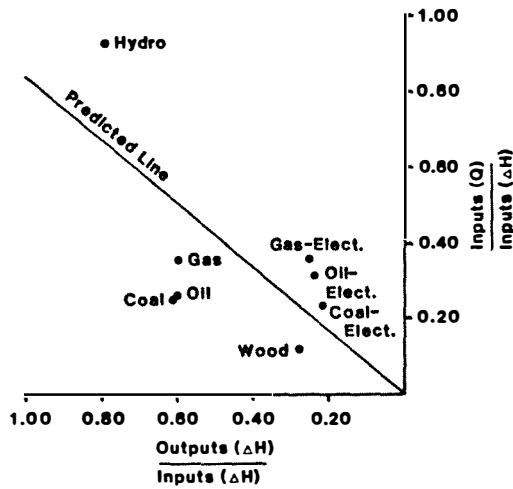


Fig. 3.4 Quality of Inputs vs Enthalpic Efficiency of Pathways 6-13, n_1 Model of N.Z. Economy, 1976.

Water Heating $w_4 = 1.01n_1$

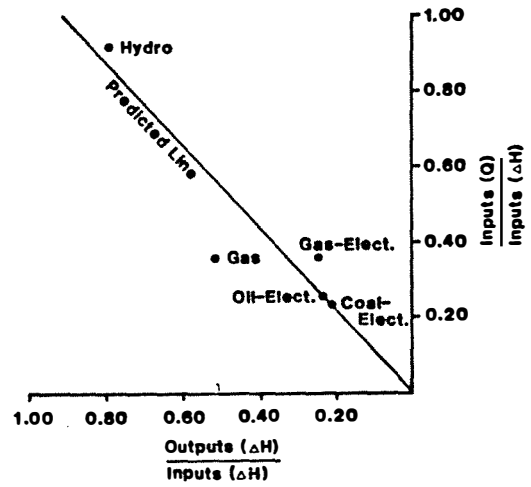


Fig. 3.5 Quality of Inputs vs Enthalpic Efficiency of Pathways 14-17, n_1 Model of N.Z. Economy, 1976.

Space Heating, $\eta_s = 0.97\eta_1$

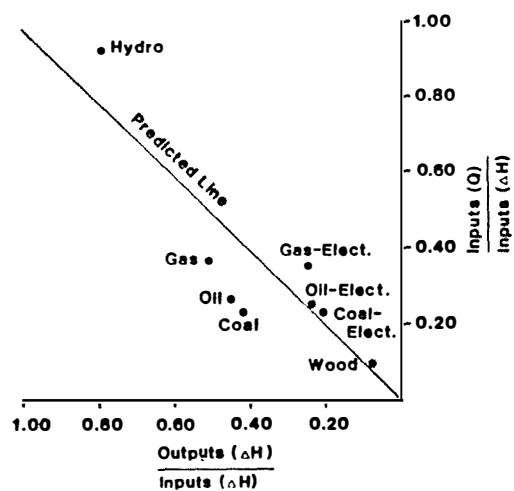


Fig. 3.6 Quality of Inputs vs Enthalpic Efficiency for Pathways 18-26, η_1 model of N.Z. Economy, 1976.

Cooking $\eta_c = 2.48\eta_1$

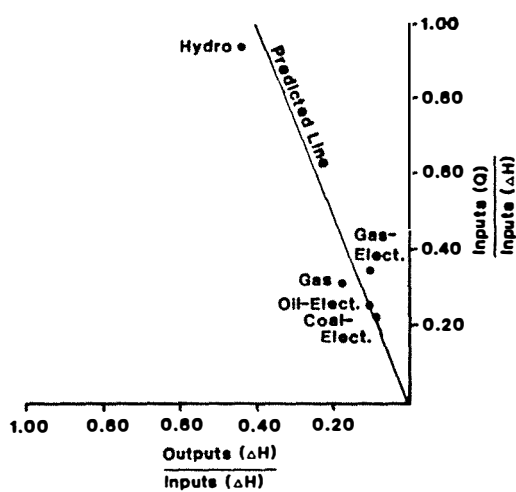


Fig. 3.7 Quality of Inputs vs Enthalpic Efficiency for Pathways 27-31, η_1 Model of N.Z. Economy, 1976.

models made good technical and physical sense and the deviations from the model could be explained.

The modelling procedure was found to be flexible - that is it was found not to be critical what variable was used as the equivalencing unit. The results, in all cases were essentially the same - that is the highest quality energy source was always hydro-electricity followed by gas, oil, coal and finally wood. Similarly, the highest quality energy use was always found to be cooking, followed by high grade transport, water heating, space heating and finally industrial heat.

One of the major limitations of these models is that they use the actual energy efficiencies of processes as they were in 1976, and not the potential energy efficiencies that could be achieved using known technology. This limitation is discussed in the next section.

3.9.2 Energy Efficiency and Technological Development

3.9.2.1 The Evidence

The energy efficiency of any process increases with technological development, up until a thermodynamic limit is reached. The evidence for this trend is presented in Figs 3.8 - 3.9 and a schematic model for this trend is proposed by Fig 3.10.

3.9.2.2 Interpretation

A limitation and possible problem with data used in these models, is that they use the actual energy efficiencies of the N.Z. Economy 1976 - for a particular pathway, this efficiency may only be a point (X) on Fig 3.10. Whereas, the potential energy efficiency is at the asymptote (Z), and what is possible in terms of current technology may be at a point (Y). The analyst has to choose, what is the appropriate set of energy efficiencies to use in the modelling process:

- (1) energy efficiencies reflecting actual present use.
- (2) energy efficiencies possible under current technology.
- (3) energy efficiencies at the thermodynamic limit.

Essentially, this choice depends on the time horizon of the analysis.

For short term analysis (approximately 0-5 years), actual energy

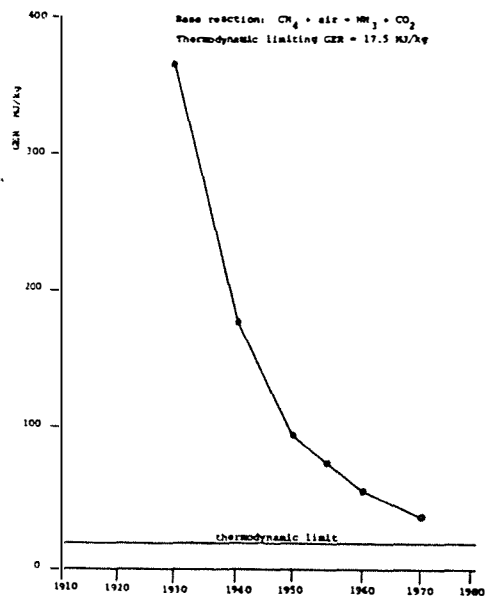


Fig. 3.8 Energy Requirements for the Production of Ammonia.
Source: IFIAS (1975).

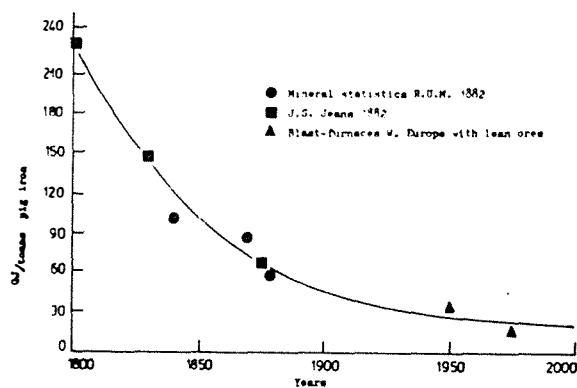


Fig. 3.9 Process Energy Requirement for the Production of Pig Iron.
Source: Slessor (1978).

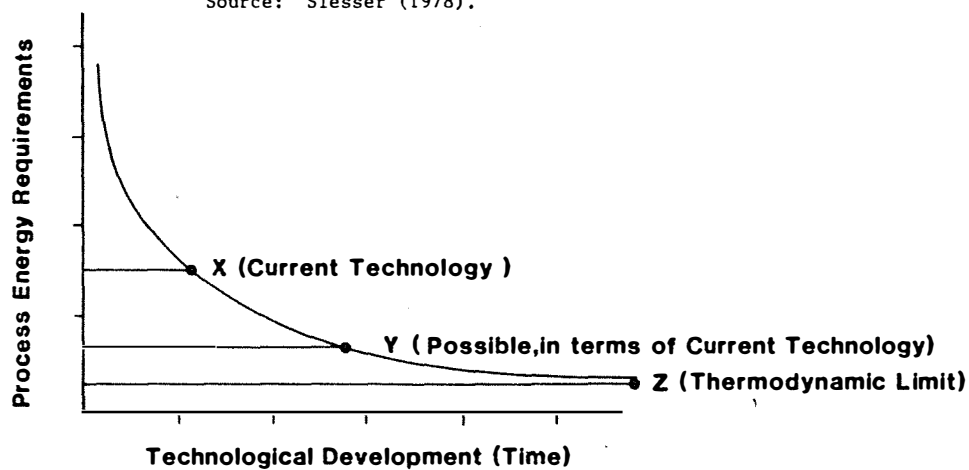


Fig. 3.10 Process Energy Requirements vs Technological Development Through Time: A Generalised Model.

efficiencies are probably appropriate and adequate. For medium term analysis (approximately 5-20 years) the second set of energy efficiencies are more appropriate and for longer term analysis (>20 years), the third set of energy efficiencies are probably most appropriate. Since Energy Analysis is nearly always concerned with longer term analysis, it is suggested that the second and third set of energy efficiencies should most frequently be used.

3.9.3 Conclusion

The models were generally found to be statistically adequate, and made good technical and physical sense. Furthermore, the modelling procedure was found to be flexible. That is, it was not found to be critical what variable was used as the equivalencing unit. However, it was recognised that a major limitation with this set of models was that they used actual energy efficiencies of processes as they were in 1976. Therefore the quality coefficients generated by the models, assumed actual rather than potential energy efficiencies. For longer term analysis it was considered more appropriate to use pathways that reflected longer run energy efficiencies.

4 AN APPLICATION TO AN ENERGY EFFICIENT ECONOMY.

4.1 Introduction

These sets of models were developed so that a set of longer-run energy quality coefficients could be determined for energy sources and uses. Generally, the most energy efficient technology available was assumed, with some allowances made for operational inefficiencies which inevitably occur in any real situation. This presented some difficulties in identifying the most energy efficient technology currently available. Furthermore, the most energy efficient technologies could not always be implied in the indirect energy requirements, as the only data available was that of Carter, Peet and Baines (1982) Input-Output Analysis of the 1971-72 New Zealand Economy.

4.2 Data Sources

Data were obtained from a wide range of literature sources detailed in Appendix C. As mentioned above, Carter, Peet and Baines (1981) Input-Output Analysis of energy use in the 1971-72 New Zealand Economy was used to estimate most of the indirect energy requirements.

4.3 Inputs and Outputs Considered

The primary energy inputs considered in this example are: (1) Hydro-electricity (2) Natural Gas (3) Oil (4) Coal (5) Wood; and the effective energy outputs considered are: (1) Electrical Output (2) High Grade Transport (3) Medium Grade Transport (4) Industrial Heat (5) Water Heating (6) Space Heating (7) Cooking. These inputs and outputs are defined in section 3.2, except medium grade transport. Medium grade transport refers to the use of energy by road vehicles which have a shorter range and less power output than those in the above category. In the New Zealand situation, this specifically refers to the use of Compressed Natural Gas in gasoline designed motor vehicles. With the discovery of the Maui natural gas field a small yet significant proportion of vehicles in New Zealand have been converted to operate on Compressed Natural Gas. There are obviously more actual and potential sources and uses of energy than these inputs and outputs. However,

these are considered to be the main classes and if necessary further inputs and outputs can be added (refer to the methodology section).

4.4 Pathways Considered

Theoretically, by linking each primary energy input (5) to each effective energy output (7), by one pathway each, 35 (5 x 7) pathways can be considered. By considering all these pathways this should facilitate the solving of the regression equations, by increasing the variability in the data set.

For some of these links (35) there were several possible pathways that could be considered. For example, high grade transport could be derived from coal in the following ways (to name just a few):

- (a) Coal -> Methanol -> Gasoline
- (b) Coal -----> Methanol
- (c) Coal -----> Crude Oil -----> Gasoline, Diesel

In a situation like this, the criterion used to narrow the alternatives to one option was the most energy efficient (in enthalpy terms) pathway possible in terms of current technology. Therefore, in the above example option (b) was chosen.

Some primary energy inputs can be converted more efficiently (in enthalpy terms) to high grade transport energy rather than medium grade transport energy. For example, crude oil can more efficiently be converted to gasoline and diesel (high grade transport energy) rather than compressed methane (medium grade transport). In a situation like this, the medium grade options were eliminated from consideration, because even in enthalpy terms they represented an inefficient use of the energy resource.

Therefore, by applying these selection criteria a list of 33 energy supply use pathways were considered for analysis:

- (1) Coal -> Electricity Generation -> Transmission -> Electrical Output
- (2) Oil -> Electricity Generation -> Transmission -> Electrical Output

- (3) Gas -> Electricity Generation -> Transmission -> Electrical Output
- (4) Wood -> Electricity Generation -> Transmission -> Electrical Output
- (5) Hydro-electricity -> Electricity Generation -> Transmission ->
Electrical Output
- (6) Coal -> Methanol -> High Grade Transport
- (7) Oil -> Gasoline, Diesel -> High Grade Transport
- (8) Gas -> Methanol -> High Grade Transport
- (9) Wood -> Methanol -> High Grade Transport
- (10) Hydro-electricity -> Hydrogen -> High Grade Transport
- (11) Gas -> Compressed Natural Gas -> Medium Grade Transport
- (12) Wood -> Methane -> Medium Grade Transport
- (13) Coal -> Methane -> Medium Grade Transport
- (14) Coal -> Industrial Heat
- (15) Oil -> Industrial Heat
- (16) Gas -> Industrial Heat
- (17) Wood -> Industrial Heat
- (18) Hydro-electricity -> Electricity Generation -> Transmission ->
Industrial Heat
- (19) Coal -> Water Heating
- (20) Oil -> Water Heating
- (21) Gas -> Water Heating
- (22) Wood -> Water Heating
- (23) Hydro-electricity -> Electricity Generation -> Transmission ->
Water Heating
- (24) Coal -> Space Heating
- (25) Oil -> Space Heating
- (26) Gas -> Space Heating
- (27) Wood -> Space Heating
- (28) Hydro-electricity -> Electricity Generation -> Transmission ->
Space Heating
- (29) Coal -> Cooking
- (30) Oil -> Cooking
- (31) Gas -> Cooking
- (32) Wood -> Cooking
- (33) Hydro-electricity -> Electricity Generation -> Transmission ->
Cooking

The technologies used in these pathways and the assumed operational

efficiencies of supply, distribution and end-use stages are detailed by table 4.1.

The model constructed in this example only had one effective output per pathway, although having several primary energy inputs per pathway. A more complex model could have several outputs per pathway, as well as several energy inputs per pathway. For example, each pathway could be considered to have one main energy output and various waste heat outputs. In this way, coefficients for different grades of waste heat, that could be converted to effective outputs by the use of the appropriate technology, could be estimated by using this technique. Also, in situations where there is a partitioning problem, several outputs could be considered for one pathway. However, it could be more difficult to obtain solutions to the regression when multiple outputs are considered. Generally, this will mean there will be less variability in the data set, and therefore more pathways will need to be considered to obtain significant results. Also, it is expected that in some instances by considering multiple outputs this could lead to the problem of correlation between variables.

4.5 Data Set and Regression Equations

The G.E.R. of each of the above pathways was calculated, using data obtained from various literature sources (refer to Appendix C).

The data were expressed in terms of one unit of output (ΔH) per equation and the equations were summarised in matrix format (refer to table 4.2), for computer analysis.

The data were then analysed by using the "Minitab" statistical programme package on Massey University's Prime 750 computer. The same set of commands as used in the previous example were used (refer to section 3.5 for details).

4.6 Statistical Analysis of Solutions to the Regression Equations

A series of models was generated, by in turn using each variable, as the equivalencing unit - that is:

TABLE 4.1 An Energy Efficient New Zealand Economy : Assumed Technologies and Operational Efficiencies

Pathway	Supply Technology	Efficiency ^a (%)	Distribution Technology	Efficiency ^a (%)	End-Use Technology	Efficiency ^a (%)
1 Coal → Electrical Output	Conventional Power Station	26	Current Transmission System	90	Current electrical and electronic technology	b
2 Oil → Electrical Output	Conventional Power Station	32	Current Transmission System	90	Current electrical and electronic technology	b
3 Gas → Electrical Output	Conventional Power Station	30	Current Transmission System	90	Current electrical and electronic technology	b
4 Wood → Electrical Output	Power Station fired by Wood	12	Current Transmission System	90	Current electrical and electronic technology	b
5 Hydro → Electrical Output	Conventional hydro-electricity generation (Dam ; Water Turbine)	b	Current Transmission System	90	Current electrical and electronic technology	b
6 Coal → High Grade Trans.	Gasification, Catalytic Conversion to Methanol	47	Current Distribution System for liquid fuels	100	Internal Combustion Engine	30
7 Oil → High Grade Trans.	Oil Refinery	92	Current Distribution System for liquid fuels	100	Internal Combustion Engine	25
8 Gas → High Grade Trans.	Catalytic conversion to methanol	59	Current Distribution System for liquid fuel	100	Internal Combustion Engine	30
9 Wood → High Grade Trans.	Gasification, Catalytic conversion to Methanol	43	Current Distribution System for liquid fuels	100	Internal Combustion Engine	30
10 Hydro → High Grade Trans.	Conventional hydro-electricity generating (Dam, Water Turbine), Current Electricity Trans. System, Electrolytic Equipment	72	Included in the Supply Column	-	Internal Combustion Engine with Storage Battery	37
11. Gas → Low Grade Trans.	Current Gas Supply Technology	b	Pipeline	90	Internal Combustion Engine	27
12. Wood → Low Grade Trans.	Gasification	43	Pipeline	90	Internal Combustion Engine	27
13. Coal → Low Grade Trans.	Gasification	47	Pipeline	90	Internal Combustion Engine	27
14. Coal → Industrial Heat	Current Coal Mining Technology	b	Current Distribution System	100	Industrial Boilers and Furnaces	70
15. Oil → Industrial Heat	Oil Refinery	90	Current Distribution System for liquid fuels	100	Industrial Boilers and Furnaces	75
16. Gas → Industrial Heat	Current Gas Supply Technology	b	Pipeline	90	Industrial Boilers and Furnaces	75
17. Wood → Industrial Heat	Current silvicultural technology and management	b	Current Distribution System	100	Industrial Boilers and Furnaces	33
18. Hydro → Industrial Heat	Conventional Hydro-generation (Dam, Water Turbine)	b	Current Transmission System	90	Heat Pumps (30%), resistance heaters (70%)	160
19. Coal → Water Heating	Current Coal Mining Technology	b	Current Distribution System	100	Enclosed Burner, Water Heating Cylinder	50
20. Oil → Water Heating	Oil Refinery	90	Current Distribution System for liquid fuels	100	Enclosed Burner, Water Heating Cylinder	65
21. Gas → Water Heating	Current Gas Supply Technology	b	Pipeline	90	Gas Water Heating Cylinder	65
22. Wood → Water Heating	Current silvicultural technology and management	b	Current Distribution System	100	Enclosed Burner, Water Heating Cylinder	33
23. Hydro → Water Heating	Conventional Hydro-generation (Dam, Water Turbine)	b	Current Transmission System	90	Heat Pumps	200
24. Coal → Space Heating	Current Coal Mining Technology	b	Current Distribution System	100	Enclosed Burner	49
25. Oil → Space Heating	Oil Refinery	90	Current Distribution System for liquid fuels	100	Enclosed Burner	57
26. Gas → Space Heating	Current Gas Supply Technology	b	Pipeline	90	Enclosed Burner	64
27. Wood → Space Heating	Current silvicultural technology and management	b	Current Distribution System	100	Enclosed Burner	35
28. Hydro → Space Heating	Conventional Hydro-generation (Dam, Water Turbine)	b	Current Transmission System	90	Heat Pumps	250
29. Coal → Cooking	Current Coal Mining Technology	b	Current Distribution System	100	Conventional Coal Fired Range	20
30. Oil → Cooking	Oil Refinery	90	Current Distribution System for liquid fuels	100	Conventional Oil Fired Range	20
31. Gas → Cooking	Current Gas Supply Technology	b	Pipeline	90	Conventional Gas Fired Range	30
32. Wood → Cooking	Current silvicultural technology and management	b	Conventional Distribution System	100	Conventional Wood Fired Range	13
33. Hydro → Cooking	Conventional Hydro-electricity Generation (Dam, Water Turbine)	b	Current Transmission System	90	Conventional Electric Range	44

Notes :

- a. Enthalpic (ΔH) Efficiency of direct energy flows, Enthalpic (ΔH) efficiencies are also implied in indirect energy flows.
b. Either input or output is outside study boundary. Therefore, no enthalpic (ΔH) efficiency can be calculated.

TABLE 4.2 Data Set : Gross Energy Requirements of Energy Supply-Use Pathways in an Energy Efficient New Zealand Economy

Pathway	Primary Energy Inputs (MJ) ^a					Effective Energy Outputs (MJ) ^{a,b}						
	X ₁ Hydro	X ₂ Gas	X ₃ Oil	X ₄ Coal	X ₅ Wood	Y ₁ Electrical Output	Y ₂ High Grade Transport	Y ₃ Medium Transport	Y ₄ Industrial Heat	Y ₅ Water Heating	Y ₆ Space Heating	Y ₇ Cooking
1 Coal → Electrical Output	0.03	0.01	0.10	4.56	0.00	1	0	0	0	0	0	0
2 Oil → Electrical Output	0.04	0.03	3.83	0.31	0.00	1	0	0	0	0	0	0
3 Gas → Electrical Output	0.04	3.84	0.17	0.04	0.00	1	0	0	0	0	0	0
4 Wood → Electrical Output	0.03	0.01	0.52	0.02	9.39	1	0	0	0	0	0	0
5 Hydro → Electrical Output	1.14	0.01	0.08	0.04	0.00	1	0	0	0	0	0	0
6 Coal → High Grade Transport	1.86	0.13	1.05	8.00	0.00	0	1	0	0	0	0	0
7 Oil → High Grade Transport	0.36	0.17	5.64	0.60	0.00	0	1	0	0	0	0	0
8 Gas → High Grade Transport	0.36	6.09	0.89	0.20	0.00	0	1	0	0	0	0	0
9 Wood → High Grade Transport	1.99	0.13	1.30	0.59	7.75	0	1	0	0	0	0	0
10 Hydro → High Grade Transport	3.98	0.14	0.93	0.21	0.00	0	1	0	0	0	0	0
11 Gas → Med. Grade Transport	0.15	4.57	0.84	0.33	0.00	0	0	1	0	0	0	0
12 Wood → Med. Grade Transport	1.06	0.25	1.35	0.42	9.40	0	0	1	0	0	0	0
13 Coal → Med. Grade Transport	0.93	0.23	1.03	9.42	0.00	0	0	1	0	0	0	0
14 Coal → Industrial Heat	0.04	0.01	0.07	1.51	0.00	0	0	0	1	0	0	0
15 Oil → Industrial Heat	0.02	0.02	1.50	0.13	0.00	0	0	0	1	0	0	0
16 Gas → Industrial Heat	0.03	1.57	0.06	0.02	0.00	0	0	0	1	0	0	0
17 Wood → Industrial Heat	0.03	0.03	0.18	0.03	3.03	0	0	0	1	0	0	0
18 Hydro → Industrial Heat	0.57	0.01	0.03	0.01	0.00	0	0	0	1	0	0	0
19 Coal → Water Heating	0.02	0.00	0.08	2.10	0.00	0	0	0	0	1	0	0
20 Oil → Water Heating	0.02	0.02	1.73	0.15	0.00	0	0	0	0	1	0	0
21 Gas → Water Heating	0.03	1.81	0.07	0.02	0.00	0	0	0	0	1	0	0
22 Wood → Water Heating	0.03	0.03	0.18	0.03	3.03	0	0	0	0	1	0	0
23 Hydro → Water Heating	0.58	0.01	0.06	0.02	0.00	0	0	0	0	1	0	0
24 Coal → Space Heating	0.01	0.06	0.10	2.16	0.00	0	0	0	0	0	1	0
25 Oil → Space Heating	0.03	0.03	1.97	0.17	0.00	0	0	0	0	0	1	0
26 Gas → Space Heating	0.04	1.84	0.07	0.02	0.00	0	0	0	0	0	1	0
27 Wood → Space Heating	0.03	0.03	0.17	0.03	2.86	0	0	0	0	0	1	0
28 Hydro → Space Heating	0.46	0.01	0.05	0.01	0.00	0	0	0	0	0	1	0
29 Coal → Cooking	0.14	0.04	0.25	5.28	0.00	0	0	0	0	0	0	1
30 Oil → Cooking	0.07	0.07	5.62	0.48	0.00	0	0	0	0	0	0	1
31 Gas → Cooking	0.10	5.16	0.07	0.20	0.00	0	0	0	0	0	0	1
32 Wood → Cooking	0.08	0.08	0.46	0.08	7.69	0	0	0	0	0	0	1
33 Hydro → Cooking	2.09	0.04	0.11	0.03	0.00	0	0	0	0	0	0	1

Notes : a. expressed in enthalpy (ΔH) terms; 1 kWhr = 3.6 MJ

b. normalised so that all effective outputs equal unity

$n_1 = 1$, hydro-electric equivalents

$n_2 = 1$, natural gas equivalents

$n_3 = 1$, oil equivalents

$n_4 = 1$, coal equivalents

$n_5 = 1$, wood equivalents

$m_1 = 1$, electrical output equivalents

$m_2 = 1$, high grade transport equivalents

$m_3 = 1$, medium grade transport equivalents

$m_4 = 1$, industrial heat equivalents

$m_5 = 1$, water heating equivalents

$m_6 = 1$, space heating equivalents

$m_7 = 1$, cooking equivalents

A detailed statistical analysis of each of these models was undertaken.

These models were also weighted according to the estimated relative demands on each output class (based on 1976 demands, derived from the New Zealand Yearbook 1977; and the flow diagram in the Ministry of Energy's, 1977 Goals and Guidelines). That is, each pathway was multiplied by a factor, which indicated the demand for the output of that pathway. By undertaking such weightings, the effect (if any) of relative demands could be tested. For the weighted data, a similar series of models were generated, by in turn using each variable as the equivalencing unit.

4.6.1 Detailed Results (for Unweighted Models)

The following sets of statistical results were obtained for each one of the above mentioned models.

$n_1=1$ (Hydro-electric equivalents)

	Estimate of Coefficient	Standard Deviation	$\uparrow$ Ratio	Level of Significance (2p) (df = 22)
n_2 (natural gas)	0.43	0.06	6.99	<0.001
n_3 (oil)	0.40	0.06	6.27	<0.001
n_4 (coal)	0.21	0.04	4.73	<0.001
n_5 (wood)	0.15	0.03	4.46	<0.001
m_1 (electrical output)	1.46	0.25	5.82	<0.001
m_2 (high grade transport)	3.71	0.33	11.26	<0.001
m_3 (medium grade transport)	3.06	0.42	7.31	<0.001
m_4 (industrial heat)	0.59	0.20	3.01	<0.01 >0.001
m_5 (water heating)	0.66	0.20	3.30	<0.01 >0.001
m_6 (space heating)	0.66	0.20	3.30	<0.01 >0.001
m_7 (cooking)	1.97	0.27	7.21	<0.001

F Ratio = 14.93* (df, $v_1 = 11$, $v_2 = 22$), significant at $p=0.001$ level.

$n_2=1$ (Natural gas equivalents)

	Estimate of Coefficient	Standard Deviation	$\uparrow$ Ratio	Level of Significance (2p) (df=22)
n_1 (hydroelectricity)	1.60	0.23	6.99	<0.001
n_3 (oil)	0.80	0.12	6.82	<0.001
n_4 (wood)	0.46	0.07	6.46	<0.001
n_5 (coal)	0.33	0.05	6.04	<0.001
m_1 (electrical output)	3.02	0.42	7.13	<0.001
m_2 (high grade transport)	7.04	0.69	10.19	<0.001
m_3 (medium grade transport)	6.29	0.65	9.63	<0.001
m_4 (industrial heat)	1.02	0.37	3.26	<0.01 >0.001
m_5 (water heating)	1.35	0.37	3.63	<0.01 >0.001
m_6 (space heating)	1.36	0.37	3.68	<0.001
m_7 (cooking)	3.98	0.46	8.64	<0.001

F Ratio = 13.43 (df, $v=11$, $v_2=22$), significant at $p=0.001$ level.

$n_3=1$ (Oil equivalents)

	Estimate of Coefficient	Standard Deviation	$\uparrow$ Ratio	Level of Significance (2p) (df=22)
n_1 (hydroelectricity)	1.59	0.25	6.27	0.001
n_2 (natural gas)	0.85	0.12	6.82	0.001
n_4 (coal)	0.44	0.08	5.25	0.001
n_5 (wood)	0.31	0.06	4.92	0.001
m_1 (electrical output)	3.04	0.46	6.55	0.001
m_2 (high grade transport)	7.16	0.76	9.36	0.001
m_3 (medium grade transport)	6.13	0.82	7.47	0.001
m_4 (industrial heat)	1.21	0.39	3.13	0.01 0.001
m_5 (water heating)	1.35	0.39	3.48	0.01 0.001
m_6 (space heating)	1.38	0.39	3.55	0.01 0.001
m_7 (cooking)	4.03	0.51	7.92	0.001

F Ratio = 10.75 (df, $v_1=11$, $v_2=22$), significant at $p=0.001$ level

$n_4=1$ (Coal Equivalents)

	Estimate of Coefficients	Standard Deviation	t Ratio	Level of Significance (2p) (df=22)
n_1 (hydroelectricity)	2.39	0.50	4.73	<0.001
n_2 (natural gas)	1.41	0.22	6.46	<0.001
n_3 (oil)	1.26	0.24	5.25	<0.001
n_4 (wood)	0.56	0.10	5.57	<0.001
m_1 (electrical output)	4.94	0.84	5.90	<0.001
m_2 (high grade transport)	11.22	1.61	6.98	<0.001
m_3 (medium grade transport)	10.57	1.30	8.13	<0.001
m_4 (industrial heat)	1.94	0.66	2.91	<0.01 >0.001
m_5 (water heating)	2.19	0.67	3.26	<0.01 >0.001
m_6 (space heating)	2.22	0.67	3.30	<0.01 >0.001
m_7 (cooking)	6.42	0.98	6.53	<0.001

F Ratio = 8.00 (df, $v_1=11$, $v_2=22$), significant at $p=0.001$ level.

 $n_5=1$ (Wood equivalents)

	Estimate of Coefficients	Standard Deviation	t Ratio	Level of Significance (2p) (df=22)
n_1 (hydroelectricity)	3.16	0.71	4.46	<0.001
n_2 (natural gas)	1.88	0.31	6.04	<0.001
n_3 (oil)	1.67	0.34	4.92	<0.001
n_4 (coal)	1.04	0.19	5.57	<0.001
m_1 (electrical output)	6.76	1.14	5.93	<0.001
m_2 (high grade transport)	14.73	2.36	6.23	<0.001
m_3 (medium grade transport)	13.87	1.97	7.06	<0.001
m_4 (industrial heat)	2.63	0.91	2.89	<0.01 >0.001
m_5 (water heating)	2.93	0.92	3.17	<0.01 >0.001
m_6 (space heating)	2.96	0.93	3.19	<0.01 >0.001
m_7 (cooking)	8.57	1.40	6.13	<0.001

F Ratio = 6.08 (df, $v_1=11$, $v_2=22$), significant at $p=0.001$ level.

 $m_1=1$ (Electrical output equivalents)

	Estimate of Coefficients	Standard Deviation	t Ratio	Level of Significance (2p) (df=22)
n_1 (hydroelectricity)	0.41	0.07	5.82	<0.001
n_2 (natural gas)	0.23	0.03	7.13	<0.001
n_3 (oil)	0.22	0.03	6.55	<0.001
n_4 (coal)	0.12	0.02	5.90	<0.001
n_5 (wood)	0.09	0.02	5.93	<0.001
m_2 (high grade transport)	1.82	0.24	7.61	<0.001
m_3 (medium grade transport)	1.62	0.22	7.24	<0.001
m_4 (industrial heat)	0.31	0.10	2.96	<0.01 >0.001
m_5 (water heating)	0.35	0.11	3.27	<0.01 >0.001
m_6 (space heating)	0.35	0.11	3.31	<0.01 >0.001
m_7 (cooking)	1.03	0.15	6.74	<0.001

F Ratio = 7.30 (df, $v_1=11$, $v_2=22$), significant at $p = 0.001$ level.

m₂=1 (High grade transport equivalents)

	Estimate of Coefficients	Standard Deviation	t Ratio	Level of Significance (2p) (df=22)
n ₁ (hydroelectricity)	0.23	0.02	11.26	<0.001
n ₂ (natural gas)	0.12	0.01	10.19	<0.001
n ₃ (oil)	0.11	0.01	9.36	<0.001
n ₄ (coal)	0.06	0.01	6.98	<0.001
n ₅ (wood)	0.04	0.01	6.23	<0.001
m ₁ (electrical output)	0.40	0.05	7.61	<0.001
m ₃ (medium grade transport)	0.83	0.08	10.50	<0.001
m ₄ (industrial heat)	0.16	0.05	3.37	<0.01 >0.001
m ₅ (water heating)	0.19	0.05	3.75	<0.01 >0.001
m ₆ (space heating)	0.18	0.05	3.78	<0.01 >0.001
m ₇ (cooking)	0.53	0.05	9.72	<0.001

F Ratio = 40.60 (df, v₁=11, v₂=22), significant at p=0.001 level.

m₃=1 (Medium grade transport equivalents)

	Estimate of Coefficients	Standard Deviation	t Ratio	Level of Significance (2p) (df=22)
n ₁ (hydroelectricity)	0.23	0.03	7.31	<0.001
n ₂ (natural gas)	0.13	0.01	9.63	<0.001
n ₃ (oil)	0.12	0.02	7.47	<0.001
n ₄ (coal)	0.07	0.01	8.13	<0.001
n ₅ (wood)	0.05	0.01	7.06	<0.001
m ₁ (electrical output)	0.43	0.06	7.24	<0.001
m ₂ (medium grade transport)	1.01	0.10	10.50	<0.001
m ₄ (industrial heat)	0.17	0.05	3.26	<0.01 >0.001
m ₅ (water heating)	0.19	0.05	3.63	<0.01 >0.001
m ₆ (space heating)	0.20	0.05	3.67	<0.01 >0.001
m ₇ (cooking)	0.57	0.07	8.62	<0.001

m₄=1 (Industrial heat equivalents)

	Estimate of Coefficients	Standard Deviation	t Ratio	Level of Significance (2p) (df=22)
n ₁ (hydroelectricity)	0.49	0.16	3.01	0.01 0.001
n ₂ (natural gas)	0.27	0.08	3.26	0.01 0.001
n ₃ (oil)	0.26	0.08	3.13	0.01 0.001
n ₄ (coal)	0.14	0.05	2.91	0.01 0.001
n ₅ (wood)	0.10	0.04	2.89	0.01 0.001
m ₁ (electrical output)	0.92	0.31	2.96	0.01 0.001
m ₂ (high grade transport)	2.15	0.64	3.37	0.01 0.001
m ₃ (medium grade transport)	1.90	0.58	3.26	0.01 0.001
m ₅ (water heating)	0.41	0.21	1.98	0.10 0.05
m ₆ (space heating)	0.41	0.21	2.00	0.10 0.05
m ₇ (cooking)	1.21	0.38	3.17	0.01 0.001

F Ratio = 1.14 (df, v₁=11, v₂=22), not significant at p=0.10 level.

m₅=1 (Water heating equivalents)

	Estimate of Coefficient	Standard Deviation	t Ratio	Level of Significance (2p) (df=22)
n ₁ (hydroelectricity)	0.50	0.15	3.30	<0.01 >0.001
n ₂ (natural gas)	0.28	0.08	3.63	<0.01 >0.001
n ₃ (oil)	0.26	0.08	3.48	<0.01 >0.001
n ₄ (coal)	0.15	0.05	3.26	<0.01 >0.001
n ₅ (wood)	0.11	0.03	3.17	<0.01 >0.001
m ₁ (electrical output)	0.94	0.29	3.27	<0.01 >0.001
m ₂ (high grade transport)	2.20	0.59	3.75	<0.01 >0.001
m ₃ (medium grade transport)	1.95	0.54	3.63	<0.01 >0.001
m ₄ (industrial heat)	0.37	0.19	1.98	<0.10 >0.05
m ₆ (space heating)	0.42	0.19	2.18	<0.10 >0.05
m ₇ (cooking)	1.23	0.35	3.52	<0.01 >0.001

F Ratio = 1.43 (df, v₁=11, v₂=22), not significant at p=0.10 level.

m₆=1 (Space Heating Equivalents)

	Estimate of Coefficient	Standard Deviation	t Ratio	Level of Significance (2p) (df=22)
n ₁ (hydro electricity)	0.50	0.15	3.30	0.01 0.001
n ₂ (natural gas)	0.28	0.08	3.68	0.01 0.001
n ₃ (oil)	0.26	0.07	3.55	0.01 0.001
n ₄ (coal)	0.15	0.05	3.30	0.01 0.001
n ₅ (wood)	0.11	0.03	3.19	0.01 0.001
m ₁ (electrical output)	0.94	0.29	3.31	0.01 0.001
m ₂ (high grade transport)	2.20	0.58	3.78	0.01 0.001
m ₃ (medium grade transport)	1.95	0.53	3.67	0.01 0.001
m ₄ (industrial heat)	0.37	0.19	2.00	0.10 0.05
m ₅ (water heating)	0.42	0.19	2.18	0.10 0.05
m ₇ (cooking)	1.24	0.35	3.56	0.01 0.001

F Ratio = 1.47 (df, v₁=11, v₂=22), not significant at p=0.10 level.

m₇=1 (Cooking equivalents)

	Estimate of Coefficients	Standard Deviation	t Ratio	Level of Significance (2p) (df=22)
n ₁ (hydro electricity)	0.36	0.05	7.21	<0.001
n ₂ (natural gas)	0.19	0.02	8.64	<0.001
n ₃ (oil)	0.18	0.02	7.92	<0.001
n ₄ (coal)	0.10	0.02	6.53	<0.001
n ₅ (wood)	0.07	0.01	6.13	<0.001
m ₁ (electrical output)	0.65	0.10	6.74	<0.001
m ₂ (high grade transport)	1.54	0.16	9.72	<0.001
m ₃ (medium grade transport)	1.36	0.16	8.62	<0.001
m ₄ (industrial heat)	0.26	0.08	3.17	<0.01 >0.001
m ₅ (water heating)	0.29	0.08	3.52	<0.01 >0.001
m ₆ (space heating)	0.29	0.08	3.56	<0.01 >0.001

F Ratio = 12.50 (df, v₁=11, v₂=22), significant at p=0.001 level.

4.6.2 Interpretation of results (for unweighted models)

4.6.2.1 Estimates of coefficients and t ratios

Irrespective of what variable was chosen as the equivalencing variable, the same pattern of estimates of the coefficients results. That is, hydro-electricity was found to be the highest quality energy input (highest coefficient), generally followed by natural gas, oil, coal and finally wood, in that order. This was a similar pattern in ranking of the quality of the inputs, as those determined in Chapter 3. Generally, high grade transport was found to be the highest quality output, followed by medium grade transport, cooking, electrical output, and then heat uses (water, space, industrial). This was a similar order, to that determined in Chapter 3, with the notable exception of cooking being determined as having a lesser quality than high grade transport. Again, these estimates make good technical and physical sense.

Generally, the t ratios indicated that accurate estimates were obtained for the coefficients generated by these models. For all models (except $m_4 = 1$, $m_6 = 1$, $m_1 = 1$), the coefficients were all significant at the $2p = 0.001$ level (except the coefficients m_4 , m_5 , m_6). This is a similar situation to the models examined in Chapter 3. That is, the exceptions to the above generalisation are due to the error associated with m_4 , m_5 , and m_6 . Also similarly to the Chapter 3 models, more accurate estimates of the coefficients were obtained for models which had a high F ratio. For example, for the model $m_2 = 1$, which had an F ratio of 40.60, the t ratios for m_4 was 3.37, for m_5 was 3.75 and for m_6 was 3.78. These t ratios were significant at the $2p = 0.01$ level. Whereas, the t ratios for these coefficients for other models with lower F ratios were significantly lower ($\underline{t} = 2.00$).

4.6.2.2 F Ratios

The F Ratios for all models were significant at the $p = 0.10$ level, and significant at the $p = 0.001$ levels for the models (n_1 , n_2 , n_3 , n_4 , n_5 , m_1 , m_2 , m_3 , m_7). As with the models examined in Chapter 3, it was found that those variables which had low t ratios, generated the less significant models when that variable was used as the

equivalencing variable.

The most significant model was:

$m_2=1$ (high grade transport equivalents), F Ratio = 40.60, followed by the following models in decreasing order:

$m_3 = 1$ (medium grade transport equivalents), F Ratio = 18.87

$n_1 = 1$ (hydro-electric equivalents), F Ratio = 14.93

$n_2 = 1$ (natural gas equivalents), F Ratio = 13.43

$m_7 = 1$ (cooking equivalents), F Ratio = 12.58

$n_3 = 1$ (oil equivalents), F Ratio = 10.75

$n_4 = 1$ (coal equivalents), F Ratio = 8.00

$m_1 = 1$ (electrical output equivalents), F Ratio = 7.30

$n_5 = 1$ (wood equivalents), F Ratio = 6.08

$m_6 = 1$ (space heating equivalents), F Ratio = 1.47

$m_5 = 1$ (water heating equivalents), F Ratio = 1.43

$m_4 = 1$ (industrial heat equivalents), F Ratio = 1.14

4.6.3 Detailed Results (Weighted Models)

The models were weighted, as it can be argued that the coefficients determined in the modelling process, depend at least to some degree on the structure of the energy economy. It is easiest to weight the pathways in the model according to end-use demand, since there is only one output per pathway. Whereas, there are several inputs per pathway which makes weighting of the pathways difficult. As no future end-use demand is known, the 1976 end-use demand was used. The end-use demand (PJ.Yr^{-1}) weighting was divided by the number of possible pathways that produce that output, to determine a weighting according to the following end-use demands;

Y_1 (Electrical Output) pathways = 6.99 PJ Yr^{-1}

Y_2 (High Grade Transport) pathways = 5.14 PJ Yr^{-1}

Y_3 (Medium Grade Transport) pathways = 0.00 PJ Yr^{-1}

Y_4 (Industrial Heat) pathways = 12.18 PJ Yr^{-1}

Y_5 (Water Heating) pathways = 2.50 PJ Yr^{-1}

Y_6 (Space Heating) pathways = 4.25 PJ Yr^{-1}

Y_7 (Cooking) pathways = 0.37 PJ Yr^{-1}

The Y_3 (Medium Grade Transport) pathways were excluded because the 1976 end-use demand for each individual pathway was estimated to be below 0.01 PJ.Yr^{-1} .

The following sets of statistical results were obtained for the weighted model:

$n_1=1$ (Hydro electric equivalents)

	Estimate of Coefficients	Standard Deviation	t Ratio	Level of Significance (2p) (df=22)
n_2 (natural gas)	0.41	0.05	7.90	<0.001
n_3 (oil)	0.44	0.06	7.62	<0.001
n_4 (coal)	0.24	0.04	5.61	<0.001
n_5 (wood)	0.14	0.03	5.22	<0.001
m_1 (electrical output)	1.49	0.18	8.27	<0.001
m_2 (high grade transport)	3.80	0.28	13.57	<0.001
m_4 (industrial heat)	0.60	0.08	7.29	<0.001
m_5 (water heating)	0.67	0.32	2.13	<0.05 >0.02
m_6 (space heating)	0.68	0.19	3.15	<0.01 >0.001
m_7 (cooking)	2.02	2.10	0.96	<0.50 >0.20

F Ratio = 22.35 (df, $v_1=10$, $v_2=23$), significant at the $p=0.0001$ level.

$n_2=1$ (Natural gas equivalents)

	Estimate of Coefficients	Standard Deviation	t Ratio	Level of Significance (2p) (df=22)
n_1 (hydroelectricity)	1.76	0.22	7.90	<0.001
n_3 (oil)	0.90	0.12	7.73	<0.001
n_4 (coal)	0.54	0.08	6.64	<0.001
n_5 (wood)	6.30	0.05	6.07	<0.001
m_1 (electrical output)	3.17	6.33	9.65	<0.001
m_2 (high grade transport)	7.61	0.69	11.00	<0.001
m_4 (industrial heat)	1.27	6.16	7.93	<0.001
m_5 (water heating)	1.43	0.65	2.21	<0.05 >0.02
m_6 (space heating)	1.45	0.39	3.72	<0.01 >0.001
m_7 (cooking)	4.24	4.33	0.98	<0.50 >0.20

F Ratio = 14.58 (df, $v_1=10$, $v_2=23$), significant at the $p=0.0001$ level

$n_3=1$ (Oil equivalents)

	Estimate of Coefficients	Standard Deviation	t Ratio	Level of Significance (2p) (df=23)
n_1 (hydro electricity)	1.64	0.22	7.62	<0.001
n_2 (natural gas)	0.80	0.10	7.73	<0.001
n_4 (coal)	0.49	0.08	6.16	<0.001
n_5 (wood)	0.28	0.05	5.59	<0.001
m_1 (electrical output)	2.99	0.31	9.58	<0.001
m_2 (high grade transport)	7.20	0.63	11.37	<0.001
m_4 (industrial heat)	1.19	0.15	7.84	<0.001
m_5 (water heating)	1.34	0.61	2.20	<0.05 >0.02
m_6 (space heating)	1.37	6.37	3.72	<0.01 >0.001
m_7 (cooking)	4.00	4.07	0.98	<0.50 >0.20

F Ratio = 16.50 (df, $v_1=10$, $v_2=23$), significant at the $p=0.0001$ level.

 $n_4=1$ (Coal equivalents)

	Estimate of Coefficients	Standard Deviation	t Ratio	Level of Significance (2p) (df=23)
n_1 (hydro electricity)	2.37	0.42	5.61	<0.001
n_2 (natural gas)	1.23	0.18	6.64	<0.001
n_3 (oil)	1.27	0.21	6.16	<0.001
n_5 (wood)	0.44	0.08	5.44	<0.001
m_1 (electrical output)	4.58	0.59	7.76	<0.001
m_2 (high grade transport)	10.78	1.35	7.98	<0.001
m_4 (industrial heat)	1.80	0.28	6.46	<0.001
m_5 (water heating)	2.05	0.99	2.07	<0.05 >0.02
m_6 (space heating)	2.08	0.61	3.42	<0.01 >0.001
m_7 (cooking)	6.04	6.57	0.92	<0.50 >0.20

F Ratio = 8.60 (df, $v_1=10$, $v_2=23$), significant at the $p=0.001$ level.

 $n_5=1$ (Wood equivalents)

	Estimate of Coefficients	Standard Deviation	t Ratio	Level of Significance (2p) (df=23)
n_1 (hydro electricity)	3.94	0.75	5.22	<0.001
n_2 (natural gas)	2.06	0.34	6.07	<0.001
n_3 (oil)	2.09	0.37	5.59	<0.001
n_4 (wood)	1.28	0.24	5.44	<0.001
m_1 (electrical output)	7.71	1.65	7.36	<0.001
m_2 (high grade transport)	17.57	2.60	6.75	<0.001
m_4 (industrial heat)	3.02	0.50	6.10	<0.001
m_5 (water heating)	3.39	1.71	1.98	<0.10 >0.05
m_6 (space heating)	3.43	1.06	3.22	<0.01 >0.001
m_7 (cooking)	9.97	11.27	0.88	<0.50 >0.20

F Ratio = 6.40 (df, $v_1=11$, $v_2=22$), significant at the $p=0.001$ level.

$m_1=1$ (electrical output equivalents)

	Estimate of Coefficients	Standard Deviation	$\bar{t}$ Ratio	Level of Significance (2p) (df=23)
n_1 (hydro electricity)	0.50	0.06	8.27	<0.001
n_2 (natural gas)	0.25	0.03	9.65	<0.001
n_3 (oil)	0.27	0.03	9.58	<0.001
n_4 (coal)	0.16	0.02	7.76	<0.001
n_5 (wood)	0.09	0.01	7.36	<0.001
m_2 (high grade transport)	2.16	0.18	11.69	<0.001
m_4 (industrial heat)	0.36	0.04	8.11	<0.001
m_5 (water heating)	0.40	0.18	2.22	<0.05 >0.02
m_6 (space heating)	0.41	0.11	3.75	<0.01 >0.001
m_7 (cooking)	1.20	1.22	0.99	<0.50 >0.20

F Ratio = 21.84 (df, $v_1=11$, $v_2=22$), significant at the $p=0.0001$ level.

 $m_2=1$ (High grade transport equivalents)

	Estimate of Coefficients	Standard Deviation	t Ratio	Level of Significance (2p) (df=23)
n_1 (hydro electricity)	0.23	0.02	13.57	<0.001
n_2 (natural gas)	0.11	0.01	11.00	<0.001
n_3 (oil)	0.12	0.01	11.37	<0.001
n_4 (coal)	0.07	0.01	7.98	<0.001
n_5 (wood)	0.04	0.01	6.75	<0.001
m_1 (electrical output)	0.40	0.03	11.69	<0.001
m_4 (industrial heat)	0.16	0.02	9.11	<0.001
m_5 (water heating)	0.18	0.08	2.30	<0.05 >0.02
m_6 (space heating)	0.18	0.05	3.91	<0.001
m_7 (cooking)	0.53	0.52	1.02	<0.50 >0.20

F Ratio = 69.10 (df, $v_1=11$, $v_2=22$), significant at the $p=0.0001$ level.

 $m_4=1$ (Industrial heat equivalents)

	Estimate of Coefficients	Standard Deviation	t Ratio	Level of Significance (2p) (df=23)
n_1 (hydro electricity)	1.16	0.16	7.29	<0.001
n_2 (natural gas)	0.58	0.07	7.93	<0.001
n_3 (oil)	0.61	0.08	7.84	<0.001
n_4 (coal)	0.36	0.06	6.46	<0.001
n_5 (wood)	0.20	0.03	6.10	<0.001
m_1 (electrical output)	2.06	0.25	8.11	<0.001
m_2 (high grade transport)	4.96	0.54	9.11	<0.001
m_5 (water heating)	0.92	0.44	2.10	<0.05 >0.02
m_6 (space heating)	0.94	0.27	3.47	<0.01 >0.001
m_7 (cooking)	2.74	2.92	0.94	<0.50 >0.20

F Ratio = 10.48 (df, $v_1=11$, $v_2=22$) significant at the $p=0.001$ level.

m₅=1 (Water heating equivalents)

	Estimate of Coefficient	Standard Deviation	t Ratio	Level of Significance (2p) (df=23)
n ₁ (hydro electricity)	0.24	0.11	2.13	<0.05 >0.02
n ₂ (natural gas)	0.12	0.06	2.21	<0.05 >0.02
n ₃ (oil)	0.13	0.06	2.20	<0.05 >0.02
n ₄ (coal)	0.08	0.04	2.07	<0.05 >0.02
n ₅ (wood)	0.04	0.02	1.98	<0.10 >0.05
m ₁ (electrical output)	0.44	0.20	2.22	<0.05 >0.02
m ₂ (high grade transport)	1.05	0.46	2.30	<0.05 >0.02
m ₄ (industrial heat)	0.17	0.08	2.10	<0.05 >0.02
m ₆ (space heating)	0.20	0.14	1.43	<0.20 >0.10
m ₇ (cooking)	0.58	1.29	0.45	<0.80 >0.50

F Ratio = 0.56 (df, v₁=11, v₂=22), not significant at the p=0.10 level.

m₆=1 (Space heating equivalents)

	Estimate of Coefficient	Standard Deviation	t Ratio	Level of Significance (2p) (df=23)
n ₁ (hydro electricity)	0.51	0.15	3.51	<0.01 >0.001
n ₂ (natural gas)	0.26	0.07	3.72	<0.01 >0.001
n ₃ (oil)	0.28	0.07	3.72	<0.01 >0.001
n ₄ (coal)	0.16	0.05	3.42	<0.01 >0.001
n ₅ (wood)	0.09	0.03	3.22	<0.01 >0.001
m ₁ (electrical output)	0.92	0.25	3.75	<0.01 >0.001
m ₂ (high grade transport)	2.22	0.57	3.91	<0.01 >0.001
m ₄ (industrial heat)	0.37	0.11	3.47	<0.01 >0.001
m ₅ (water heating)	0.41	0.29	1.43	<0.20 >0.10
m ₇ (cooking)	1.23	1.85	0.66	<0.80 >0.50

F Ratio = 1.67 (df, v₁=11, v₂=22), not significant at the p = 0.10 level.

m₇=1 (Cooking equivalents)

	Estimate of Coefficient	Standard Deviation	t Ratio	Level of Significance (2p) (df=23)
n ₁ (hydro electricity)	0.0191	0.0199	0.96	<0.50 >0.20
n ₂ (natural gas)	0.0095	0.0096	0.98	<0.50 >0.20
n ₃ (oil)	0.0101	0.0102	0.98	<0.50 >0.20
n ₄ (coal)	0.0059	0.0064	0.92	<0.50 >0.20
n ₅ (wood)	0.0033	0.0037	0.88	<0.50 >0.20
m ₁ (electrical output)	0.0337	0.0342	0.99	<0.50 >0.20
m ₂ (high grade transport)	0.0814	0.0799	1.02	<0.50 >0.20
m ₄ (industrial heat)	0.0134	0.0143	0.94	<0.50 >0.20
m ₅ (water heating)	0.0151	0.0335	0.45	<0.80 >0.50
m ₆ (space heating)	0.0153	0.0231	0.66	<0.80 >0.50

F Ratio = 0.11 (df, v₁=11, v₂=22), not significant at the p=0.10 level.

4.6.4 Interpretation of Results (Weighted Models)

4.6.4.1 Estimate of Coefficients and t Ratios

Again a similar pattern resulted, with hydro-electricity being the highest quality input (highest estimate of coefficient), followed by natural gas, oil, coal and then wood. This is the same pattern which resulted in the unweighted models (Chapter 4) and the models in Chapter 3. Also, similarly to those sets of models, high grade transport and cooking were found to be the highest quality outputs, followed by electrical output and then by low quality heat uses (water heating, space heating and industrial heat).

All models, except $m_7 = 1$, made good physical and technical sense. In this model ($m_7 = 1$), the estimates of the coefficients appear to be too low compared with $m_7 = 1$; although the general ordering of the other coefficients in terms of their energy quality is sensible.

Weighting had the effect of making inaccurate estimates of coefficients (as indicated by low t ratios) even more inaccurate; and the opposite effect of making accurate estimates of coefficients even more accurate. Nevertheless, most estimates of coefficients were significant at the $2p=0.001$ level.

4.6.4.2 F ratios

The most significant model was:

$m_2 = 1$ (high grade transport equivalents), F Ratio = 69.10 followed by the following models in decreasing order:

$n_1 = 1$ (hydro-electric equivalents), F Ratio = 22.35

$m_1 = 1$ (electrical output equivalents), F Ratio = 21.84

$n_3 = 1$ (oil equivalents), F Ratio = 16.50

$n_2 = 1$ (natural gas equivalents), F Ratio = 14.50

$m_4 = 1$ (industrial heat equivalents), F Ratio = 10.48

$n_4 = 1$ (coal equivalents), F Ratio = 8.60

$n_5 = 1$ (wood equivalents), F Ratio = 6.40

$m_6 = 1$ (space heating equivalents), F Ratio = 1.67

$m_5 = 1$ (water heating equivalents), F Ratio = 0.66

$m_7 = 1$ (cooking equivalents), F Ratio = 0.11

The first 8 models were all significant at the $p = 0.10$ level.

Weighting had the effect of increasing, still further, the F ratios, of those models which were already high. And oppositely, decreasing still further, the F ratios of those models which were already low (refer to table 4.3). This effect seemed to be generally proportional to the weighting.

Consequently, the range of F ratios, for these weighted models, was greater than the range of F ratios for the unweighted models - ranging from $F = 0.11$ for $m_7 = 1$, to $F = 69.10$ for $m_2 = 1$. Therefore, for unweighted models, it appears to be more critical which variable is used as the equivalencing variable.

4.6.5 Model Selection and Improvement (Using Unweighted Models)

The unweighted models were used as the basis to the model selection and improvement, as generally they generated the most consistently significant statistical results.

The "best" model appeared to be $m_2 = 1$ (high grade transport equivalents) as it had the highest F ratio, and it makes good physical and technical sense. As it is conceptually difficult to understand and use "high grade transport equivalents", it is recommended that the coefficients be converted to hydro-electric equivalents $n_1(m_2)$ by dividing each coefficient by 0.22961

	high grade transport equivalents (m_2)	hydro-electric equivalents [$n_1(m_2)$]
n_1 (hydro-electricity)	0.22961	1.0000
n_2 (natural gas)	0.11725	0.5106
n_3 (oil)	0.11168	0.4864
n_4 (coal)	0.061433	0.2676
n_5 (wood)	0.043346	0.1888
m_1 (electrical output)	0.39768	1.7320
m_2 (medium grade transport)	0.82509	3.5934

Table 4.3: Comparison of F Ratios for Weighted and Unweighted Models of an Energy Efficient Economy

Model	Weighted F Ratio ^a	df	Unweighted F Ratio ^a	df	Weight of Output
$n_1 = 1$	22.35	11,22	14.93	10,23	-
$n_2 = 1$	14.58	11,22	13.43	10,23	-
$n_3 = 1$	16.50	11,22	10.75	10,23	-
$n_4 = 1$	8.60	11,22	8.00	10,23	-
$n_5 = 1$	6.40	11,22	6.08	10,23	-
$m_1 = 1$	21.84	11,22	7.30	10,23	6.99(m_1)
$m_2 = 1$	69.10	11,22	40.60	10,23	5.14(m_2)
$m_3 = 1$	-	11,22	18.17	10,23	0.00(m_3)
$m_4 = 1$	10.48	11,22	1.14	10,23	12.18(m_4)
$m_5 = 1$	0.56	11,22	1.43	10,23	2.50(m_5)
$m_6 = 1$	1.67	11,22	1.47	10,23	4.25(m_6)
$m_7 = 1$	0.11	11,22	12.50	10,23	0.37(m_7)

^a The F ratios for both sets (weighted and unweighted) models are strictly comparable, because the degrees of freedom are different. However, they are very nearly comparable since the degrees of freedom are nearly identical.

Table 4.4: Comparison of Estimates of Co-efficients Standardised so $n_1=1$, and F Ratios for Models (n_1 - n_7 , m_1 - m_7) of an Energy Efficient Economy (Unweighted)

Basis for Model	Estimates of Co-efficients												F Ratio
	n_1	n_2	n_3	n_4	n_5	m_1	m_2	m_3	m_4	m_5	m_6	m_7	
$n_1=1$ (Hydro)	1.00 ^{a,b}	0.43 ^b	0.40 ^b	0.21 ^b	0.15 ^b	1.46 ^b	3.71 ^b	3.06 ^b	0.59 ^b	0.66 ^b	0.66 ^b	1.97 ^b	14.93
$n_2=1$ (Gas)	1.00 ^{a,b}	0.63 ^a	0.50	0.29	0.21	1.89	4.40	3.93	0.75	0.84	0.85	2.49	13.43
$n_3=1$ (Oil)	1.00 ^{a,b}	0.53	0.63 ^a	0.28	0.20	1.91	4.49	3.84	0.76	0.85	0.87	2.53	10.75
$n_4=1$ (Coal)	1.00 ^{a,b}	0.59	0.53	0.42 ^a	0.24	2.07	4.70 ^a	4.43 ^a	0.81	0.92	0.93	2.69	8.00
$n_5=1$ (Wood)	1.00 ^{a,b}	0.59	0.53	0.33	0.32 ^a	2.14	4.66	4.39	0.83	0.93	0.94	2.71	6.08
$m_1=1$ (Electrical)	1.00 ^{a,b}	0.57	0.52	0.30	0.21	2.41 ^a	4.40	3.91	0.75	0.84	0.85	2.48	7.30
$m_2=1$ (H.G. Transport)	1.00 ^{a,b}	0.51	0.49	0.27	0.19	1.73	4.36	3.59	0.69	0.77	0.78	2.29	40.60
$m_3=1$ (M.G. Transport)	1.00 ^{a,b}	0.55	0.50	0.31	0.22	1.87	4.36	4.32	0.74	0.83	0.84	2.46	18.87
$m_4=1$ (Industrial Heat)	1.00 ^{a,b}	0.55	0.52	0.30	0.21	1.85	4.34	3.84	2.02 ^a	0.82	0.83	2.44	1.14
$m_5=1$ (Water Heat)	1.00 ^{a,b}	0.55	0.52	0.29	0.21	1.87	4.36	3.87	0.73	1.98 ^a	0.84	2.45	1.43
$m_6=1$ (Space Heat)	1.00 ^{a,b}	0.56	0.53	0.30	0.21	1.88	4.39	3.89	0.74	0.83	2.00 ^a	2.47	1.47
$m_7=1$ (Cooking)	1.00 ^{a,b}	0.54	0.52	0.29	0.21	1.84	4.32	3.81	0.73	0.82	0.83	2.81 ^a	12.58

a Highest or highest equal estimate in that column.

b Lowest or lowest equal estimate in that column.

m_3 (high grade transport)	1.0000	4.3552
m_4 (industrial heat)	0.15839	0.6898
m_5 (water heating)	0.17720	0.7717
m_6 (space heating)	0.17924	0.7806
m_7 (cooking)	0.52693	2.2949

Similarly, if another model is chosen as the model to use, the coefficients can be converted to hydro-electric equivalents - that is:

<u>Equivalencing</u> <u>Unit</u>	<u>Symbol</u>
$n_2 = 1,$	$n_1 (n_2)$
$n_3 = 1,$	$n_1 (n_3)$
$n_4 = 1,$	$n_1 (n_4)$
$n_5 = 1,$	$n_1 (n_5)$
$m_1 = 1,$	$n_1 (m_1)$
$m_3 = 1,$	$n_1 (m_3)$
$m_4 = 1,$	$n_1 (m_4)$
$m_5 = 1,$	$n_1 (m_5)$
$m_6 = 1,$	$n_1 (m_6)$
$m_7 = 1,$	$n_1 (m_7)$

(refer to table 4.4).

It should be noted (by analysing table 4.4), that there is a marked tendency for a coefficient to be over estimated (c.f. with other models), when it is used as the equivalencing unit. This tendency is most marked in models with low F ratios, and does not exist in models with higher F ratios. This lends support to the method of choosing the model(s) with the highest F ratio(s).

4.7 Post Regression Analysis of Pathways, for the m_2 Model

4.7.1 Residuals of Pathways (Relative Net Energy Yields)

The residual $[(-Y_2) - (-\hat{Y}_2)]$ is equivalent to the relative net energy yield (Q) of each pathway. Table 4.5 details the actual value $(-Y_2)$, predicted value $(-\hat{Y}_2)$, standard deviation of $(-Y_2)$, residual $[(-Y_2) - (-\hat{Y}_2)]$, and standardised residual of each equation (pathway) in this model (it should be noted that these values are routinely

Table 4.5: Analysis of Residuals for High Grade Transport Equivalents ($m_2=1$) for an Energy Efficiency Economy

Pathway	Actual $-X_1$ ($-Y_2$)	Predicted $-X_1$ ($-\hat{Y}_2$)	Standard Deviation of $-Y_2$	Residual {($-Y_2$)-($-\hat{Y}_2$)}	Standardised Residual
1. Coal → Electrical Output	0.0000	-0.0983	0.0567	0.0983	1.14
2. Oil → Electrical Output	0.0000	0.0618	0.0607	-0.0618	-0.74
3. Gas → Electrical Output	0.0000	0.0832	0.0578	-0.0832	-0.97
4. Wood → Electrical Output	0.0000	0.0767	0.0682	-0.0767	-0.99
5. Hydro → Electrical Output	0.0000	-0.1234	0.0576	0.1234	1.44
6. Coal → High Grade Transport	1.0000	1.0510	0.0712	-0.0510	-0.68
7. Oil → High Grade Transport	1.0000	0.7693	0.0669	0.2307	2.93
8. Gas → High Grade Transport	1.0000	0.9084	0.0718	0.0916	1.23
9. Wood → High Grade Transport	1.0000	0.9895	0.0623	0.0105	0.13
10. Hydro → High Grade Transport	1.0000	1.0470	0.0798	-0.0470	-0.72
11. Gas → Med. Grade Transport	0.0000	-0.1407	0.0729	0.1407	1.92
12. Wood → Med. Grade Transport	0.0000	0.0316	0.0748	-0.0316	-0.44
13. Coal → Med. Grade Transport	0.0000	0.1091	0.0783	-0.1091	-1.62
14. Coal → Industrial Heat	0.0000	-0.0475	0.0475	0.0475	0.52
15. Oil → Industrial Heat	0.0000	0.0240	0.0486	0.0240	-0.26
16. Gas → Industrial Heat	0.0000	0.0405	0.0483	-0.0405	-0.44
17. Wood → Industrial Heat	0.0000	0.0053	0.0490	-0.0053	-0.06
18. Hydro → Industrial Heat	0.0000	-0.0224	0.0483	0.0135	0.25
19. Coal → Water Heating	0.0000	-0.0347	0.0485	0.0347	0.38
20. Oil → Water Heating	0.0000	0.0322	0.0493	-0.0322	-0.35
21. Gas → Water Heating	0.0000	0.0510	0.0489	-0.0510	-0.56
22. Wood → Water Heating	0.0000	-0.0135	0.0490	0.0135	0.15
23. Hydro → Water Heating	0.0000	-0.0349	0.0486	0.0349	0.38
24. Coal → Space Heating	0.0000	-0.0260	0.0486	0.0260	0.29
25. Oil → Space Heating	0.0000	0.0616	0.0500	-0.0616	-0.68
26. Gas → Space Heating	0.0000	0.0547	0.0490	-0.0547	-0.60
27. Wood → Space Heating	0.0000	-0.0240	0.0487	0.0240	0.26
28. Hydro → Space Heating	0.0000	-0.0663	0.0483	0.0663	0.73
29. Coal → Cooking	0.0000	-0.1378	0.0600	0.1378	1.64
30. Oil → Cooking	0.0000	0.1545	0.0723	-0.1545	-2.09
31. Gas → Cooking	0.0000	0.1211	0.0654	-0.1211	-1.52
32. Wood → Cooking	0.0000	-0.1096	0.0631	0.1096	1.34
33. Hydro → Cooking	0.0000	-0.282	0.0669	0.0282	0.36

Table 4.6: Numerical Calculations for Pathways of the $n_1(m_2)$ Model of an Energy Efficient New Zealand Economy

Pathways	Outputs (OQ)	Inputs (IQ)	Outputs (OH)	Inputs (IH)	Relative Efficiency (Q) (OQ/IQ)	Efficiency (H) (OH/IH)	Quality of Inputs (IQ/IH)	Quality of Outputs (OQ/OH)	Relative Net Energy Yield (OQ/IQ)
1. Coal → Electrical Output	1.7320	1.3035	1.0000	4.7000	1.3287	0.2128	0.2773	1.7320	0.4285
2. Oil → Electrical Output	1.7320	1.9828	1.0000	4.2100	0.8735	0.2375	0.4710	1.7320	-0.2508
3. Gas → Electrical Output	1.7320	2.0933	1.0000	4.0900	0.8274	0.2445	0.5118	1.7320	-0.3613
4. Wood → Electrical Output	1.7320	2.0637	1.0000	9.9700	0.8393	0.1003	0.2070	1.7320	-0.3317
5. Hydro → Electrical Output	1.7320	1.1943	1.0000	1.2700	1.4502	0.7874	0.9404	1.7320	0.5377
6. Coal → High Grade Transport	4.3552	4.5729	1.0000	11.0400	0.9523	0.0906	0.4142	4.3552	-0.2177
7. Oil → High Grade Transport	4.3552	3.3236	1.0000	6.7700	1.3104	0.1477	0.4909	4.3552	1.0316
8. Gas → High Grade Transport	4.3552	3.9517	1.0000	7.5400	1.1621	0.1326	0.5241	4.3552	0.4035
9. Wood → High Grade Transport	4.3552	4.3035	1.0000	11.7600	1.0120	0.0850	0.3659	4.3552	0.0517
10. Hydro → High Grade Transport	4.3552	4.5556	1.0000	5.2600	0.9560	0.1901	0.8661	4.3552	-0.2004
11. Gas → Medium Grade Transport	3.5934	2.9763	1.0000	5.8900	1.2073	0.1698	0.5053	3.5934	0.6171
12. Wood → Medium Grade Transport	3.5934	3.7249	1.0000	12.4800	0.9647	0.0801	0.2985	3.5934	-0.1315
13. Coal → Medium Grade Transport	3.5934	4.0643	1.0000	11.6100	0.8841	0.0861	0.3501	3.5934	-0.4709
14. Coal → Industrial Heat	0.6898	0.4829	1.0000	1.6300	1.4285	0.6135	0.2963	3.5934	0.2069
15. Oil → Industrial Heat	0.6898	0.7874	1.0000	1.6700	0.8760	0.5988	0.4715	0.6898	-0.0976
16. Gas → Industrial Heat	0.6898	0.8659	1.0000	1.6800	0.7966	0.5952	0.5154	0.6898	-0.1761
17. Wood → Industrial Heat	0.6898	0.7121	1.0000	3.3000	0.9687	0.3030	0.2158	0.6898	-0.0223
18. Hydro → Industrial Heat	0.6898	0.5922	1.0000	0.6200	1.1648	1.6129	0.9552	0.6898	0.0976
19. Coal → Water Heating	0.7717	0.6205	1.0000	2.2000	1.2437	0.4546	0.2820	0.7717	0.1512
20. Oil → Water Heating	0.7717	0.9035	1.0000	1.9200	0.8541	0.5208	0.4706	0.7717	-0.1318
21. Gas → Water Heating	0.7717	0.9933	1.0000	1.9300	0.7769	0.5181	0.5146	0.7717	-0.2216
22. Wood → Water Heating	0.7717	0.7121	1.0000	3.3000	1.0837	0.3030	0.2158	0.7717	0.0596
23. Hydro → Water Heating	0.7717	0.6194	1.0000	0.6700	1.2458	1.4925	0.9244	0.7717	0.1523
24. Coal → Space Heating	0.7806	0.6668	1.0000	2.3300	1.1706	0.4292	0.2862	0.7806	0.1138
25. Oil → Space Heating	0.7806	1.0396	1.0000	2.2000	0.7509	0.4546	0.4725	0.7806	-0.2590
26. Gas → Space Heating	0.7806	1.0186	1.0000	1.9700	0.7663	0.5076	0.5170	0.7806	-0.2380
27. Wood → Space Heating	0.7806	0.6752	1.0000	3.1200	1.1561	0.3205	0.2164	0.7806	0.1054
28. Hydro → Space Heating	0.7806	0.4919	1.0000	0.5300	1.5869	1.8868	0.9280	0.7806	0.2887
29. Coal → Cooking	2.2949	1.6938	1.0000	5.7100	1.3549	0.1751	0.2966	2.2949	0.6011
30. Oil → Cooking	2.2949	2.9408	1.0000	6.2400	0.7804	0.1603	0.4713	2.2949	-0.6457
31. Gas → Cooking	2.2949	2.8219	1.0000	5.5300	0.8132	0.1808	0.5102	2.2949	-0.5270
32. Wood → Cooking	2.2949	1.8157	1.0000	8.3900	1.2639	0.1192	0.2164	2.2949	0.4792
33. Hydro → Cooking	2.2949	2.1714	1.0000	2.2700	1.0569	0.4405	0.9566	2.2949	0.1235

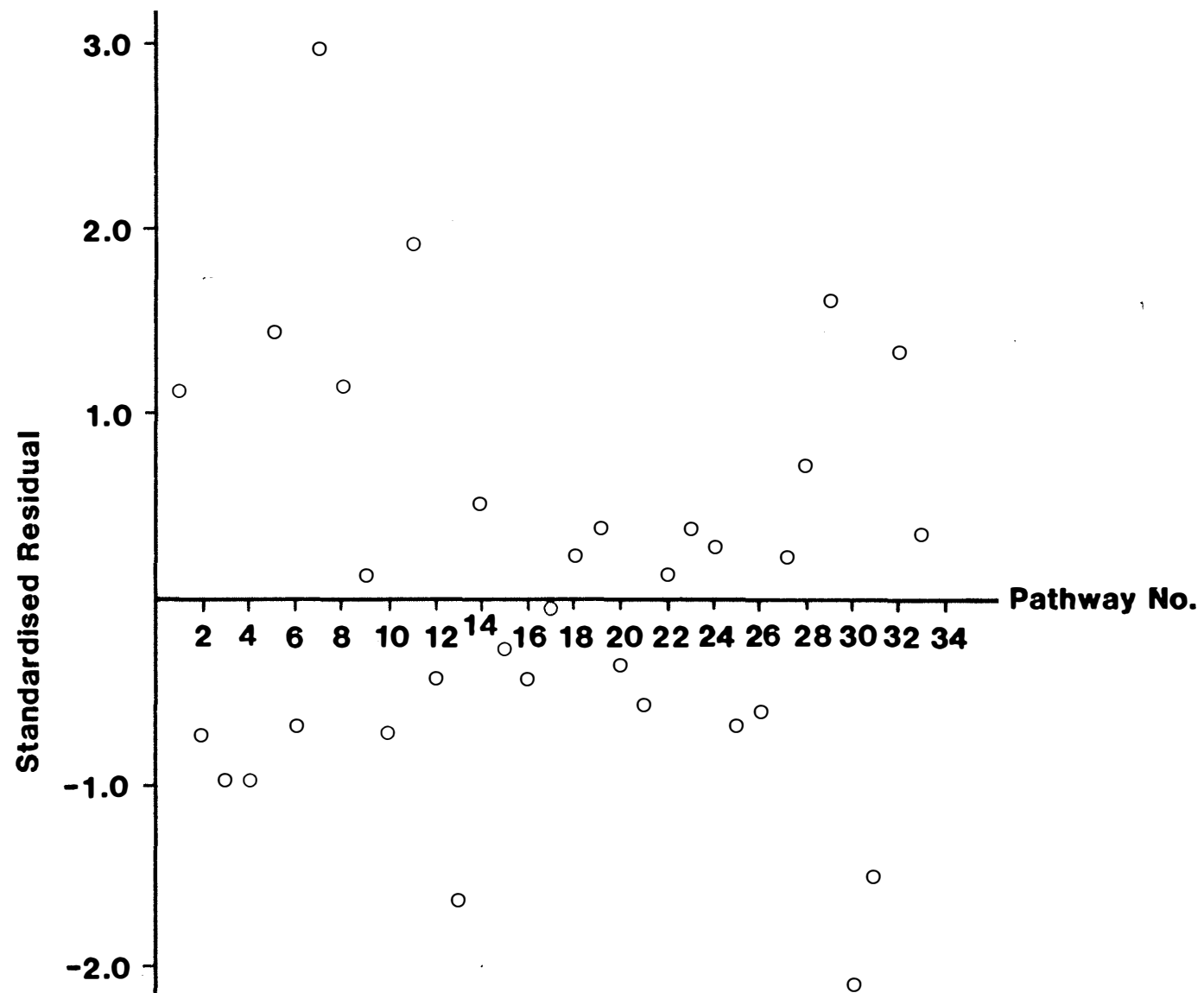


Fig. 4.1: Residual Plot: Standardised Residual vs Pathways for m_2 Model of an Energy Efficient Economy.

produced by most regression programme packages).

The pathway which has the highest relative net energy yield (i.e. has the highest positive residual) is: Oil → High Grade Transport. This indicates that this is a relatively efficient pathway, which has extra significance as it is the main pathway in the present economy (refer to Chapter 3). Somewhat oppositely, there is a marked tendency for those pathways which are non-existent or have very small flows in the existing economy, to have low relative net energy yields (i.e. have a negative residual):

(4) Wood → Electrical Output,	-0.0767 ($m_2 = 1$)
(6) Coal → High Grade Transport,	-0.0510 ($m_2 = 1$)
(10) Hydro → High Grade Transport,	-0.0470 ($m_2 = 1$)
(12) Wood → Medium Grade Transport,	-0.0316 ($m_2 = 1$)
(13) Coal → Medium Grade Transport,	-0.1091 ($m_2 = 1$)
(20) Oil → Water Heating,	-0.0322 ($m_2 = 1$)
(30) Oil → Cooking,	-0.1545 ($m_2 = 1$)

The residual plot (Fig. 4.1), is satisfactory as the residuals appear to be randomly distributed around the origin. Therefore, there is no need to modify the general equation used in this model.

4.7.2 Relative Efficiency of Pathways

The relative efficiency (Q) of each pathway is the Outputs (Q) divided by the Inputs (Q). It should be noted that for a perfectly fitted model, all equations have a relative efficiency (Q) equal to unity. Therefore, pathways (1, 5, 7, 8, 9, 11, 14, 18, 19, 22, 23, 24, 27, 28, 29, 32, 33) which have relative efficiencies (Q) greater than unity, can be said to be relatively efficient (Q). Whereas, pathways (2, 3, 4, 6, 10, 12, 13, 15, 16, 17, 20, 21, 25, 26, 30, 31) which have relative efficiencies (Q) less than unity, can be said to be relatively inefficient (Q). As was mentioned in the previous section, there is some tendency for the most efficient (Q) pathways, to be the predominant pathways in the actual economy.

It should be noted that these efficiency (Q) calculations indicate what primary energy source should be "matched" with what effective energy class; from a relative efficiency (Q) point of view:

- (1) Hydro -> Electrical Output, Efficiency (Q) = 1.4502
- (2) Oil -> High Grade Transport, Efficiency (Q) = 1.3104
- (3) Gas -> Medium Grade Transport, Efficiency (Q) = 1.2073
- (4) Coal -> Industrial Heat, Efficiency (Q) = 1.4285
- (5) Hydro -> Water Heating, Efficiency (Q) = 1.2458
- (6) Hydro -> Space Heating, Efficiency (Q) = 1.5869
- (7) Coal -> Cooking, Efficiency (Q) = 1.3549

It should also be noted, that it is not always the most efficient (Q) to "match" a low quality energy source, with a low quality end-use, which is often implied in the literature (e.g. Lovins, 1977). Often, a high quality energy source can efficiently be used for a low quality end-use, as long as the appropriate technology is used. For example, these results indicate hydro-electricity (a high quality energy source) is the most efficient (Q) means of providing low grade heat for water and space heating, provided heat pump technology is used. Obviously, this would not be the case if resistance heaters were used as they have a lower thermal efficiency (100%) than heat pumps ($\approx 200 - 250\%$). In addition, it should be noted, that the role of electricity is to upgrade ambient temperature solar heat - this role can be fulfilled by providing only a small input of electricity because of its relatively high quality.

These results also indicate that low grade energy sources, can sometimes be relatively efficiently (Q) converted to high grade energy sources, for relatively high grade end-uses. This is the case in the conversion of coal to electricity (pathway one), which has a relative efficiency (Q) of 1.3287.

4.8 Central Hypothesis: Relationship Between Quality of Inputs, Quality of Outputs and Enthalpic Efficiency

These plots (Figs 4.2 - 4.8) demonstrate the relationship between three important variables, implicit in the Central Hypothesis:

- (1) Quality of Inputs (IQ/IH), on the Y axis.
- (2) Enthalpic Efficiency (OH/IH), on the X axis.
- (3) Quality of Outputs (OQ/OH), gradient.

Firstly, the plots demonstrate that there is a statistical linear relationship between the quality of inputs (IQ/IH) and the enthalpic

$$\text{Electrical Output} = 1.73n_1(m_2)$$

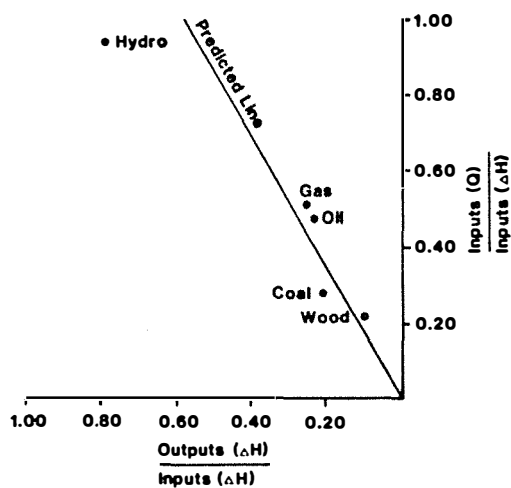


Fig. 4.2 : Quality of Inputs vs Enthalpic Efficiency of Pathways 1-5, $n_1(m_2)$ Model of an Energy Efficient N.Z. Economy.

$$\text{High Grade Transport} = 4.36n_1(m_2)$$

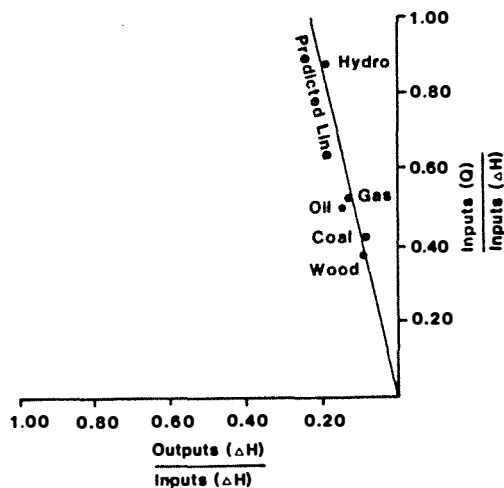


Fig. 4.3 Quality of Inputs vs Enthalpic Efficiency of Pathways 6-10, $n_1(m_2)$ Model of an Energy Efficient N.Z. Economy.

$$\text{Industrial Heat} = 0.69n_1(m_2)$$

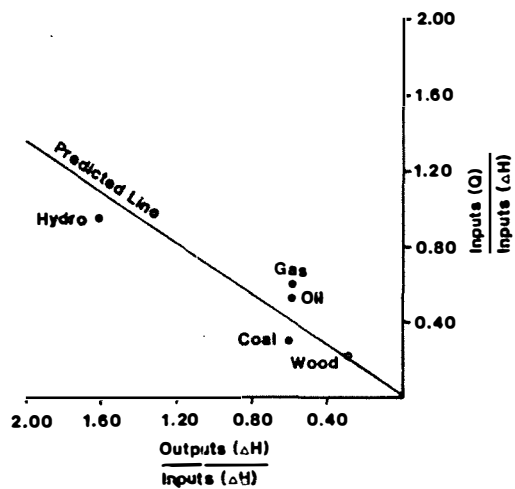


Fig. 4.4 Quality of Inputs vs Enthalpic Efficiency of Pathways 14-18, $n_1(m_2)$ Model of an Energy Efficient N.Z. Economy.

$$\text{Medium Grade Transport} = 3.59n_1(m_2)$$

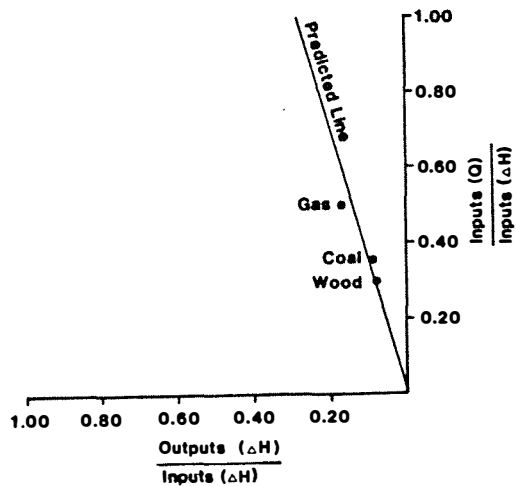


Fig 4.5 Quality of Inputs vs Enthalpic Efficiency of Pathways 11-13, $n_1(m_2)$ Model of an Energy Efficient N.Z. Economy.

$$\text{Water Heating} = 0.77n_1(m_2)$$

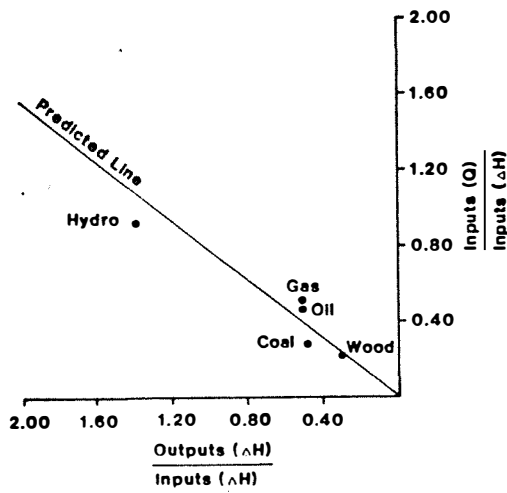


Fig. 4.6 Quality of Inputs vs Enthalpic Efficiency of Pathways 19-23, $n_1(m_2)$ Model of an Energy Efficient N.Z. Economy.

$$\text{Space Heating} = 0.78n_1(m_2)$$

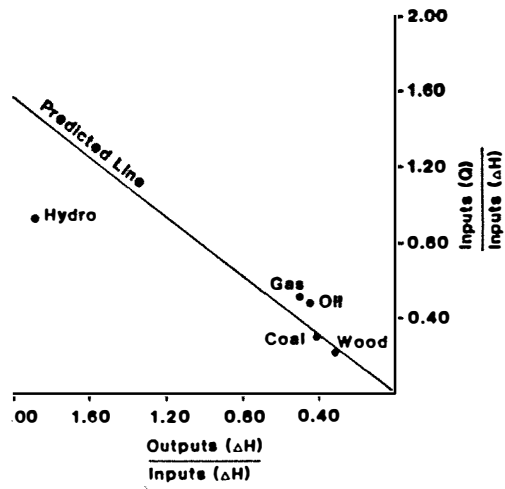


Fig. 4.7 Quality of Inputs vs Enthalpic Efficiency of Pathways 24-28, $n_1(m_2)$ Model of an Energy Efficient N.Z. Economy.

$$\text{Cooking} = 2.22n_1(m_2)$$

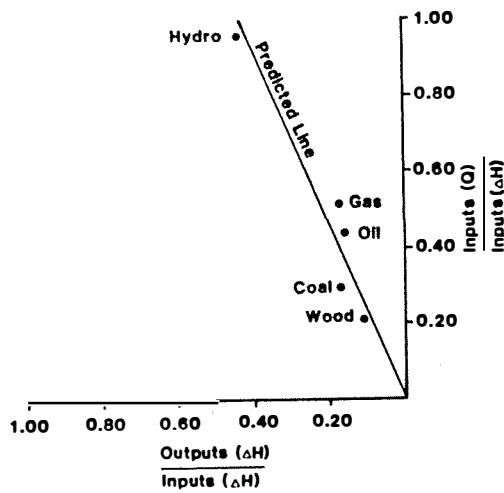


Fig. 4.8 Quality of Inputs vs Enthalpic Efficiency of Pathways 29-33, $n_1(m_2)$ Model of an Energy Efficient N.Z. Economy.

efficiency of the pathway. The higher the quality of the inputs (IQ/IH), the higher the enthalpic efficiency (OH/IH), of the pathway. Statistically, this relationship holds true (i.e. is statistically significant). This holds true irrespective of the actual inputs and outputs of the pathway (i.e. the independence assumption of regression analysis).

Secondly, the plots demonstrate that in a statistical sense each output has a fixed energy requirement (in quality equivalent terms). If this relationship was perfect, all points would fall on the plotted lines. Again, this relationship is significant irrespective of the actual mix of inputs and outputs.

4.9 Linear Programming Extensions

4.9.1 Introduction

The data matrix used in the multiple linear regression analysis, can form the basis of some linear programming (optimisation) runs. Some preliminary runs using the data matrix for the New Zealand Economy (1976) are included here. The quality coefficients ($n_1(m_2)$) derived from the "efficient" economy regression model, were used as they were considered to best reflect the long-run quality coefficients of the economy. If necessary, pathways from the "efficient" economy regression model, could be included in these linear programming runs. However, in this case it was somewhat subjectively assumed that it was unlikely that many of these pathways could "realistically" be expected to be options in the New Zealand situation.

4.9.2 Formulation of the model

4.9.2.1 Notations

For convenience and ease of reference the same notations as used in the regression model are used here.

4.9.2.2 Objective function(s)

The objective function ($f(x)$) for Run 1 was to minimise the sum of

the quality equivalents of the primary energy inputs:

$$\sum_{i=j}^{i=1} Q_i = \sum_{i=j}^{i=1} n_1 (x_1)_i + \sum_{i=j}^{i=1} n_2 (x_2)_i + \dots + \sum_{i=j}^{i=1} n_n (x_n)_i \quad (4.1)$$

The quality equivalents were measured in terms of hydro-electricity equivalents ($n_1 (m_2)$).

The objective function ($f(x)$) for Run 2 was to minimise the sum of quality equivalents of the "non-renewable" primary energy inputs (Coal, Gas, Oil):

$$\sum_{i=j}^{i=1} Q_i = \sum_{i=j}^{i=1} n_2 (x_2)_i + \sum_{i=j}^{i=1} n_3 (x_3)_i + \sum_{i=j}^{i=1} n_4 (x_4)_i \quad (4.2)$$

4.9.2.3 Constraints

Fundamentally, in models such as this, there are supply-side and demand-side constraints:

(1) Supply-Side Constraints

For "renewable" resources or "flow" resources, there is an upper limit on the rate of flow per given time period. For example, with hydro-electricity there is an upper physical limit to the amount of electricity that can be generated per year - this limit is obviously defined by the nature of our river and lake systems, the flow of water through these systems and our technical ability to utilize that flow. The Ministry of Energy (1981), estimate this limit to be 155 PJ/yr. However, in these runs a generating capacity of 71 PJ/yr was used as the upper limit, as this figure represented the present generating capacity - that is:

$$\sum_{i=j}^{i=1} (x_1)_i \leq 71.0 \quad (4.3)$$

Similarly an upper constraint can be placed on the amount of wood residues available :

$$\sum_{i=j}^{i=1} (x_5)_i \leq 15.0 \quad (4.4)$$

This figure was obtained from a study undertaken by Patterson (1979).

For "non-renewable" or "stock" resources, specifying flow rates per time unit, implies a whole set of economic and ultimately philosophical problems about appropriate resource depletion rates. As this "resolution" was considered outside the scope of this thesis, the specification of such flow rates (upper limits) on the use of "non-renewable" resources was not considered here. However, it should be noted that in Linear Programming studies, economists tend to use the "target year approach", to "overcome" this problem.

A specification and use of only two supply side constraints is obviously very rudimentary. A more sophisticated approach should involve the use of a wide range of social, economic, environmental, technical and physical constraints which limit the supply of primary energy sources. It should be noted that these constraints are often interrelated, and as long as these interrelationships can be quantified, they can be specified in the model. A post-optimal analysis should also be undertaken so as to explore the effect of varying the constraints.

(2) Demand-Side Constraints

There is an obvious demand for a certain amount of effective energy for each of the end-use classes, used in the regression model. These are specified by the following constraints:

$$\sum_{i=j}^{i=1} (Y_1)_i = 34.96 \quad (4.5)$$

$$\sum_{i=j}^{i=1} (Y_2)_i = 25.70 \quad (4.6)$$

$$\sum_{i=j}^{i=1} (Y_3)_i = 0.05 \quad (4.7)$$

$$\sum_{i=j}^{i=1} (Y_4)_i = 60.90 \quad (4.8)$$

$$\sum_{i=j}^{i=1} (Y_5)_i = 12.51 \quad (4.9)$$

$$\sum_{i=j}^{i=1} (Y_6)_i = 21.25 \quad (4.10)$$

$$\sum_{i=j}^{i=1} (Y_7)_i = 1.84 \quad (4.11)$$

Consumer acceptability constraints could be super-imposed on these constraints. For example, it could be argued that using coal for space heating or even cooking, although technically possible, is unacceptable to most consumers because of inconvenience factors.

4.9.3 Some preliminary results

4.9.3.1 Run 1 (Minimisation of IQ)

As is indicated by Table 4.7, the optimal solution for this run is 188.06 $n_1(m_2)$ which compares with the actual energy use of 255.50 $n_1(m_2)$. This is primarily achieved by using coal for all industrial heating and for all space heating, instead of the actually used fuels. Consequently, the use of coal is 155 PJ/yr in the optimal solution, compared with the actual usage of only 75 PJ/yr. The usage of all other primary energy sources is less in the optimal solution, than was actually the case in 1976. Hydro-electricity is the preferred primary energy source, for electrical output and for cooking. Gas is the preferred primary energy source for water heating. The model's formulation allowed oil to be the only primary energy source for high grade transport and gas to be the only primary energy source for medium grade transport.

It should be noted that none of the supply constraints was reached in the optimal solution, so the model simply "chose" the most efficient (Q) pathway, for supplying each effective demand class.

4.9.3.2 Run 2 (Minimisation of IQ - non-renewable)

As is indicated by Table 4.8, the optimal solution for run 2 was 152.76 $n_1(m_2)$ which compares with 119.33 $n_1(m_2)$ for the actual economy. In this model both the supply constraints (i.e. on hydro-electricity and wood) were reached, therefore it is no longer simply a matter of "choosing" the most efficient (Q) pathway. The hydro-electricity "quota" supplies all of the electrical output (34.96 PJ/yr), all of the cooking demand (1.84 PJ/yr), all of the water heating demand (12.51 PJ/yr), and a very small portion of the space heating demand (0.65 PJ/yr). The wood "quota" is entirely used for supplying a small portion of the industrial heat demand (4.95 PJ/yr). The rest of the

Table 4.7: Solution of Linear Programming Run 1 (Minimisation of IQ)

	Optimal Solution	Actual (1982)
Objection Function ($n_1(m_2)$)	188.06	255.5
Activity of Rows (PJ)		
X_1 , Hydro	55.98	70.97
X_2 , Oil	29.55	44.12
X_3 , Gas	155.25	226.41
X_4 , Coal	155.00	75.14
X_5 , Wood	0.00	9.44
ΣX	395.78	426.08
Y_1 , Electrical Output	34.96	34.96
Y_2 , High Grade Transport	25.70	25.70
Y_3 , Medium Grade Transport	0.05	0.05
Y_4 , Industrial Heat	60.90	60.90
Y_5 , Water Heating	12.51	12.51
Y_6 , Space Heating	21.25	21.25
Y_7 , Cooking	1.84	1.84
ΣY	157.21	157.21
Activity of Columns (Pathways)		
4. Hydro $\rightarrow$ Electrical Output	34.96	27.51
5. Oil $\rightarrow$ High Grade Transport	25.70	25.70
6. Gas $\rightarrow$ Medium Grade Transport	0.05	0.05
7. Coal $\rightarrow$ Industrial Heat	60.90	18.80
19. Gas $\rightarrow$ Water Heating	12.51	0.48
20. Coal $\rightarrow$ Space Heating	21.25	2.63
31. Hydro $\rightarrow$ Cooking	1.84	1.33

Table 4.8: Solution of Linear Programming Run 2 (Minimisation of IQ - non-renewable)

	Optimal Solution	Actual (1982)
Objective Function ($n_1(m_2)$)	119.33	152.76
Activity of Rows (PJ)		
X_1 , Hydro	71.00	70.97
X_2 , Oil	7.24	44.12
X_3 , Gas	156.95	226.41
X_4 , Coal	146.84	75.14
X_5 , Wood	15.00	9.44
ΣX	397.03	426.08
Y_1 , Electrical Output	34.96	34.96
Y_2 , High Grade Transport	25.70	25.70
Y_3 , Medium Grade Transport	0.05	0.05
Y_4 , Industrial Heat	60.90	60.90
Y_5 , Water Heating	12.51	12.51
Y_6 , Space Heating	21.25	21.25
Y_7 , Cooking	1.84	1.84
ΣY	157.21	157.21
Activity of Column (Pathways)		
4. Hydro $\rightarrow$ Electrical Output	34.96	27.51
5. Oil $\rightarrow$ High Grade Transport	25.70	25.70
6. Gas $\rightarrow$ Medium Grade Transport	0.05	0.05
7. Coal $\rightarrow$ Industrial Heat	55.94	18.80
10. Wood $\rightarrow$ Industrial Heat	4.95	1.74
15. Hydro $\rightarrow$ Water Heating	12.51	9.47
20. Coal $\rightarrow$ Space Heating	20.60	0.48
27. Hydro $\rightarrow$ Space Heating	0.65	7.24
31. Hydro $\rightarrow$ Cooking	1.84	1.33

industrial heat demand (55.94 PJ/yr) and the space heating demand (20.60 PJ/yr) is supplied by coal. Oil and Gas respectively supply the high grade and medium grade transport, which is the only "choice" available in this model's formulation.

4.9.4 Some Improvements and Extensions

The following improvements and extensions of these very rudimentary models are suggested.

4.9.4.1 Objectives

Energy policy formulation and planning should obviously be multi-objective, as is evidenced by the policy statements in the Ministry of Energy (1980, 1981b) Energy Plans. No one objective should override all other objectives, as society has many differing needs and values which are required to be fulfilled. However, despite this almost truistic statement, energy optimisation models and indeed many economic planning models, are pre-dominately single-objective - in the case of energy models they are usually cost minimising formulations (e.g. Smith, 1978).

Therefore, a more sophisticated formulation of these models, should attempt to take account of these multi-objectives. There is a diverse literature on various multi-objective and goal programming approaches (e.g. Lee, 1972). It is also considered useful, to "experiment" with differing objectives of different weightings, so as to explore the possibilities for policy formulation. This is especially important when there is a high degree of uncertainty associated with the relative importance of various policy objectives.

4.9.4.2 Constraints

As has been mentioned previously, there are many more constraints that could be added to these model formulations. Essentially, these are energetic optimisation models, so therefore economic, social and environmental constraints have not been superimposed on these models. However, without mentioning them, the possibilities are almost endless.

Greater emphasis could be placed on the supply-side constraints, in conjunction with less emphasis on the demand-side constraints, which

is usually the case in energy optimisation modelling. That is, the optimal demand structure of the economy could be determined given a set of energy supply constraints. Instead the opposite is usually the case in energy modelling. This could indicate the "best" economic structure, for our given set of primary energy resources.

4.9.4.3 Substitution Possibilities and Interdependence Equations

Essentially these models are formulated so that there are a given number of independent pathways, linking a primary energy source with an effective output class (these pathways are formulated as being independent, because this is an assumption used in regression modelling, from which the problem matrix was derived). However, in reality there are many possibilities for substitution between different energy forms; and often the level of supply or use of one energy form is dependent on the level of supply or use of another energy form. Equations allowing for and describing these possibilities should be included in the model formulation.

4.9.4.4 Inclusion of Future Supply and Use Options

These models only included actual supply-use pathways, whereas there are many other possible supply options and some other possible use options (e.g. refer to table 4.1). These future supply and use options should be included in the model formulation.

4.9.4.5 Post-Optimal Sensitivity Analysis

This is a most important, but often neglected, element of linear programming, as it helps the analyst understand the "dynamics" of the system being modelled. This is particularly important when modelling in public policy areas, where there is much uncertainty about policy goals and the effects they may have.

5 DISCUSSION

5.1 Uses and Applications of Data Derived from the Modelling Procedure

Essentially, the quality coefficients derived from the modelling procedure, enable energy to be expressed in terms of common quality units (quality equivalents). This should in turn provide a means of overcoming the "energy quality" problem, which has previously hindered EA applications and uses, and hindered its acceptance as an acceptable evaluative procedure. In addition, the use of quality equivalents derived from the modelling procedure, can be of assistance in technology and process efficiency assessment, in end-use matching of energy sources to uses, in policy-making and formulation, and can be of assistance in improving energy statistics.

5.1.1 Net Energy Analysis

In Net Energy Analysis, Net Energy Ratios (N.E.R.) are frequently used to assess the efficiency of net energy production. The N.E.R. is simply the system's output (ΔH), divided by the system's input (ΔH). Similarly, the Net Energy Yield (N.E.Y.), which is the system's output (ΔH) minus the system's input (ΔH), is frequently used to assess the amount of net energy yield.

Net Energy Ratios can be misleading because the inputs and outputs of the industry or system are of differing qualities. For example, with many biomass energy production systems the energy inputs are high quality energy resources (particularly electricity) and the outputs are only medium quality energy resources. This was found to be the case with wood gasification and catalysis to methanol (Earl, 1978), and the production of biogas from wastes (Slessor and Lewis, 1979). Therefore, particularly in countries such as New Zealand, where most consumer-level electricity can not be converted back to fossil fuel energy units, this leads to inflated Net Energy Ratios when conventional enthalpy units (ΔH) are used in the calculation. In fact, by converting all inputs and outputs to common quality equivalents this means that some systems actually produce no net energy, and therefore

they are not viable as energy producing systems.

The opposite is the case in the estimation of Net Energy Yields of nuclear power stations where the main output is a high quality energy resource (electricity) and the main inputs are medium quality energy resources (fossil fuels) (Chapman, 1975). That is, in this case if the Net Energy Ratio is expressed in conventional enthalpy units (ΔH), it is deflated. This is because no weight is given to the fact that a high quality energy resource (electricity) is produced from lower quality energy resources (fossil fuels). Therefore, in cases like these the use of quality coefficients to convert all inputs and outputs to quality equivalent terms, should add more weight to the Net Energy concept in technology evaluation and assessment.

5.1.2 Technology and Process Assessment and End-Use Matching

The use of data derived from the modelling procedure and the direct use of the modelling procedure, can be used to assess different process technologies and assist in end-use matching of energy sources and uses. The use of such data in Net Energy Analysis, in assessing energy supply technologies, was discussed in the foregoing section (section 5.1.1).

Examination of the residuals, and other post-analysis calculations, indicated some primary energy sources had the ability to be converted to effective energy outputs, more efficiently than others (given the assumed technologies). That is, more efficiently in quality equivalent terms. For example, hydro-electricity was found to be the most efficient (1.45) means of generating electricity (refer to Table 4.6). This was compared with lesser relative efficiencies for coal (1.33), oil (0.87), wood (0.84) and gas (0.83), for generating electricity. By examining the enthalpic efficiencies (ΔH), it would not be evident that coal was the second most efficient means of generating electricity. The data included in Table 4.6, indicates that oil and gas, are more efficiently used for providing energy for transport.

The data derived from the modelling procedure, is particularly

useful for comparing the energy efficiency, of technologies which produce the same output or meet the same demand requirement, but utilize different primary energy sources. For example, previously comparing using wood for providing space heating, with hydro-generated electricity via a heat pump, was plagued with the methodological problem of energy quality. Essentially, the two processes used different sources of energy of different grades or quality. However, now, by using the quality coefficients, the two sources can be converted to quality equivalents and be directly compared. Also, this procedure overcomes the problem of dealing with multiple inputs of energy all of different qualities (which is usually the case in most real situations).

5.1.3 Policy - Making and Formulation

Energy planners and policy-makers, often use terms such as "low" energy options, or energy "efficient" options. For example, it is a stated policy objective of New Zealand energy planners to "ensure that energy is used efficiently" (Ministry of Energy, 1979). However, these terms "low" and "efficient" have rather nebulous and obscure meanings - it cannot be taken that the energy planners mean "most efficient" in enthalpy terms, because it logically follows that the whole country would be running on hydro-electricity.

Obviously, by using some measurement, such as quality equivalents, which take into account the energy quality of different primary sources of energy, the terms "energy efficient" and "low energy" have more meaning in policy formulation. If quality equivalents, are to be used in policy formulation, some thought should be given to the time horizon of the plans or strategies involved. As is discussed in section 3.9.2.2, if the plan has a long time horizon, long-run quality coefficients which reflect thermodynamic limits should be used.

In conjunction with any such policy making, optimisation modelling techniques, can form a useful basis to formulating short or long term policies or scenarios. As a first approximation the same data matrix used for the regression analysis, can be used (refer to section 4.9 for a Linear Programming example of this application).

5.1.4 Energy Statistics

Most official energy statistics are couched in enthalpy (ΔH) terms; with a few countries using Fossil Fuel Equivalents to take account of the different qualities of different forms of energy, particularly hydro-electricity as opposed to fuel generated electricity. For example, the O.E.C.D. Energy Balances (1973 - 1979), used oil equivalents; and the New Zealand Ministry of Energy (1981) used coal equivalents on one occasion, in their publication "Energy Planning '81".

The use and publication of such statistics, can lead to serious mistakes in planning especially when the planners are not well-versed in energetics and thermodynamics; and can present misleading information to the public and other agencies which have some interest in energy matters. For example, two completely different pictures emerge of energy use in New Zealand, when energy is measured in enthalpy (ΔH), and quality equivalent terms (refer to Table 5.1).

Therefore, it is suggested that energy statistics, be presented in both enthalpy (ΔH) and quality equivalent terms. The use of Fossil Fuel Equivalents, as discussed in section 2.1.2, is not considered to be adequate, particularly when it is only used to account for hydro-electricity alone.

There is a problem inherent in the use of quality equivalents, and that is that they are only applicable to a given economy with its given mix of technologies. Therefore, as an economy changes so will its quality equivalents, and it is also difficult to compare a quality equivalent from one country to another. However, if long-run coefficients are used (which reflect thermodynamic limits), this problem should largely be resolved, although the different structural nature of different economies may marginally affect the quality coefficients between countries.

5.2 Possible Extensions of the Modelling Procedure Relevant to Energy Analysis and Theories of Production

One of the major limitations and points of criticism of the

Table 5.1: Comparison of Energy Consumption Statistics for New Zealand (1981), Expressed in Enthalpy and Quality Equivalents Terms

	Enthalpy (ΔH)		Quality Equivalents ($n_1(m_2)$)	
	(PJ)	(%)	(PJ.Q)	(%)
Primary Energy Input				
Hydro-electricity	74	19	74	35
Natural gas	46	12	24	11
Oil	195	49	95	44
Coal	70	18	19	9
Wood	10	3	2	1
TOTALS	395	100	214	100

Totals may not add up, because of roundings.

Data sources:

- (a) Department of Statistics (1982), "New Zealand Yearbook 1982"
- (b) Patterson (1979).

conventions established by the I.F.I.A.S, and EA based on these conventions, is that not all energy resources (particular solar) and labour inputs are taken into account. This approach has tended to take account of high quality renewable energy resources, and neglect lower quality renewable energy resources. This approach is to some extent justifiable in modern economies where such inputs are no longer significant in terms of sustaining high levels of economic growth. However, these inputs can be critical, particularly in less developed economies with less energy intensive systems, or in more developed countries such as New Zealand which depends to a large extent on renewable energy resources (hydro-electricity and solar energy via agricultural and forestry systems) for its high level of economic growth. In such circumstances it could be considered appropriate to include renewable energy resources as x variables in the regression model.

Coefficients for labour inputs could be expressed in terms of man-years per effective energy output. In effect, these would be an expression of the energy equivalents of labour, such as those implicit in data presented by Steinhart and Steinhart (Fig 9, 1975), De Wit (1975) and Echiburu (1977). In a similar fashion, a coefficient for land inputs could also be determined, so that the energy equivalent of land could also be used. This approach could be particularly useful in studying agricultural, horticultural and forestry systems, where land is an important input into the production process. Leach (1976) has, in effect, used this approach in his study of "Energy in Food Production" (refer to Fig 13). Here, Energy (GJ) was plotted against Land (ha), for various production options for producing 1000 gallons of milk, and the resulting gradient of line was determined to be 24 GJ/ha. Presumably, Leach (1976) "fitted" the line by sight, but obviously the correct mathematical method is "least-squares" (regression) fitting.

It is also useful to note that Leach (1976), considers there to be three "fundamental" resources, which all resources "reduce back to": Energy, Labour and Land. Regression analysis, could well provide a focus for integrating this concept on a more rigorous mathematical basis. It should be noted, that although trade-offs or substitution are possible between these resources, none of them is absolutely substitutable for the other, and this could lead to difficulties in

proposed "Theory of Value" or "Theories of Production" based on this precept. It is also interesting to note, that the concept of "quality" applies to all three of these resources: quality of land (as indicated by different land classes), quality of labour (unskilled through to skilled), and energy quality (as discussed in the foregoing sections).

5.3 Evaluation of the Modelling Procedure for Solving the Energy Quality Problem

Generally, the two applications of the modelling procedure, which are detailed in Chapters 3 and 4, were successful. The modelling procedure was flexible - that is, it was generally found not to be critical what variable was used as the equivalencing unit. Statistically significant results were obtained in all cases, and the standardised coefficients for all cases were very similar. Furthermore, the results made good technical and physical sense. Hydro-electricity was always found to be the highest quality energy source, followed by gas, oil, coal, and then wood. There was more variation in the ranking of the energy uses. However, generally cooking, high grade transport and medium grade transport were found to be the highest quality end-uses, followed by electrical output, and then by space, water and industrial heating.

The modelling procedure can be applied, to any system or economy, where the outputs are linearly proportional to the inputs. This is the case in almost all systems and economies, and in cases where the relationship is not linear, non-linear regression should be used. The essential problem is to identify a classification of inputs and outputs, that results in a data matrix which best "fits" the general equation. This can often be an instructive process as it can provide insight into the physical and technical reasons why inputs and outputs should best be classified in a particular way.

Besides providing a means of quantitatively assessing the quality of inputs and outputs, the modelling procedure directly provides information into the relative efficiency of the pathways which make up the model. This can assist in technology and process assessment, and in end-use matching of energy sources and uses. The modelling procedure also has an indirect benefit in providing data, which can

solve some of the methodological problems encountered in net energy analysis, compilation of energy statistics, and in energy policy formulation.

However, probably most importantly the methodology provides a conceptual framework, with a concomitant mathematical basis, for simultaneously explaining energy quality. In this way the concepts of energy quality or grade of sources and uses, which have been widely referred to on a more conceptual level in the literature, can be given a more precise mathematically based meaning. This has led to providing a means of resolving the "energy quality problem", as well as providing a wider construct for the concept of energy quality.

The main weakness of the technique, is that the quality coefficients are dependent, at least to a small extent, on the weightings placed on the pathways (or the implied structure of the economy). This means that the quality coefficients will change to some extent, as the structural nature of the economy changes over time. This also means that quality coefficients, between countries or systems, cannot always be interchangeable and comparable in their use, particularly when the systems or economies are significantly structurally different.

A fundamental weakness of the technique is that it is essentially empirical rather than theoretical in its approach. The observation was made that all inputs (ΔH) and outputs (ΔH) of known energy systems, appeared to be convertible to common energy units (quality equivalents). A general equation was derived expressing this hypothesis. The general equation was statistically tested using data from two cases (N.Z. Economy 1976, Efficient N.Z. Economy), and found to be an empirically correct observation within fairly accurate statistical limits. Attempts could be made to establish a theoretical basis for this equation, based on thermodynamics, if extensive testing found it to be valid in all cases. However, because of the uncertainties and lack of definition associated with systems which the equation could be applied to (e.g. national economic systems), it seems to be extremely unlikely that such attempts at theoretical abstraction would be successful.

Nevertheless, more thermodynamic rigour could be introduced by linking each primary energy source to an effective energy output, by using the most energy efficient means as defined by thermodynamic limits (refer to section 3.9.2). This would mean that all models had the same basis, unlike the models used in Chapters 3 and 4, which assumed certain technologies - this approach would be independent of assuming technologies and only dependent on thermodynamic limits. However, it should be noted that this approach assumes infinitely slow reversible processes. In addition, the determination of these "thermodynamically efficient" pathways is far more difficult and time consuming, than using empirical data.

In conclusion, it is considered that the modelling procedure, provided a flexible and widely applicable method for resolving the "energy quality problem", as well as providing a broader conceptual framework for the concept of energy quality. The major limitation of the method is that, it appears to be dependent, usually to only a small extent, on the structure of the system or economy being examined.

5.4 Further Uses of Regression Analysis in Energy Analysis

Regression analysis potentially provides a means of solving, at least elements of, three main methodological problems facing EA - that is:

(1) Partitioning Problem As discussed in Chapter 1 regression analysis has provided a useful tool for overcoming partitioning problems when the outputs (independent variables) are not proportional to each other (Cleland, Earle and Boag, 1981; Rao et al., 1981; Jacobs, 1981). The problem becomes confounded and essentially unsolvable when the outputs are proportional to each other. Regression analysis was successfully used in this manner by the author (Patterson and Earle, 1982a), to estimate energy intensities (MJ/Kg) of various cooking modes, in the Catering Industry.

(2) Boundary Problem As is discussed in section 5.2 labour could be included in the regression equation, so that an energy equivalent of labour could be determined. In fact, the assumption of including or not including labour in the systems boundary, could be tested by regression analysis, by testing whether the labour variable (a dependent variable) had a statistically significant effect on the

output of the system (independent variable). Incidentally, within such an analytical framework the effect of land on the systems output could also be tested - that is:

$$Y = aA + bB + cC + D \quad (5.1)$$

Y = Output (probably measured in \$)

A = Energy Input (energy equivalents)

B = Land Input (land equivalents)

C = Labour Input (labour equivalents)

a = Energy coefficient (\$/energy equivalents)

b = Land Input (\$/land equivalent)

c = Labour Input (\$/labour equivalent)

D = constant

This leads to a general criterion for resolving the Boundary Problem - if a variable (or factor) does not have a significant effect on increasing the output of a system, then there is no reason for including it within the system boundary. This "causative" effect can be tested by regression analysis, or any other appropriate technique. Unfortunately, the application of such a criterion and testing procedure can often be cumbersome and tedious, and therefore outweigh the value of undertaking such a procedure. In short, regression analysis or for that matter probably any other analytical procedure, provides no simple answer to the boundary problem.

(3) Valuation Problem As is demonstrated in the foregoing sections, regression analysis can provide a means of resolving the "energy quality" problem associated with EA, but it does not resolve the valuation problem in its entirety. Fundamentally, the technique does equate different forms of energy in terms of their differing qualities, but not in terms of their other characteristics. Most importantly, the technique does not enable the equivalencing of "non-renewable" with "renewable" energy resources; or more correctly energy sources with a high supply rate per unit of time (renewable), compared with energy

sources with a low supply rate per unit of time (non-renewable). Fundamentally, this is a problem which EA has in common with conventional Economics.

In summary, regression analysis provides a means for equivalencing differing variables (dependent variables), in terms of an output variable (independent variable). This can provide a useful tool in resolving some of the methodological problems inherent in EA. Problems result when variables cannot be equated, for analytical reasons or for more deep seated philosophical reasons. Moreover, it should be recognised that the ability to equate variables does not mean that variables can be completely substituted for each other. For example, Land can be equated with Energy in terms of some "Energy equivalent of Land", but Land is only substitutable for Energy and vice versa in terms of a given range (refer to De Wit, 1975).

5.5 Conclusions

The general equation outlined in chapter 2, provides a conceptual framework and a logical basis, for resolving and clarifying the "energy quality" problem, associated with the application and use of EA. The equation can be solved by regression analysis, yielding statistically accurate results. Regression analysis can also be used to overcome some of the partitioning and boundary problems also associated with EA. This approach to resolving the "energy quality" problem, has some limitations related in part to its fundamentally empirical rather than theoretical approach. Nevertheless, this method was found to be flexible and versatile, as it can be applied to any system or economy. Furthermore, data derived from this procedure can be used in assisting energy planning and policy making, technology assessment, and will directly improve the informativeness of energy statistics.

PART B: LINEAR PROGRAMMING MODELLING OF ENERGY USE
IN THE NEW ZEALAND FOOD SYSTEM

6 INTRODUCTION AND METHODOLOGY

6.1 Introduction and Literature Review

6.1.1 Previous Energy Analyses of Food Supply

Before the early 1970's, the study of the energy requirements of food supply was mainly confined to the then growing discipline of Ecology, and mainly focused on "natural" food chains or webs (e.g. Lindeman, 1942). The increased awareness of the population, food and resource depletion problems facing mankind, provided much of the impetus for the first energy analyses of man-modified food systems. Odum (1971) made one of the earliest transitions from Ecology to Energy Analysis, in his book entitled "Environment, Power and Society", where he analysed energy use in industrial food systems. Slesser (1973), from a background of Chemical Engineering, also provided one of the earliest energy analyses of food supply systems, determining the energy requirements for a variety of agro-food products. Other major researchers who initiated research in this area included: Leach (Leach and Slesser, 1973), Commoner et al. (1974), Pimentel et al. (1973), and Hirst (1974). From about this time onwards (1973-74), literally thousands of research articles and books have covered energy analysis of food supply (Dialog Literature Search, 1984). These studies vary in scale, from studies of national food systems (e.g. United States Food System - Steinhart and Steinhart, 1974), to sector level studies (e.g. United Kingdom Fishing Industry - Edwardson, 1975), to the product/process level (e.g. energy use in various food processing operations - Singh, 1978).

Energy Analyses of National Food Systems.

Various studies (Hirst, 1974; Steinhart and Steinhart, 1974; Booz, Allen and Hamilton Inc., 1976) have estimated the total energy requirements of the United States food system. These estimates range from 12% (Hirst, 1974) to 17% (Booz, Allen and Hamilton, 1976) of the primary energy used in the United States economy. Similar estimates have been made for the Australian (18.9%, O.E.C.D. 1982), Swedish (12.2%, Olsson, 1980) and United Kingdom (21.5%, O.E.C.D. 1982) food

systems. A higher estimate of 30% has been made for the New Zealand food system by Patterson and Earle (1984), due primarily to the greater relative activity of the agro-food sector in the New Zealand economy. Other less rigorous studies have been undertaken of other national food systems, including those of Hong Kong (Boyden *et al.*, 1982) and various O.E.C.D. nations (O.E.C.D., 1982). All these analyses have revealed similar sectorial uses of energy within the food systems (refer to Table 6.1). In most cases, the greatest requirement for energy is in the final preparation and cooking of foods, followed by food processing and production, with only a relatively small amount of energy being required for transport and distribution. The largest indirect energy requirement was found to be for packaging and for fertilizers.

Energy Analyses of Food Sectors.

The literature on energy analyses of food sectors is very prolific, particularly on articles covering agricultural sectors and to a lesser extent articles covering the food processing sectors. For example, studies have covered energy analyses of potato production (Shyam and Nagaich, 1982), corn production (Smil, 1982), beet-sugar production (Department of Energy, 1982); as well as broader studies of entire agricultural sectors in nations such as Pakistan (Jameel, 1982), New Zealand (McChesney *et al.*, 1982), and the United States (Enlow, 1982) - to cite some examples from the most recent literature. Similarly, studies have covered energy analyses of food processing - also to cite some examples from the most recent literature: dairy processing industry (Vickers and Miller, 1983), poultry processing industry (Combes and Boykin, 1980) and meat processing (Ferguson and Hendrickson, 1979). Relatively few studies have been undertaken of the other sectors of the food system, despite the fact that studies have indicated that these sectors (particularly the household) have considerable energy requirements.

Energy Analyses at the Product/Process Level.

There is also a quite considerable literature, focusing on this level of analysis. Much data has been collected in terms of energy requirements (MJ) per unit mass or per unit mass of protein, or per

Table 6.1: Energy Requirements of Selected National Food Systems

	United States ^a	Australia ^b	New Zealand ^c	Sweden ^d	United Kingdom ^e
Production	17.6	28.9	27.8	26.5	21.5
Processing	29.1	25.9	31.6	33.3	31.2
Distribution	15.8	10.4	17.9	10.2	12.2
Preparation	37.5	34.7	22.7	29.9	35.0
% of National Primary Energy Requirements	17.0	18.9	30.0	12.2	21.5

Data Sources:

- a. Booz, Allen and Hamilton (1976)
- b. O.E.C.D. (1982) for 1976-77
- c. Patterson and Earle (1984), for 1980-82, includes shopping for food in distribution
- d. Olsson (1980)
- e. O.E.C.D. (1982), for 1978.

unit of metabolic energy (MJ), for a particular process or food chain step. For example, Leach (1976) has compiled such data for the United Kingdom situation, and Pimentel (1980) has compiled such data for the United States situation. Such coefficients, are considered to be broad measures of the efficiencies of supply of such products. Other studies have focused on the technical efficiencies and engineering aspects for various process or design options - for example, to cite a few examples from the most recent literature: advanced gas-fired system in agriculture (Lowry and Brady, 1983), and irrigation technologies (Harrer and Wilfert, 1983).

6.1.2 Previous Optimisation Models of Food Supply-Use Studies

Linear optimisation models (Linear Programming) have been relatively widely used to solve food supply-use problems. These models have been used to solve:

(1) Nutrition Problems. An optimum least cost (\$) diet is determined from a set of foodstuffs, given a set of nutritional constraints. A Dialog literature (1984) search has revealed that this has been a popular area of research, particularly with respect to developing nations. The first such model was constructed by Smith (1959), using 572 foodstuffs and 12 nutritional constraints. Other such studies up until 1974 were summarised by Edwardson (1974). More recent studies have accommodated food preferences, and variety in diet, as well as overcoming the problem of oversupply of certain nutrients (Anderson and Earle, 1982).

(2) Maximisation of Food Output. These models have been used to determine the maximum output from agro-food systems, usually having land areas available for production as a major set of constraints. For example, Bernalhand and Ferenczi (1979) used such models to determine a maximum optimum for the Hungarian agricultural system; and Arora and Sharma (1979) investigated increased agricultural production in Uttar Pradesh given a set of land-use constraints.

Only a few linear programming models have been used to explore/solve food-energy problems. Penn and Irwin (1977) investigated the impact of various energy supply shortages on the United States food and fibre system, by using a linear programming Input-Output model. Fluck (1980) reported that Rehkugler (1976) determined a minimum energy

diet given a set of 10 nutritional requirements. Such a diet consisted mainly of cereals and fresh vegetables, with less preference given to dairy and meat products.

6.1.3 Critical Review of Previous Studies

6.1.3.1 Concepts of Energy Efficiency

Concepts of "efficiency" are all pervasive in the literature concerning energy analysis of food supply. Often the term "efficiency" is used in a glib indeterminant fashion, although the term has a precise mathematical meaning - that is, it is a ratio of a single output to a single input (Pearson and Corbet, 1980). The most commonly used measures of energy efficiency of food supply are:

(1) $\Sigma \Delta H$ metabolic energy outputs/ $\Sigma \Delta H$ primary energy inputs
(commonly termed energy ratio).

(2) Σ mass outputs/ $\Sigma \Delta H$ primary energy inputs
(commonly termed energy productivity).

(3) Σ mass of protein outputs/ $\Sigma \Delta H$ primary energy inputs.

In addition, Rawitscher and Mayer (1977, 1979) have attempted to relate various other nutritional outputs such as vitamins, to energy inputs.

As summarised by Fluck and Baird (1980) these concepts of efficiency have many weaknesses. Firstly, these measures of energy efficiency enumerate energy in enthalpy (ΔH) terms, which takes no account of quality of energy inputs (refer to Part A for a full discussion of this problem and a methodology for resolving this problem). Secondly, such measures of efficiency (as with all measures of efficiency) only relate one single output to one single input. The human diet does not require solely a certain amount of metabolic energy (as implied in 1), or solely a certain mass of food (as implied in 2), or solely a certain mass of protein (as implied in 3). However, the human diet does collectively require certain amounts of metabolic energy, protein, trace elements, vitamins and amino acids - not just one single output. Therefore, fundamentally, concepts of efficiency have little or no value in resolving energy-food-supply-use problems.

6.1.3.2 Concepts of Optimality

The concept of optimality is more powerful than the concept of efficiency. However, it has only been alluded to in the literature in a very qualitative manner. Optimality is defined as the "best" or "most favourable" use of a set of resources given a set of constraints or requirements. Within such a framework of "optimality", Pearson and Corbet (1980), for example, discussed the so called economic and energy "efficiency" of New Zealand agriculture. Pearson and Corbet (1980) discussed achieving agricultural policy objectives (economic and energetic) in terms of physical, social and economic constraints.

Fundamentally, however, most food-supply-use problems, are more appropriately approached as "optimality" rather than "efficiency" problems. There is a literature (section 6.1.2) which has explored such optimisation problems, in terms of the formalism of Linear Programming and conventional economic wisdom. However, as yet (excepting Rehkugler, 1976) such an approach has not been introduced into energy analysis in general or into energy analysis with respect to food supply-use problems.

6.1.3.3 Numeraire and Energy Analysis

It has been widely argued that "energy" is a more fundamental unit of account than "money" (Slessor, 1973; Odum and Odum, 1976). This point has been particularly strongly argued in the energy-food literature (for example, Ashby, 1976; in his forward to the seminal collection of works in Duckham et al. 1976). The basic tenets of this argument are:

- (1) That energy is considered to be the primary resource that "drives" all economic and natural systems.
- (2) That energy resources unlike material resources are absolutely depletable, due to the Second Law of Thermodynamics. Energy quality is always degraded, when energy is "used". Whereas, material resources can always be manufactured, recycled or reused out of used or virgin materials, by using more energy.

Hence, the author acknowledges that energy is the primary physical resource that underpins economic growth, and therefore is often an

appropriate numeraire in macro-level studies. However, the critical nature of material, land and labour resources and their inter-relationships with energy should be taken into account:

- (1) Material resources are reducible to energy units. However, over time increasingly more energy is required to supply material resources as lower grades of ore are used, until a base level is approached (refer to Fig.6.1). This often critical factor should, whenever possible, be incorporated into Energy Analyses.
- (2) Land resources are finite and constant over time given sustainable cultivation practices and geological stability, and are only dependent on inputs of energy over geological time periods.
- (3) Labour resources are constant over time assuming demographic stability; but do depend on indirect inputs of energy for food, shelter, clothing and other material comforts which sustain a particular standard of living.

It should also be recognised that there is a critical relationship between time and these fundamental resources. The production rate of a process or system can be increased, by inputs of one or more of these fundamental resources. This is the case in modern agriculture, where to meet the food demands given a limited amount of land and usually labour, the production rate is increased by greater inputs of material and energy resources. Whereas in 'natural' agro-ecosystems the production rate is much slower being not dependent on large amounts of essentially fossil fuels. Many of the other trade-offs between time and energy are outlined by Slessor (1978).

In the past, most often land and labour resources have been excluded from Energy Analyses and material resources have been reduced to energy terms. Sometimes attempts have been made to reduce labour inputs to energy terms, although no consensus has emerged as to what method is correct (refer to section 1.2.1.4). The approach in this study has been to include land, labour and energy resources in the analysis as the three most fundamental resource inputs (this is the same as the method recommended by Leach, 1976). Land and labour resources are treated as being essentially constant, assuming constant land and labour availabilities. Energy is considered to be the variable input which increases or decreases output, within the given constraints of land and labour supply.

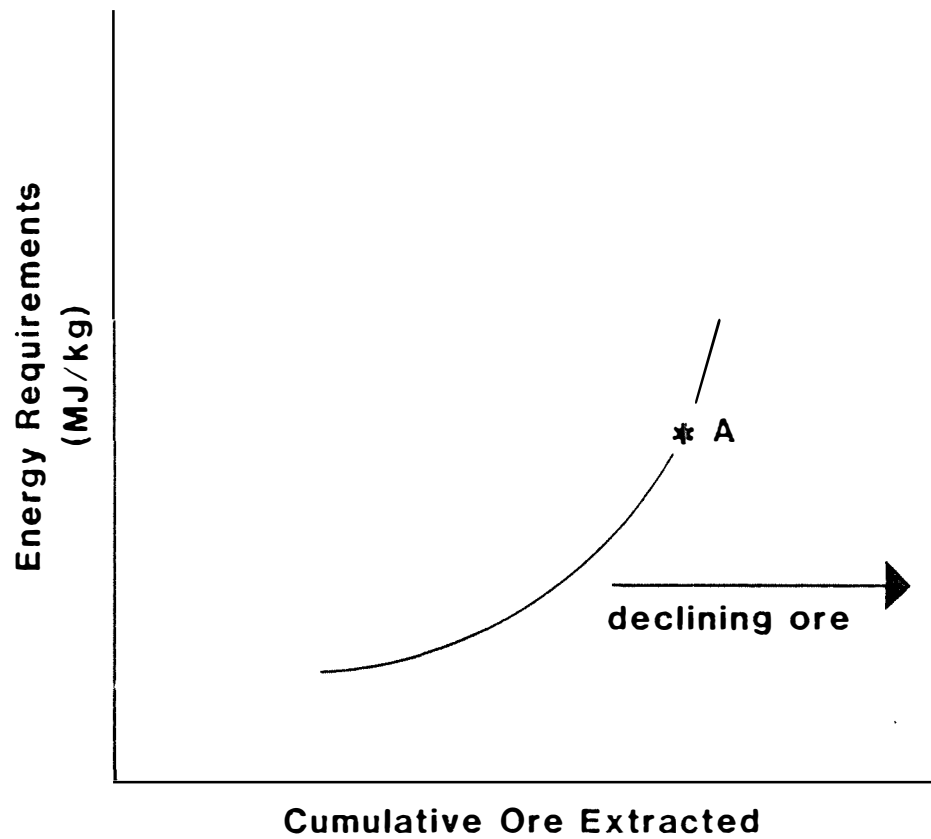


Figure 6.1: Schematic relationship between energy requirements (MJ/kg) of materials and ore grade. 'A' is the point representing the energy requirements of using recycled ores.

6.1.4 Net Energy Concept

The concept of net energy is central to EA. Net energy is simply the energy output (gain) of a system minus the energy input (loss) of a system. Net energy is required for the physical growth of any system or economy. Hence the fundamental nature of the net energy concept in EA.

Economies must gain net energy by either indigenous primary energy sources and/or by external trade to provide growth:

(1) Net Energy Gain From Primary Energy Sources. Primary energy sources are defined as those which have a net energy ratio greater than unity (Odum and Odum, 1976). Sources of energy which do not yield net energy ratios greater than unity are secondary energy sources, and do not provide net growth, as they consume more energy than they provide. Such energy analyses of primary energy sources are well represented in the literature. Studies range from analyses of nuclear power stations (Chapman, 1975); to biological energy resources (Earl, 1978; Lewis and Slessor, 1978); to analyses of more conventional primary energy sources (Slessor, 1978 Table 6.1).

(2) Net Energy Gain From External Trade. This source of net energy has not been quite as well researched as those detailed in (1). Studies of the net energy gained from trading agricultural products for Oil in the United States has been studied by Odum and Odum (1976), and Herendeen (1978) researched the net energy yielded by the trade in the Norwegian economy. Despite the lack of research in this area, the net energy gained from New Zealand's export of agro-food products is a very important source of net energy to the economy. Hence, the energy balance of New Zealand's external trade has been relatively well researched. Stephenson and Saha (1980) estimated that New Zealand's external trade had a net energy yield of 16PJ in 1976 (expressed in enthalpy terms). Baines and Peet (1982) compared the net energy yield of exporting meat for oil, with biological energy supply options. Other studies of New Zealand's energy balance of trade have been undertaken by Baines et al. (1981) and Odum and Odum (1979).

6.1.5 Reiteration and Statement of Objective for Part B

The New Zealand food system has two main functions: to supply agro-food products for external trade, which can be exchanged for oil and energy intensive goods, so providing net energy for the growth of the New Zealand economy (production function); to supply food to physically sustain the New Zealand population by providing metabolic energy and other essential nutritional outputs (consumption function).

Therefore in terms of an Energy Analysis - Optimisation framework, valid objectives are to maximise net energy gain by trading agro-food products, and to minimise net energy loss in the domestic consumption. (These objectives are mathematically equivalent). Herein lies the objective for Part B which is: "to explore/determine the 'optimum use' of resources in the New Zealand food system, in terms of this construct of net energy gain".

This is a major departure from other related studies:

- (1) Optimal rather than efficient energy use is being focused on (refer to sections 6.1.3.1 and 6.1.3.2).
- (2) The question of optimum resource use in food system is being explored in terms of the net energy concept, rather than in terms of a construct based on conventional economic wisdom (refer to section 6.1.3.3 and 6.1.4).

6.2 Methodology: Data Collection and Analysis

6.2.1 Classification of Sectors

The sectors of the food system were classified as follows:

- (1) Production The steps of the food system where biological materials are produced from primary natural resources, ready for processing or direct consumption. This includes, dairy farming, sheep and beef farming, cropping, horticultural activities, poultry farming, pig farming and fishing.
- (2) Processing Those steps in the food chain where biological raw materials are converted into foodstuffs ready for distribution to the point of final consumption.
- (3) Wholesale Distribution Those storage and transportation steps in

Table 6.2: Survey Classification and the New Zealand Standard Industrial Classification

Survey Classification	New Zealand Standard Industrial Classification	
	Number	Name
Production		
Factory Supply Dairy Farms	11111	Principally Dairy Farming
Town Supply Dairy Farms	11112	Predominantly Dairy Farming with Sheep
	11113	Predominantly Dairy Farming with Beef
	11114	Predominantly Dairy Farming with Other Farming
Pig Farming	11116	Principally Pig Farming
	11117	Predominantly Pig Farming
South Island High Country	1112	Sheep Farming
South Island Hill Country	1113	Beef Farming
North Island Hard Hill Country		
North Island Hill Country		
North Island Intensive Fattening		
South Island Fattening - Breeding		
South Island Intensive Fattening		
South Island Mixed Cropping and Fattening		
Mixed Livestock and Other Farming	11141	Mixed Livestock Farming
Poultry Farming	11145	Poultry Farming
Cropping	1116	Cropping
	1117	General Mixed Farming
Horticulture and Production Not Elsewhere Classified	1118	Fruit and Vegetable Growing
	11192	Hop Gardens
	11197	Bee Keeping
Fishing	1301	Ocean and Coastal Fishing
	1302	Fishing Not Elsewhere Classified
Processing		
Meat Export Works	31111	Meat Export Works
Abattoirs	31112	Other Abattoirs and Rural Slaughter Houses
Ham, Bacon and Meat Smallgoods	31113 (part)	Meat Packers and Cannerys
	31114	Ham, Bacon and Smallgoods
Poultry Processing	31115	Poultry Slaughter Houses
Co-operative Dairy Factories	31121	Co-operative Dairy Factories
Milk Processing Plants	31122	Milk Processing Plants
Icecream Factories	31123	Icecream Factories
Fruit and Vegetable Processing	31130	Canning and Preserving of Fruit and Vegetables
	31113 (part)	Meat Packers and Cannerys
Fish Processing	31141	Land Based Fish Factories
Oil and Fat Processing	31150	Vegetable and Animal Oils and Fats
Grain Milling	31161	Grain Milling
Breakfast Cereals	31162	Prepared Grain Breakfast Foods
Bread, Cake, Pastry and Pie Baking	31117	Meat Pies and Puddings
	31171	Bread Bakeries
	31172	Cake, Pastry and Pie (other than meat) Factories
	31173	Cake and Pastry Kitchens
Biscuit Baking	31174	Biscuit Factories
Sugar Refining	31180	Sugar Factories and Refineries
Confectionery	31190	Cocoa, Chocolate and Sugar Confectionery
Foods Products NEC	31120	Food Products Not Elsewhere Classified
	31175	Macaroni, Vermicelli, Spaghetti and Noodles
Soft Drinks	31340	Soft Drinks and Cordials
Wholesale Distribution		
Grocery Products	61211 (most)	Grocery Products
Refrigerated Products	61211 (part)	Grocery Products
Meat	61212	Meat and Meat Products
Fish	61213	Fish
Dairy and Related Products	61215	Dairy Products
Food NEC	61219	Foods NEC
Fruit and Vegetables	61220	Fresh Fruit and Vegetables
Retailing		
Groceries and Supermarkets	62211	Grocers
	62213	Supermarkets
Dairies	62212	Dairies
Butcheries	62214	Butchers
Greengroceries and Fruiteries	62220	Greengrocers and Fruiterers
Others	62215	Fish Shops
	62216	Delicatessens
	62219	Food NEC
Milk Vending	62218	Milk Vendors
Catering	63110	Takeaway Food Stores
	63120	Tea, Coffee Houses, Cafes, Unlicensed Restaurants
	63140	Licensed Restaurants and Cabarets
Shopping		
Groceries	62211	Grocers
Dairies	62212	Supermarkets
Supermarkets	62213	Dairies
Butcheries	62214	Butchers
Fish Shops	62215	Fish Shops
Delicatessens	62216	Delicatessens
Food NEC	62219	Food NEC
Greengroceries and Fruiteries	62220	Greengrocers and Fruiterers

the food chain from the processing plant's gate to the retailer's door. In the case of non-processed foods, it is those storage and transportation steps in the food chain from the first storage step (beyond the farm gate) to the retailer's door.

(4) Retailing Those steps in the food chain where food is sold for final consumption. These steps of the food chain usually occur between the last wholesale distribution step and the shopping step of the food chain.

(5) Shopping Those transportation steps in the food chain from retail establishments to households undertaken by household members.

(6) Household Preparation and Storage Those preparation and storage steps in the food chain which are undertaken in permanent dwellings immediately prior to final consumption.

(7) Household Production Production of biological raw materials in the household garden for consumption as food.

(8) Catering-Hotel Sector

Please refer to Table 6.2, for the N.Z.S.I.C. classification of these sectors.

6.2.2 Classification of Inputs and Outputs

Inputs and outputs were classified as either being exogenous or endogenous. Exogenous inputs/outputs cross the systems boundary and endogenous inputs/outputs remain internal to the system.

6.2.2.1 Exogenous Inputs

Exogenous inputs include Energy, Land, Labour and Food Imports:

(1) Energy These inputs were either direct or indirect (via another input of another good or service). These energy inputs (whether direct or indirect) can be traced back to primary inputs of Coal, Gas, Oil, Hydro-electricity, Wood, energy embodied in primary level capital or energy embodied in imports (refer to Carter, Peet and Baines, 1981 for a full classification of these primary energy inputs).

(2) Land These inputs were classified according to the Ministry of Works and Development (1979) 8 classes (with 4 sub-classes) classification system, making in total 32 land input classes. Only the direct land inputs were taken into account. Indirect land inputs are associated with several inputs of materials and capital. For example,

wood is required for packaging and buildings, and indirectly land is required to grow the wood. No data were available for estimating the indirect land requirements. However, such indirect requirements for land, were considered to be small.

(3) Labour These inputs are expressed in terms of man-year equivalents. Only direct labour inputs were taken into account. Indirect labour inputs are associated with almost all inputs into the food system. For example, labour inputs are embodied in the supply of all packaging and fertilizer inputs. No data are available for estimating the indirect labour requirements. As the indirect labour requirements are considered to be quite large, a fuller analysis should include indirect labour requirements.

(4) Food Imports These were classified according to the N.Z.S.I.C. production classification system.

6.2.2.2 Exogenous Outputs

Exogenous outputs included Nutritional Outputs and Food Exports:

(1) Nutritional Outputs These outputs include: Dietary Fibre, Metabolic Energy, Protein, Fat, Calcium, Phosphorus, Magnesium, Iron, Sodium, Zinc, Potassium, Vitamin A, Vitamin B1, Vitamin B2, Niacin, Vitamin B6, Free Folic Acid, Total Folic Acid, Vitamin C, Vitamin D and Vitamin E.

(2) Food Exports These were classified according to the N.Z.S.I.C. production classification system.

6.2.2.3 Endogenous Inputs and Outputs.

These referred to the inputs and outputs from sectors or food system steps, which do not immediately cross the systems boundary.

6.2.3 Estimation of Energy Inputs

The primary energy inputs into each sector or food chain step were estimated, drawing on surveys undertaken by the Food Technology Research Centre (Patterson and Earle, 1984), and various other statistical sources. Sector level data were used when more detailed food chain step level data were not available.

6.2.3.1 Primary Energy Inputs Considered

The following primary energy inputs were considered based on Carter, Peet and Baines (1981) classification method, used in their recently completed Input-Output based Energy Analysis of the New Zealand economy:

- (1) Hydro-electricity (ELECT). This refers to hydro-electricity at the point of generation, before transmission.
- (2) Natural gas (GAS). This refers to natural gas as it lies in the gas well.
- (3) Oil (OIL). This refers to oil products as they are imported in their various degrees of refinement, or indigenous oil as it lies in the oil well.
- (4) Coal (COAL). This refers to coal as it lies in the ground.
- (5) Wood (WOOD). This refers to wood as it leaves the forest.
- (6) Capital (CAPTL). This refers to energy embodied in primary level capital. Refer to Carter, Peet and Baines (1981) for a full discussion and definition of primary level capital.
- (7) Imported (IMPORT). This refers to energy embodied in the importation of merchandise into New Zealand. Refer to Baines, Peet and Carter (1981) for a full discussion and definition of this input.

Primary energy inputs are either direct (consumer level energy expressed in primary energy terms) or indirect (material, capital inputs not including endogenous food inputs, expressed in primary energy terms). In the coding system indirect inputs are preceded by the character "X". Indirect inputs of wood are not included as such inputs were not included in Carter, Peet and Baines (1981) analysis, from which most of the indirect inputs were calculated. Furthermore, direct inputs of solar energy were not included, in accordance with I.F.I.A.S (1974) convention.

All primary energy was expressed in terms of Gross Energy Requirements (GER) which includes the sum of all direct and indirect energy requirements. To avoid double counting, some sector energy requirements were also expressed in terms of Total Energy Requirements (TER). The TER does not include indirect inputs of energy from other sectors of the food system. For example, the poultry farming industry has an indirect energy requirement embodied in the supply of feed. The

GER would include the energy requirement of feed, but TER would not include the energy requirement of feed.

6.2.3.2 Production Sector

For full methodological details readers should refer to Patterson and Earle (1984). Data from the previous surveys were inadequate, because not all inputs were covered, and not all studies adhered to the I.F.I.A.S. (1974) conventions. Therefore, data had to be reanalysed.

The direct energy requirements (TJ/yr) were generally obtained from survey data collected by the Joint Centre for Environmental Sciences, and/or Producer Boards. Full references to the exact sources are contained in Patterson and Earle (1984). Often several sources were consulted or at least used for cross-checking purposes.

The estimation of the indirect energy requirements (TJ/yr), involve estimating the energy requirements of Materials and Services, the energy requirements of Capital, and the energy requirements of supplying the direct energy. Generally, the Materials and Services energy requirement involved:

- (a) estimating the cost (\$)
- (b) backdating the cost (\$) to 1971-72 terms
- (c) multiplying this cost (\$) by the appropriate energy intensity (MJ/\$), to obtain the total energy requirement of materials and services.

The costs (\$) were generally obtained from Producer Board Surveys, which are detailed in Patterson and Earle (1984).

The Capital energy requirements were estimated using the same method. Except the cost (\$) of the capital was obtained from the New Zealand Yearbook (1981). The costs (\$) were backdated to 1971-72 terms, by using the appropriate cost indices from the Monthly Abstract of Statistics (1972-80). The energy requirements of direct energy were estimated using data from Carter, Peet and Baines (1981).

An alternative method was used for calculating the direct energy requirements (TJ/yr) for the Horticulture and Production NEC, Poultry Farming and Fishing sectors. This involved using ratios from Carter,

Peet and Baines (1981). Full details of the calculations are outlined in Patterson and Earle (1984).

The total energy intensities (MJ/kg) were directly abstracted from the literature. It should be recognised that these total energy intensities were usually underestimates because not all inputs have been taken into account, particularly the energy requirement of direct energy.

6.2.3.3 Processing Sector

Data from previous surveys were inadequate because:

- (1) the survey years varied and differed quite markedly from the base year (1978-79 - 31 March to 1 April). To correctly associate energy inputs with other inputs/outputs, the base year must be consistent.
 - (2) sector definitions used in some surveys were vague, and did not conform with the New Zealand Standard Industrial Classification used for estimating the other inputs and outputs from the sectors.
- Therefore, it was considered necessary to re-analyse the data for 1978-79, and use the previous surveys detailed in section 7.3.2.1 only for checking purposes.

Detailed data from the Census of Manufacturing (1978-79), were used for these purposes. These unpublished data were supplied to the Food Technology Research Centre, on a confidential basis by the Department of Statistics (1982a). From these data the direct energy requirements were calculated, in consumer level terms and converted to primary level terms by using data from Carter, Peet and Baines (1981). The indirect energy requirements (material and packaging), were calculated by abstracting the costs (\$ 1978-79) of these inputs from the Census of Manufacturing data; backdating these data to 1971-72 costs (\$) by using the General and Wholesale Price Indices from the Abstracts of Statistics (1971-79); and then multiplying these costs (\$ 1971-72) by the appropriate energy co-efficients (MJ/\$ 1971-72) from Carter, Peet and Baines (1982). The indirect energy requirements of the capital (buildings and equipment) were calculated by using the capital expenditure data (\$ 1978-79) from the Census of Manufacturing (1978-79); backdating these data to 1971-72 costs (\$) by using the Ministry of Works and Development Construction Cost Indices (1971,

1979) and then multiplying these costs (\$ 1971-72) by the appropriate coefficients (MJ/\$, 1971-72) from Carter, Peet and Baines (1982).

6.2.3.4 Export-Import Sector

A weighted mean energy coefficient (MJ/\$) was calculated using data from Chudleigh (1979) to calculate the direct energy co-efficient (MJ/\$), and data from Carter, Peet and Baines (1982) to calculate the indirect energy co-efficient (MJ/\$). This could lead to misleading results as it assumes that the transport energy requirements of exporting-importing is proportional only to the monetary value (\$) of the product. This problem cannot be rectified until more accurate data becomes available.

6.2.3.5 Wholesale Distribution Sector

Data were drawn from a detailed survey of the Total Energy Requirements of the Wholesale Distribution of Foods, in New Zealand. Readers should refer to this publication (Patterson and Earle, 1982e) for full methodological details.

Initially, base data were collected from personal visits (38) to warehouses, distribution depots, storage facilities, produce agents and produce markets. Subsequently, to broaden the data base, a postal survey was undertaken of all food wholesale establishments (551) covered by the N.Z.S.I.C. which had not already been visited. The response rate for this survey was 42% after adjustments had been made for "no address" and "not applicable" returns. Although, as most of the large establishments returned completed questionnaires, about 80% of the total sales of the sector were covered.

Some data were also obtained from retail proprietors who in terms of our definition of wholesale distribution (refer section 6.2.1), undertook some wholesale distribution. This survey did not cover the wholesale distribution of fresh baked products, milk and cream.

The direct energy intensities (MJ/kg) for each storage and transport step were estimated directly from the survey returns.

The indirect energy intensities (MJ/kg) for the capital inputs into each storage step were estimated by using survey cost data (\$, 1980 - backdated to \$, 1972) and energy intensity data (MJ/\$, 1972) from Carter, Peet and Baines (1981).

The indirect energy intensities (MJ/kg) of the transport step were estimated by multiplying the direct energy intensity (MJ/kg) by the appropriate direct energy intensity: indirect energy intensity ratio (MJ/\$: MJ/\$) from Carter, Peet and Baines (1981).

The indirect energy intensities (MJ/kg) for supplying the direct energy were estimated using data from Carter, Peet and Baines (1981) using the same method as outlined for the processing sector (refer to section 6.2.3.3)

The direct and indirect energy requirements (PJ/yr) of the sector were estimated by multiplying the energy intensity data (MJ/kg, sometimes MJ/\$) by the appropriate annual throughputs (kg/yr, sometimes \$/yr) of each food chain step.

6.2.3.6 Retail Storage Sector

Data were drawn from a detailed survey of the Total Energy Requirements of the Retailing of Food, in New Zealand. Readers should refer to this publication (Patterson and Earle, 1982c) for full methodological details. A sample survey was undertaken of 120 retail food establishments in the Palmerston North area as the energy data collected in the Census of Distribution (1978) were inadequate in its coverage, primarily because it only covers establishments with 10 or more staff. Detailed energy data were collected particularly of the direct energy requirements of these establishments, with other data being collected so that the indirect energy requirements could be estimated. A comparison of turnover and floor area data collected in this survey with turnover and floor area data collected in Census of Distribution (1978) indicated that this sample should be representative of the national situation. Furthermore, acceptable sampling error were obtained for all shop types except the Greengroceries and Fruiteries grouping which fortunately had very low total energy requirements.

The direct energy intensity (MJ/kg) for each type of retail establishment for several different categories of energy requirement were estimated. These categories included direct energy intensities (MJ/kg) for refrigeration and non-refrigeration storage modes in retail establishments. The indirect energy intensities (MJ/kg) of each retailing step were estimated using the same method as in the wholesale distribution sector (refer to section 6.2.3.5 for details).

The total energy requirements (PJ/yr) of the sector were estimated by extrapolating from the sample survey.

For milk vending, the total energy intensities (MJ/kg) and total energy requirements (PJ/yr) of this grouping were estimated by using base data from the Milk Vendor's Cost Survey (1977-78) undertaken by the Agricultural Economics Research Unit (1978) at Lincoln College. Data were converted to the appropriate forms by using data from Carter, Peet and Baines (1981).

6.2.3.7 Shopping

Data were drawn from a detailed survey of the Total Energy Requirements of Shopping for Food, in New Zealand. Readers should refer to this publication (Patterson and Earle, 1982b) for full methodological details.

A sample survey of food shoppers in Palmerston North was undertaken because of the lack of data in the desired form. In total data were collected from 680 customers who purchased foods from 7 shops in Palmerston North (2 Supermarkets, 2 Greengroceries and Fruiteries, 1 Dairy, 1 Grocery and 1 Butchery). An examination of the link data indicated that the sample was probably representative of the national situation, although further surveys need to be undertaken to fully verify this. The sampling errors for all surveyed parameters were within acceptable limits.

Detailed data were collected from each customer which enabled us to estimate a range of statistics for each trip including the direct and total energy intensities (MJ/kg). The direct energy intensities (MJ/kg) were estimated using data from Beca, Carter, Ferner and

Hollings (1977) in conjunction with survey data about the type of vehicle, vehicle capacity, distance travelled and the amount of food purchased. Because most trips were multi-purpose and involved the purchase of non-foods an allowance had to be made for this.

The indirect energy intensities (MJ/kg) were estimated using ratio data from Carter, Peet and Baines (1980).

Detailed analysis of variance statistical tests were undertaken to indicate what factors influenced the total energy intensities (MJ/kg) of shopping for food. Factors that were examined included customers characteristics (age, sex, socio-economic status) weather conditions and shopping day.

The total energy requirements (PJ/yr) of shopping for food in New Zealand were estimated by multiplying the total energy intensities (expressed in terms of MJ/\$ 1981) by the total national sales of each shop type (\$ 1981/yr). The survey data were backdated using the appropriate food components of the Consumers Price Index (Department of Statistics, 1980c).

6.2.3.8 Household preparation and storage

Data were drawn from a detailed survey of the Household Preparation and Storage of Foods in New Zealand. Readers should refer to this publication (Patterson and Earle, 1982d) for full methodological details.

The direct energy requirements (PJ/yr) were estimated primarily from data obtained in a survey jointly undertaken by the New Zealand Electricity Department (1972) and the Department of Statistics (1974). This survey covered electricity usage by a sample of 2,000 households throughout New Zealand. Other base data for the estimation of the direct energy requirements (PJ/yr) were obtained from Peet, Henderson and Hobbs (1978), Census of Population and Dwellings (1978) and various other sources.

The indirect energy requirements (PJ/yr) were obtained by multiplying cost data (backdated to \$, 1972) by energy intensity (MJ/\$

1972) from Carter, Peet and Baines (1980). The cost (\$) of the indirect inputs were abstracted from the Household Sample Survey (1980) for materials, from data obtained from appliance suppliers for various appliances and from the New Zealand Valuers Institute (1974) for building costs.

The indirect energy requirements (PJ/yr) for supplying the direct energy were estimated using data from Carter, Peet and Baines (1980) using the same method as outlined for the processing sector (see section 6.2.3.3).

The direct energy requirements (MJ/yr) for various cooking appliances were also estimated from data presented by Fechter and Porter (1979), Collinson (1979), Smith (1977) and from appliance specifications. Subsequently, by using data from standard cooking books (primarily Edmonds Cookery Book, 1976) the direct energy intensities (MJ/kg) for various cooking steps were estimated. The direct energy intensities (MJ/kg) for the baseload steps were estimated by dividing the direct energy requirements (PJ/yr) by the estimated annual throughputs (kg/yr). The annual throughputs (kg/yr) were primarily obtained from the New Zealand Food Balance Sheet which is published by the Department of Statistics (1977a).

Similarly, the indirect energy intensities (MJ/kg) were obtained by dividing the indirect energy requirements (MJ/yr) by the annual throughputs (kg/yr).

6.2.3.9 Household production

The household expenditure (\$), of items used in the household production of food, were obtained from the 1978-79 Household Survey (Department of Statistics). These included items such as fertilizers, pesticides, spades and other garden equipment. Items which were obviously or considered predominately to be used for ornamental gardens were not included. These expenditure data (\$), were backdated to 1971-72 terms, by using various cost indices. The expenditure (\$) data were multiplied by the appropriate energy intensities (MJ/\$) obtained from Carter, Peet and Baines (1980), so as to obtain the total energy requirements (TJ/yr). This estimate (TJ/yr) was divided by the total

household food production (tonnes/yr) obtained from the Department of Statistics (1976), to obtain the total energy intensity for the household production of foods.

6.2.3.10 Catering

Data were drawn from a detailed survey of Energy Use in the Catering Industry, in New Zealand. Readers should refer to this publication (Patterson and Earle, 1982a) for full methodological details.

The direct energy requirements (TJ/yr) were estimated from a national survey of 1,357 catering establishments, and a more detailed sample survey of 53 establishments in the Palmerston North area. The indirect energy requirements (TJ/yr) were estimated, by multiplying cost (\$) data of buildings and equipment, by energy co-efficients (MJ/\$) from Carter, Peet and Baines (1982).

The direct energy intensities (MJ/kg) of various cooking food preparation, and baseload steps were estimated by using multiple linear regression. That is, the partitioning (allocation) problem of allocating one energy input, to general outputs was overcome by solving the following equation by multiple linear regression:

$$\sum_{i=1}^{i=j} Y = b_1 \sum_{i=1}^{i=j} (x_1)_i + b_2 \sum_{i=1}^{i=j} (x_2)_i \dots + b_n \sum_{i=1}^{i=j} (x_n)_i \quad (6.1)$$

where:

y = Direct energy consumption of a Catering Establishment (MJ)

$x_1 \dots x_n$ = throughput per annum for the various cooking and food preparation modes (kg)

$b_1 \dots b_n$ = energy intensity (MJ/kg) for the various cooking and food preparation modes.

i = various catering establishments.

Similar, regression techniques for overcoming the partitioning problem

have been used by Cleland, Earle and Boag (1981), Rao et al. (1981) and Jacobs (1981).

The indirect energy intensities (MJ/kg) were estimated by dividing the annual indirect energy requirements (TJ/yr) of 33 catering establishments in the Palmerston North area, by their annual throughputs (kg/yr).

6.2.3.11 Hotels

Data were obtained from Lion Breweries (pers. com. I. Wells, 1982) which enabled an estimate of the direct energy requirements (TJ/yr) of hotels to be made. The mean energy requirement (TJ/yr) of the sample of 92 hotels, was simply multiplied by the total number of hotels in New Zealand which obtained from the Census of Distribution (1978). These direct energy requirements were converted to primary energy terms, by using data from Carter, Peet and Baines (1981). A reasonably acceptable sampling error (Standard error = 9.2%), was calculated. The indirect energy requirements (TJ/yr), were estimated by assuming that the indirect : direct ratio for Catering establishments, also applied for Hotels.

Data on the end-uses of direct energy in Hotels were also obtained from Lion Breweries (pers. com. I. Wells, 1982). No energy intensity (MJ/kg) data were available, nor could it be easily calculated from data for existing sources.

6.2.4 Estimation of Other Inputs and Outputs

6.2.4.1 Direct Land Inputs

Data were abstracted from survey data from Patterson and Earle (1984). Readers should refer to that survey for further methodological details. Only land inputs in the production sector were explicitly considered, as other land inputs were considered to be negligible or mainly in urban areas. The main data sources used for estimating the land inputs (ha/yr) were: Moffat (1980), New Zealand Meat and Wool Board's Economic Services (1980), Sheep and Beef Farm Survey (1978-79), Agriculture Statistics (1978-79) and the New Zealand Yearbook (1981).

No data were available indicating the class(es) of land inputs used by the various production sectors.

6.2.4.2 Direct Labour Inputs

The Labour inputs for the Production Sector, were obtained from: Moffat (1980), New Zealand Dairy Board's (1980) Economic Survey of Factory Supply Dairy Farms (1978-79), New Zealand Meat and Wool Boards' Economic Services (1980), Sheep and Beef Farm Survey (1978-79), Agriculture Statistics (1978-79) and the New Zealand Yearbook (1981). The labour inputs for the processing sector were obtained from the Census of Manufacturing (1978-79), and from survey data collected in previous surveys by the Food Technology Research Centre. Labour inputs for the Catering-Hotel sector were obtained from the Census of Distribution (1978-79). Although labour statistics were available for the wholesale and retail sectors (Census of Distribution, 1978-79), these were not available in a form which were compatible with the "step-wise" nature of the model formulation; and therefore labour inputs from these sectors were not included. Furthermore, no labour input data were available for the fishing and export-import sectors, although it is expected that such labour requirements will be very small. In addition, no account was taken of the labour requirements of shopping or household preparation of foods, as no data is again available.

However, it should be noted that the fact that not all labour inputs were taken into account, has no influence on the determination of the optimal solution. This is because in all the model formulations, labour was considered to be a "free variable". The purpose of including labour inputs was to provide extra information for the analyst.

All labour inputs were expressed in terms of equivalent man-years. Base data were not always expressed in these terms, therefore the following conversion equivalents were assumed in estimating the labour inputs:

Unpaid members of family assisting on farm	= 0.25 man-year equivalents.

Part-time employee = 0.50 man-year equivalents.

Casual workers = 0.25 man-year equivalents.

6.2.4.3 Food Imports and Exports

The 1978-79 levels of imports and exports of agro-food products were obtained from External Trade Statistics : Exports 1978-79, and the External Trade Statistics : Imports 1978-79, published by the Department of Statistics (1980). The products were re-classified according to the product classification used in the Census of Manufacturing (1978-79).

6.2.4.4 Nutritional Outputs

The main data source for the nutritional composition of foods was Paul and Southgate (1978). This data source, was selected as the main source as it provided the widest coverage of nutritional elements, and most of the foods used in the New Zealand household were covered by this source. Paul and Southgate (1978) is the standard British reference for the nutritional composition of foods and is based on earlier research by McCance and Widdowson.

However, not all foods used in the New Zealand Household are covered by Paul and Southgate (1978), and therefore as a second priority the following data sources were used: Thomas and Corden's (1970) Australian Food Tables; United States Department of Agriculture (1976) Composition of Foods (Handbooks 8-1 to 8-7) and the United States Department of Agriculture (1975) Handbook No 456 on the Nutritional Values of American Foods. The nutritional composition of kiwifruit was obtained from unpublished data obtained from the Department of Scientific and Industrial Research (pers. com. Clarke, 1983).

6.2.4.5 Endogenous Inputs and Outputs

The endogenous inputs and outputs from the production sectors, were obtained primarily from : Moffat (1980) New Zealand Dairy Board's (1980) Economic Survey of Factory Supply Dairy Farms in New Zealand, New Zealand Meat and Wool Boards' Economic Service (1980) Sheep and

Beef Farm Survey (1978-79), Agriculture Statistics (1978-79), New Zealand Horticulture Statistics (1979) and the New Zealand Yearbook (1981). For full computational and methodological details readers should refer to Patterson and Earle (1984).

The endogenous inputs and outputs for the processing sectors, were obtained from detailed Census of Manufacturing (1978-79) data supplied by the Department of Statistics (1982). Some of these data were found to be incorrect (particularly meat and fish sectors), and had to be subsequently adjusted to conform with data obtained from other sources such as Riepen (1981) and the above cited references.

The endogenous inputs-outputs for the Catering Sector were obtained from a detailed sample survey of Catering Establishments in the Palmerston North area. Readers should refer to Patterson and Earle (1982a) for full methodological details.

The endogenous inputs-outputs for the Hotel sector were estimated using sales data (food, alcohol) from the Census of Distribution 1978-79, and output data from the Census of Manufacturing 1978-79. The same mix of sales of foods for Catering establishments was assumed to apply for Hotels.

As the other sectors included in the model (Wholesale, Retail, Export-Import and Household) were formulated in terms of food chain steps, rather than sectors, no input-output data were required for these sectors. This is because, for each food step, there was just one output and one input. A wastage of 5% was assumed for most household steps, making an output of 950 tonnes.

6.3 Methodology: Linear Programming

6.3.1 Introduction

As discussed in section 6.1, energy-food utilization problems can be more meaningfully addressed, in terms of an optimisation construct, rather than a simple construct of efficiency which can only relate one single input to one single output. Assuming linearity, the problem is therefore a linear optimisation (or traditionally termed linear

programming) problem.

6.3.1.1 Linearity assumption

In general terms this means that any variable will increase in a linearly proportional manner. Specifically, in terms of this model and the activities of the food system, this usually means that given an increase or decrease in inputs into a sector, that the outputs will increase or decrease in direct linear proportion. For example, if the inputs into the sugar refinery double, so will the outputs double accordingly. Or, if all the inputs into dairy farming (including land) double, so will all the outputs.

This is obviously the case in most sectors and food chain steps - for example, if a retail outlet increases its sales (outputs) by 10% it will obviously have to purchase 10% more goods (inputs) from the wholesaler. This is less obviously the case in the production and processing sectors, where "economies" and sometimes "diseconomies" of scale do occur. However, there is quite strong evidence that this is not the case, at least in the processing sector. Firstly, Cleland and Earle (1980) in their very extensive study of the food manufacturing sector found that in all cases the inputs were linearly proportional to the outputs - that is, linear fits of the production data were found in all cases. Secondly, Vickers and Miller (1983), found all production (outputs) to be linearly proportional to inputs of energy, except possibly butter production.

Therefore, in this model linearity can be assumed, which in turn facilitates easier programme formulation and computation. However, if non-linear production functions do exist the model could be reformulated to take account of these, and in practice this usually means using linear approximations of non-linear functions.

6.3.1.2 Interdependencies Between Sectors, and Input-Output Analysis

Traditionally, most food use (nutrition) problems have been formulated in such a way that the variables have assumed to be independent of each other. However, in a model such as this one where

all sectors of the food system are being modelled, the interdependencies between each sector/step must be modelled. For example, if the production of biscuits is to be increased, so must the production of all upstream industries such as flour processing, sugar refining and grain production be increased. Traditionally, in Input-Output analysis (first developed by Leontief, 1951), has been used to deal with linear interdependencies in economic systems. Subsequently, Input-Output analysis has been extended to include Linear Programming applications (refer to O'Connor and Henry, 1975).

Both Input-Output approaches, require a square matrix (termed a coefficient matrix, or technical coefficient matrix and usually denoted in matrix notation as "A"). The coefficient matrix (A) consists of an identical set of columns and rows, with the inputs being represented by reading down the columns and the outputs being represented by reading across the rows. The matrix is required to be converted to the (I - A) format, for Linear Programming purposes, where I = the Identity Matrix. It should also be noted that by inverting this matrix (I - A), the total requirements of a unit of output from each sector can be determined (refer to Wright, 1974). This is because it is possible to express $(I-A)^{-1}$ as a convergent power series, thus:

$$(I - A)^{-1} y = d = y + Ay + A^2 y + A^3 y + \dots \quad (6.2)$$

where y = variable vector

d = is the final output vector

(refer to Department of Statistics, 1980c for fuller mathematical details).

Despite the relative simplicity and versatility of this approach, there are a number of rather restrictive assumptions implicit in the interpretation of results derived from such I-O analyses (refer O'Connor and Henry, 1975; and Slessor, 1978). Of particular relevance to this analysis, are the linearity problem (discussed above) and the problem of fixed flows between sectors. Input-Output analysis and Linear Programming extensions assume that all flows between sectors must remain in the same fixed proportions - that is, there is no allowable substitution of even the same input from another sector, and the outputs must go to the same sectors in the same proportions as the

original model. This very restrictive assumption was overcome at least to some extent, by not considering there to be only one homogenous input and output from each sector, but a series of inputs and outputs from "dummy sectors" representing the various products. However, this still assumes that there is a fixed proportion of inputs and outputs from a sector, but there is still room for total substitution of input-output flows between sectors. This assumption of fixed proportions is not totally unrealistic, as the nature of many production and processing activities do require that:

- (1) certain outputs (e.g. meat and wool from farms, meat and meat by-products such as hides) be in direct proportion to each other
- (2) certain inputs be in direct proportion to each other, because of formulation requirements.

6.3.2.3 Solution of Linear Programming Models and Other Sets of Linear Equations

The linear programming problem can be represented by the following set of simultaneous linear equations:

maximise/maximise : $C_1 X_1 + C_2 X_2 + \dots + C_m X_m$

subject to: $a_{11} X_1 + a_{12} X_2 + \dots + a_{1m} X_m \begin{matrix} \geq \\ \leq \end{matrix} b_1$

$\vdots$

$\vdots$

$\vdots$

$\vdots$

$\vdots$

$\vdots$

$\vdots$

$\vdots$

$\vdots$

$\vdots$

$\vdots$

$\vdots$

$\vdots$

$a_{n1} X_1 + a_{n2} X_2 + \dots + a_{nm} X_m \begin{matrix} \geq \\ \leq \end{matrix} b_n$

where: $X_1 \geq 0, X_2 \geq 0, \dots, X_m \geq 0$

(This non-negativity restriction applies in most but not all cases)

c = objective function co-efficients (refer to "cost" or "profit"

co-efficients in economic jargon)

a = general co-efficients

X = variables

b = constraints

In matrix notation this problem can be written more compactly:

min/max: $Z = C X$

subject to: $A X = B$

$X \geq 0$

It should be noted that usually $m > n$ - that is, there are usually

more unknowns than equations, for the linear programming problem. This leads to a typology of sets of simultaneous linear equations and concomitant solution methods:

(1) Underdetermined Matrix ($m > n$). This usually represents the linear programming problem, where there are more unknowns than equations. Danzig (1951) first developed the Simplex Method for solving such problems, in the late 1940's and subsequently more sophisticated solution methods have been developed (refer to Cooper and Steinburg, 1974).

(2) Determined Matrix ($m = n$). This represents the Input-Output problem, where the number of equations equal the number of unknowns. The matrix is square in this case, and there is only one unique solution. Leontief et al. (1953) developed solution methods for such problems during the 1930's.

(3) Overdetermined Matrix ($n > m$). This represents the Regression problem, where there are more equations than unknowns (refer to section A). Such problems are usually solved by using a least squares fitting method. It appears that this solution method was independently developed by Gauss (1777 - 1855) and Legendre (1752 - 1833) (refer to Draper and Smith, 1981).

6.3.2 Coefficients Matrix

6.3.2.1 Formulation

Conventionally, as prescribed by textbooks (e.g. O'Connor and Henry, 1975) it is recommended that LP - IO problems be formulated in terms of a square matrix ($I - A$), using an initially formulated I-O coefficients matrix (A). However, in that case because of the use of "dummy sectors" for the products, the matrix would have to be in the vicinity of 5,000 columns x 5,000 rows, resulting in a very large sparse matrix which would almost certainly lead to computational problems.

By using a rectangular matrix, entering a product as either a row (coefficient) or a column (variable), the size of the model could be substantially reduced - that is, a matrix of about 2,000 x 800 could represent all coefficients and variables.

6.3.2.2 MPS format

Coefficient matrices can be formulated for computer solution, by either using a matrix generator or formatting the data in MPS format. Particularly for larger matrices it is usual to formulate the coefficient matrix, by using a matrix generator. Generally matrix generator packages are used as they are less tedious and more systematic, and are part of most commercial linear programming packages. However, in this case a Matrix Generator could not be used because of programming faults in the commercial LP package which was available on Massey University's Prime Computer. Therefore, the matrix was formulated using MPS format, which was originally developed for IBM computers, but has now been accepted as the standard method for formulating LP problems.

MPS format consists of the following sections:

1. NAME
2. ROWS
3. COLUMNS
4. RHS
5. RANGES (optional)
6. BOUNDS (optional)
7. ENDATA

The coefficients are specified in sections 3 and 4. The row labels specify the coefficients (j) names, and column labels specify the variables (i) name, and this is followed by the value a_{ij} . Hence, the inputs into a notational sector called Fish and Chip Shops (FCSHOP), of potatoes (POTAT), fat (FAT), labour (LABOUR) and energy (ENERGY) would be formatted:

```
FCSHOP POTAT -3000
FCSHOP FAT -200
FCSHOP LABOUR -4
FCSHOP ENERGY -700
```

The values are negative, because they represent consumption by the sector. The output of this notional sector, of fried chips (CHIPS) would be formatted:

```
FCSHOP CHIPS 2500
```

This value is positive, because it represents production by the sector.

It should be noted that there are some restrictions in the codes that can be used in naming coefficients (refer to Scion Ltd., 1981). Essentially, the names may be up to eight characters in length and be left justified, as leading blanks are treated as part of the name. A full list of the code names used in this model appear in the Appendix E.

6.3.2.3 Units of Coefficients

The units of most coefficients used in this study, are terms of physical rather than economic units. Most product coefficients are expressed in terms of 1000 tonnes or 1000 litres. Labour coefficients are expressed in terms of 1000 equivalent man-years, and Land units are expressed in terms of 1000 hectares. Readers should refer to the Appendix D, for a full list of the coefficients used in matrices in this study.

6.3.2.4 Scaling of Coefficients

Ill-scaled matrices lead to computational problems, as large numbers are generated in the inversion process, which leads to storage problems (refer to Murtagh, 1981). It was found during early solution runs of various matrices in this study, that ill-scaled coefficients were causing such problems, and therefore several rows and columns had to be rescaled.

6.3.2.5 Sensitivity Analysis

There is some uncertainty associated with some of the matrix coefficients. Therefore, the RANGING command was used to test the sensitivity of changes in these coefficients. This tests changes that are allowable in the matrix co-efficients while the problem still remains optimal (for further details refer to Murtagh, 1981). If some coefficients are particularly sensitive to changes, or have a significant impact on the rest of the model, further research should be undertaken to improve the accuracy of these coefficients.

6.3.3 Objective Functions

6.3.3.1 Selection and Use of Objective Functions

As discussed in section 6.1.4, the maximisation of net energy gain or the minimisation of net energy loss (both are mathematically equivalent), were considered to be the most appropriate objective functions for use in EA. Accordingly, the following objective functions were used:

Run 1 Maximisation of Net Energy Gain (Q), given the 1978-79 levels of domestic consumption, production, processing, exports and imports. (Standard Run)

Run 2 Minimisation of Net Energy Loss (Q), given nutritional requirements of domestic consumption, allowing no exports, minimal imports, and given land area and other constraints.

Run 3 Maximisation of Net Energy Gain (Q), given 1978-79 domestic consumption, export level double the 1978-79 levels, land area and other constraints.

Run 4 For contrast, the more conventional economic objective of maximising net export earnings (DOLNET) was used as the objective function for Run 4.

It should be noted that the purpose of this study is not to generate a "blueprint" or prescriptive set of results which is often the assumed purpose of LP (e.g. refer to Sharpe and Roy, 1980). The use of LP in this study, is more for instruction than prescription; so therefore the choice of various objective functions, does not presuppose a reflection of societal and economic goals and objectives.

6.3.3.2 Units of Objective Functions

The objective function for Runs 1, 2 & 3, of Net Energy (Q) is measured in terms of Terajoules of hydro-electricity equivalents [$n_1(m_2)$] (refer to section 4.6.5).

The objective function for Run 4, of net export earning (DOLNET), is expressed in terms of 10^6 \$ 1978-79.

6.3.3.3 MPS format

The first free row (denoted by N) in the rows section is assumed to be the objective function. Therefore, when (Q) was the objective function the entry could be.

ROWS

N Q

N DOLNET

If DOLNET was the objective function the order would be reversed:

ROWS

N DOLNET

N Q

6.3.4 Constraints

"Constraints" is the term used in LP jargon to describe the right hand side vector (b) of the general LP problem equation, specified at 6.3.2.3. These so called "constraints" also include what might, depending on the instance, more correctly be termed "limitations", "restrictions" or "requirements".

6.3.4.1 Specification of Constraints

In this study there were four main sets of "constraints" used:

(1) Nutritional Requirements of the New Zealand Population This is considered to be a primary requirement of food production in New Zealand (e.g. Smith and McChesney (1979) state: "The primary function of a food production system is to provide an adequate supply of food of suitable nutritional quality...."). These nutritional requirements were estimated by using the Recommended Dietary Allowances (RDA's) recommended by the National Academy of Sciences (1980). The RDA specify the minimum daily allowance for nutritional outputs. The total requirement for each nutritional output for N.Z. population was calculated knowing the RDA for each nutritional output for each population cohort (National Academy of Sciences, 1980), and the total number in each population cohort (N.Z. Department of Statistics,

1976). As no population cohort data were available for 1978-79, these nutrient requirements had to be scaled up for 1978-79, using the increase in population between 1976-79 (Department of Statistics, 1980). This assumed the same demographic structure in 1976 and 1979.

(2) Land Availability Constraint There is a limited amount of various classes of land available for agro-food production. The Ministry of Works and Development (1982) Land Resource Inventory computer retrieval system was used to determine the amount of land (in hectares) available, by class (7), subclass (4) and location (North or South Island). This excluded land currently (1978-79) used for other purposes, such as forestry. The total amount of land was not allowed to exceed the 1978-79 usage of land for agro-food production. Only certain production activities were allowed to be performed on certain classes of land. For example, Dairy farming could only use Class I, II, III land. Sometimes there were climatic (for horticulture) or locational restrictions also imposed on the land use.

(3) Balance Equations Constraints were placed on product rows, of >0 , to ensure that production (or supply) did not exceed the consumption.

(4) Collector Rows Constraints were placed on some rows of $=0$, to sum the rest of the values in the rows, in a column which has had a -1 value entered. Murtagh (1981) terms this programming "device" a collector row.

It could be argued that for some seasonal industries (Beattie, 1979), that there is a labour constraint on production. However, in view of unemployment and underemployment experienced in the New Zealand economy in the late 1970's and early 1980's, it could also be argued that a certain minimum level of employment should also be specified in the model. In any case, no constraint of any sort could be placed on labour because of the lack of data concerning labour inputs into some sectors (refer to section 6.2.4.2).

6.3.4.2 MPS Format

Constraints are entered in the RHS section of the MPS input. For example, if the total land area (LAND) should not exceed 3,000 units (1 unit = 10 ha), this constraint would be entered

```
RHS 1    LAND    3000
```

The fact that it is less than 3000 units, is specified in the rows

sections

L LAND

(L meaning less than).

6.3.5 Bounds

"Bounds" is the term used in LP jargon to describe restrictions in variables (columns). Due to the nature of the formatting there were more "bounds" restrictions, than "constraints" restrictions in this model - this is not usually the case.

6.3.5.1 Specification of Bounds

In this study there were seven main sets of bounds restrictions used:

(1) Allowable Export Markets There is a severe limit to the market size for most agro-food products which New Zealand exports. Due to the lack of quantitative studies, and due to uncertainties with many of these markets, no exact limit on these market sizes can be made. The approach used here was to use various restrictions on market sizes, up to twice the 1978-79 levels, for all products. These sets of limits, are very important in determining the objective function value (whether Q or DOLNET). Therefore, it is particularly important that more quantitative research is undertaken in this area.

(2) Restricted Imports In Run 2, all imports were restricted except three (sugar, molasses and food emulsifiers) which were very necessary for the functioning of the domestic market.

(3) Sector Activities In Run 1 (Standard Run), all sector activities were set at unity - that is at 1978-79 levels.

(4) Fish Production Limits Fish Production, for the purposes of this analysis, was limited to the 1978-79 level of production. It is recommended that this limit should be set at the maximum sustainable level of the fisheries, when these data become available. It should be noted that for the inshore species (Snapper, Trevally and Terakihi) that the annual catches are declining indicating that the maximum sustainable limit has been exceeded for these fisheries. Whereas, the opposite is occurring for certain offshore fisheries (pers. com. Duncan, 1984).

(5) Home Production The home production of fruit and vegetables was

assumed to have an upper limit equal to the 1978-79 level.

(6) 1978-79 Final Demand for Food Another way of specifying the domestic demand for food (other than specifying nutritional requirements) was to fix the level of final demand at the 1978-79 level, by placing bound restrictions equal to this level for all food demand products. This had the effect of placing greater emphasis on consumer preference.

(7) Non-negativity Restrictions As with most models non-negativity restrictions were placed on all variables (refer to the general equation in section 6.3.1.3).

6.3.5.2 M.P.S. Format

Bounds are placed on the Bounds section of the M.P.S. input. For example, if fish production (FISH) should not exceed 1978-79 levels, this restriction would be entered

UP B FISH 1

(UP, standing for Upper Bound).

6.3.6 Solution Method

6.3.6.1 Preliminary Considerations

There were a number of limitations and restrictions which had to be considered before a method of solution could be established. Firstly, there was a limitation in the LP software package (Sciconic) available on the Massey University computing system, which meant that problems with coefficient matrices of greater than 1200 columns could not be solved. Consequently, all coefficient matrices could not be combined so to obtain a problem file of the total food-use problem, as the resulting file would be approximately 3000 columns by 700 rows. Secondly, experience in attempting to solve some of the more difficult sub-problems which were subsequently used, indicated that it was improbable that a problem of this size could be easily solved.

In practice, the most efficient method (in terms of CPU seconds used), in obtaining a solution was to sequentially solve two sub-problems, termed

the "General Model" and the "Distribution Model".

6.3.6.2 Base Files

The Base Files, formed the basic components to any LP problem, and were stored on PRIMOS level of Massey University's Prime Computing System:

ROWS

- (i) General - specifying the rows and types of rows for the General Model.
- (ii) Distribution - specifying the rows and types of rows for the Distribution Model.

COLUMNS (Coefficient Matrices)

- (iii) Energy Transformation Matrix
- (iv) Production Matrix
- (v) Processing Matrix
- (vi) Export-Import Matrix
- (vii) Distribution Matrix
- (viii) Household Matrix
- (ix) Catering-Hotels Matrix

RHS

- (x) Nutritional Requirements
- (xi) Land Use Constraints

BOUNDS

- (xii) Imports -equal to 1978-79 levels
- (xiii) Imports - up to twice 1978-79 levels
- (xiv) Imports - limited imports of sugar, molasses and food emulsifiers
- (xv) Exports - equal to 1978-79 levels
- (xvi) Exports - up to twice 1978-79 levels
- (xvii) Sector Activities - equal to 1978-79 levels
- (xviii) Fish and Household Production - up to 1978-79 levels
- (xix) Domestic Consumption equal to 1978-79 levels.

Adjustments could readily be made to these files, by using the editor programme available on the Prime system.

6.3.6.3 Models

These base files were combined to form two sub-problems which were in this case sequentially solved

(1) General Model This consisted of Basic Files (i), (iii), (iv), (v), (vi), (viii) & (ix). For all RUNS, this model was solved first, and the results of this solution were then used to solve the Distribution Model.

(2) Distribution Model This consisted of base files (ii) and (vii).

6.3.6.4 Runs

All runs consisted of sequential solutions of the General Model and then the Distribution Model. Various different constraints and bounds were appended to these models, in the various RUNS. These constraints and bounds were selected from files (x) - (xviii). In this report only four RUNS are reported on. However, other Runs were attempted and other Runs are possible by using the library of Base Files in various combinations, and by using minor adjustments to these Base Files.

6.3.6.5 Global Optimum Versus Separately Determined Optima

Due to primarily practical reasons concerning the LP package, but also due to solution efficiency (in terms of CPU seconds required), two separate determined optima were used to find an overall solution. However, as is often indicated in the literature (e.g. Driebeek, 1969), these separately determined optima may not equal a global optimum.

Evidence, fortunately does indicate that this is not the case in this problem - or at the least does indicate that the two separate optima do very closely sum to the global optimum. Firstly, except for the case of dried fruit and vegetables versus fresh fruit and vegetables, the mix of products selected by the General Model, did not significantly influence the mix of distribution routes selected by the Distribution Model. This is because the minimum energy requirements of distributing all products (except dried fruit and vegetables) are the same, as more or less the same set of distribution routes are available for all products. The energy requirements of distributing dried fruit

and vegetables are less, because of the reductions in weight. However, evidence from Patterson and Earle (1984), indicated that this reduction in energy requirements for dried fruit and vegetables is nearly offset by higher process energy requirements of drying fruit and vegetables; and this is totally offset by the loss of nutrients during processing of dried products (Paul and Southgate, 1978). Secondly, although the Distribution Model is large in terms of matrix size, this sector usually accounts for a relatively small portion of total energy use (2.18% for 1978-79, according to Patterson and Earle, 1984). Therefore, as the Distribution Model is solved secondly, the global optimum should not be critically affected because of the low energy use of the distribution sector.

6.3.6.6 Computer Solution

The SCICONIC software package, was used to solve the LP problems, derived from combining Base Files and Models, into various Runs (refer Scicon, 1981). This software package provides algorithms for solving linear, non-linear and integer programming problems. It is based on the Simplex method, originally devised by Danzig (1951), which involves finding a basic feasible solution, and then approaching an optimum by an iterative process (refer to Cooper and Steinberg (1974) or other basic texts for further details).

6.3.7 Recommended Extensions

This study primarily concentrated on obtaining optimal solutions to Runs, and exploring how these solutions varied by interchanging sets of constraints and bounds. However, the use of post-optimality analysis and parameteric programming, is recommended as a further area of research, using these solutions as a starting basis. Once optimal solutions are obtained, Ranging and Parametric Programming procedures are easily carried out by most commercial LP packages (refer to Murtagh, 1981). One possibility would be to explore the impact on the optimal solution by reducing the RHS vector LAND. In effect this would test the impact of using land for other purposes than agro-food production - for example, for forestry or biomass production. Other studies have used Parametric Programming to explore the impact of reducing nutritional requirements (refer to Edwardson, 1974; Anderson,

1975). In this way Parametric Programming can be used to explore the trade-offs between important variables such as Land, Energy and Labour, assuming optimality.

7 GENERAL, PRODUCTION, PROCESSING AND EXPORT-IMPORT MATRICES

7.1 General Matrix

This coefficients matrix was used in all RUNS, and it consisted of equations representing the objective function(s), and the energy transformation matrix.

7.1.1 Objective Functions7.1.1.1 Net Energy Yield (Q)

The maximisation of Net Energy Yield (Q) and the minimisation of Net Energy Loss (Q loss), were used for the objective functions for Runs 1,2 & 3. As can be ascertained from the following equation both functions are mathematically equivalent:

$$Q_{\text{gain}} - Q_{\text{loss}} = Q \text{ (Row 25)} \quad (7.1)$$

where:

$$(1) \quad Q_{\text{gain}} = a_{14} x_{14}$$

$$a_{14} = Q/\text{DOLNET} (41.04 n_1(m)_2) \cdot \text{TJ}/\$1978-79 \times 10^6)$$

$$x_{14} = \text{DOLNET} (\$1978-79 \times 10^6)$$

$$(2) \quad Q_{\text{loss}} = \sum_{i=n}^{i=1} -a_i x_i$$

a_i = quality coefficients for various primary energy input classes:

$$a_1, a_8 = -Q/\text{Coal Inputs} \quad (-0.2676 n_1(m)_2) \cdot \text{TJ}/\text{TJ.yr}^{-1})$$

$$a_2, a_9 = -Q/\text{Oil Inputs} \quad (-0.4864 n_1(m)_2) \cdot \text{TJ}/\text{TJ.yr}^{-1})$$

$$a_3, a_{10} = -Q/\text{Natural Gas Inputs} \quad (-0.4864 n_1(m)_2) \cdot \text{TJ}/\text{TJ.yr}^{-1})$$

$$a_4, a_{11} = -Q/\text{Hydroelectricity Inputs} \quad (-1.0000 n_1(m)_2) \cdot \text{TJ}/\text{TJ.yr}^{-1})$$

$$a_5, = -Q/\text{Wood Inputs} \quad (-0.1888 n_1(m)_2) \cdot \text{TJ}/\text{TJ.yr}^{-1})$$

$$a_6, a_{12} = -Q/\text{Capital Inputs} \quad (-0.5313 n_1(m)_2) \cdot \text{TJ}/\text{TJ.yr}^{-1})$$

$$a_7, a_{13} = -Q/\text{Imports Inputs} \quad (-0.4415 n_1(m)_2) \cdot \text{TJ}/\text{TJ.yr}^{-1})$$

x_i = variables for various primary energy input classes:

x_1, x_8	= Direct and Indirect Coal Inputs	(TJ.yr ⁻¹)
x_2, x_9	= Direct and Indirect Oil Inputs	(TJ.yr ⁻¹)
x_3, x_{10}	= Direct and Indirect Natural Gas Inputs	(TJ.yr ⁻¹)
x_4, x_{11}	= Direct and Indirect Hydroelectricity Inputs	(TJ.yr ⁻¹)
x_5	= Direct Wood Inputs	(TJ.yr ⁻¹)
x_6, x_{12}	= Direct and Indirect Capital Inputs	(TJ.yr ⁻¹)
x_7, x_{13}	= Direct and Indirect Imports Inputs	(TJ.yr ⁻¹)

The values of the coefficients were derived from the following sources:

- (1) -Q/Coal Inputs, -Q/Oil Inputs, -Q/Natural Gas Inputs, -Q/Hydroelectricity Inputs and -Q/Wood Inputs were directly abstracted from Section 4.6.5.
- (2) -Q/Imports Inputs: The Primary Energy Inputs (ΔH) of 23 OECD countries from which New Zealand imports goods from, were considered to be reasonably representative of the Primary Energy Inputs (ΔH) required to produce goods for import into New Zealand, as according to an analysis of the External Trade Statistics 81% of New Zealand goods are imported from these countries. Therefore, a weighted mean, hydroelectricity equivalent [$n_1(m_2)$]: to primary energy input (ΔH , TJ) ratio, for these countries was calculated, using energy consumption data of OECD countries (OECD, 1981). This mean was weighted according to the amount of goods imported into New Zealand from each OECD country.
- (3) -Q/Capital Inputs: The same mix of Primary Energy Inputs (ΔH , Coal, Gas, Oil, Elect., Imports), used in the New Zealand economy, was assumed to be required to produce the Capital Output of the New Zealand economy. On this basis, a weighted mean, hydroelectricity equivalent [$n_1(m_2)$]: primary energy input (ΔH , TJ), for capital was calculated (refer to Table 7.1).
- (4) Q/DOLNET: This was calculated by:
 - (a) multiplying the imports of oil (173×10^3 TJ) for 1978, obtained from the Department of Statistics (1980d), by the quality coefficient for oil ($0.4864 n_1(m_2).TJ$), to obtain imports of oil in quality equivalent terms

Table 7.1: Calculation of a Hydro-Electricity Equivalent ($n_1(m_2)$):
Primary Energy Input (ΔH) Ratio for the New Zealand Economy

Primary Input	¹ ΔH	² $n_1(m_2)/\Delta H$	³ $n_1(m_2)$
Coal	47	0.2676	12.5772
Oil	192	0.4864	93.8752
Hydro	70	1.0000	70.0000
Gas	47	0.5106	23.9982
Imported	120	0.4415	52.9800
TOTAL	477	N.A	253.4306

1. Energy Inputs into the New Zealand Economy 1978-79 (N.Z. Yearbook, 1980; Baines, Peet and Currier, 1981).
2. Column 1 x Column 2.
3. Hydro-Electricity Equivalent ($n_1(m_2)$): Primary Energy Input Ratio (ΔH)
 $= \Sigma \text{Column 3} \div \Sigma \text{Column 1} = 0.5313.$

- (84.1472 $n_1(m_2)$.PJ).
- (b) multiplying the imports of merchandise (114×10^3 TJ) for 1978, obtained from Carter, Peet and Baines (1981), by the quality coefficient for imported merchandise (Q/Imports), to obtain imports of merchandise in quality equivalent terms ($50.3310 \, n_1(m_2)$.PJ).
- (c) Calculating the value of all imports, from the Department of Statistics (1980d) for 1978-79 ($\$3,276.655 \times 10^6$).
- (d) Adding (a) and (b), and dividing the sum by (c), to obtain a weighted mean quality coefficient ($41.04 \, Q/DOLNET$) for all Imports (Oil and Merchandise). This is a weighted mean, which assumes that the ratio of oil:merchandise imports remains the same as for 1978-79. The comparative coefficients for Oil and Merchandise imports respectively are $166.1Q/DOLNET$ and $16.7/Q \, DOLNET$.

An auxillary equation was written to convert the value of food imports (DOLNET expressed in negative terms) to quality equivalent (Q), assuming the Q/DOLNET ratio.

7.1.1.2 Net Dollar Yield (DOLNET)

The maximisation of Net Dollar Yield (DOLNET) was used as the objective function for Run 4. The following equation represents this function (row 27):

$$\sum_{i=1}^{i=n} a_{25i} x_i - (a_2 x_2) - (a_7 x_7) - (a_9 x_9) - (a_{13} x_{13}) = DOLNET \quad (7.2)$$

where:

- a_{25i} = DOLNET earnings for exports (+) and imports (-) for i food products (expressed in $\$1978-79 \times 10^6$)
- a_2, a_9 = DOLNET/primary oil inputs ($0.00292834 \, \$1978-79 \times 10^6 / TJ.yr^{-1}$)
- a_1, a_{13} = DOLNET/primary imported inputs ($0.0243013 \, \$1978-79 \times 10^6 / TJ.yr^{-1}$)
- x_i = exported, imported products (usually 000 tonnes)
- x_2, x_9 = Direct and indirect oil inputs ($TJ.yr^{-1}$)
- x_7, x_{13} = Direct and Indirect Imported Inputs ($TJ.yr^{-1}$)

This means that the sum of the objective function row (row 27), is equal to the net export earnings agro-food products, once the cost of all necessary imports of oil, merchandise and food are subtracted.

The values of the coefficients were derived from the following sources:

- (1) DOLNET/i food products: These coefficients were obtained from the External Trade Statistics, published by the Department of Statistics (1980a).
- (2) DOLNET/Primary Oils Inputs: These coefficients were calculated by dividing the value ($\$1978-79 \times 10^6$) of oil imports into New Zealand for 1978-79 obtained from the Department of Statistics (1980a), by the calorific value (TJ) of oil imports into New Zealand for 1978-79.
- (3) DOLNET/Primary Imported Inputs: These coefficients were calculated by dividing the value ($\$1978-79 \times 10^6$) of imported merchandise for 1978-79 obtained from the Department of Statistics (1980a), by the primary energy requirements (TJ) of the merchandise obtained from Carter, Peet and Baines (1981).

7.1.2 Energy Transformation Matrix

The energy transformation matrix includes the arithmetic for summing the various primary energy inputs (TJ.yr^{-1}) into the system, and for converting these primary energy inputs (ΔH) into quality equivalent terms ($\text{TJ.n}_1(\text{m}_2).\text{yr}^{-1}$) (refer to table 7.2):

Rows 1 - 7	These rows are direct primary energy inputs of Coal, Oil, Gas, Hydroelectricity, Wood, Imported Energy and Capital Energy (TJ.yr^{-1}). These are the classifications of primary energy inputs used by Carter, Peet and Baines (1981), and adopted in this analysis. The sum of each one of these inputs is equal to the activity of the respective column.
Row 8	This row sums all the direct primary energy inputs into the system (TJ.yr^{-1}).
Rows 9-14	These rows are indirect primary energy inputs of Coal, Oil, Gas, Hydroelectricity, Imported Energy, and Capital Energy (TJ.yr^{-1}). These are classifications of primary energy inputs used by Carter,

Table 7.2: Energy Transformation Matrix, for New Zealand Food System Model (1978-79)

Columns Rows		1	2	3	4	5	6	7	8	9	10	11	12	13	Con- straint
		D Coal	D Oil	D Gas	D Elect	D Wood	D Impor	D Captl	X Coal	X Oil	X Gas	X Elect	X Impor	X Captl	
1	D Coal	-1													= 0
2	D Oil		-1												= 0
3	D Gas			-1											= 0
4	D Elect				-1										= 0
5	D Wood					-1									= 0
6	D Impor						-1								= 0
7	D Captl							-1							= 0
8	D Total														> 0
9	X Coal								-1						= 0
10	X Oil									-1					= 0
11	X Gas										-1				= 0
12	X Elect											-1			= 0
13	X Impor												-1		= 0
14	X Captl													-1	= 0
15	X Total														> 0
16	Total														> 0
17	Q Coal	0.2676							0.2676						> 0
18	Q Oil		0.4864							0.4864					> 0
19	Q Gas			0.5106							0.5106				> 0
20	Q Elect				1.0000							1.0000			> 0
21	Q Wood					0.1888									> 0
22	Q Impor						0.4415						0.4415		> 0
23	Q Captl							0.5313						0.5313	> 0
24	Q	0.2676	0.4864	0.5106	1.0000	0.1888	0.4415	0.5313	0.2676	0.4864	0.5106	1.0000	0.4415	0.5313	> 0
25	H	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	> 0

Peet and Baines (1980) and adopted in this analysis. The sum of each one of these inputs is equal to the activity of the respective column. An indirect energy input, refers to an energy input into the food system via some good or service used in the system.

- Row 15 This row sums all indirect primary energy inputs into the system (TJ.yr^{-1}).
- Row 16 This row sums all total (direct plus indirect) primary energy inputs into the system (TJ.yr^{-1}).
- Row 17-23 These rows convert the sum of each primary energy input (TJ.yr^{-1}), to hydroelectricity equivalents ($\text{TJ.n}_1(\text{m}_2).\text{yr}^{-1}$) by using the appropriate conversion factor (refer to section 4.6.5).
- Row 24 This row sums the primary energy inputs into the system expressed in terms of hydroelectricity equivalents [$\text{n}_1(\text{m}_2)$]. This row was often used as the objective function.
- Row 25 This row sums the primary energy inputs into the system expressed in terms of enthalpy (ΔH) values. It is equivalent to row 16.

7.3 Production Matrix

7.3.1 Introduction

The Production Sectors, are defined as those sectors which produce biological materials from primary resources, ready for food processing or direct consumption as food. Specifically, they include the following sectors:

(1) Factory Supply Dairy Farms	FDFAR
(2) Town Supply Dairy Farms	TDFAR
(3) Pig Farming	PIG
(4) South Island High Country	SHIGH
(5) South Island Hill Country	SHILL
(6) North Island Hard Hill Country	XHHILL
(7) North Island Hill Country	XHILL
(8) North Island Intensive Fattening	XIFAT

(9) South Island Fattening-Breeding	SFAT
(10) South Island Intensive Fattening	SIFAT
(11) South Island Mixed Cropping and Fattening	SMIXC
(12) Mixed Livestock and Other Farming	XMIXL
(13) Cropping	CROP
(14) Horticulture and Production Not Elsewhere Classified	HORT
(15) Poultry Farming	POULT
(16) Fishing	FISH

Readers should refer to Patterson and Earle (1984) for more detailed definitions of these sectors.

7.2.2 Energy Inputs

7.2.2.1 Previous Studies

Previous studies have attempted to estimate the energy requirements of the Production Sectors of the New Zealand Food System. Brown and Pearson (1977) estimated that the mean Gross Energy Requirement (G.E.R.) of the production sector for the years 1971-72 to 1975-76 to be 22,590 TJ/yr (this excluded fishing). Pearson and Corbet (1976) estimated the G.E.R. of the production sector (excluding fishing) to be 20,000 TJ/yr, but acknowledged that the G.E.R. might be as high as 25,000 TJ/yr when all "minor" inputs are taken into account. Smith and McChesney (1979) estimated the G.E.R. of the production sector to be about 31,000 TJ/yr. In the most recently published analysis, McChesney, Sharp and Hayward (1982), indicated that the G.E.R. of the production sectors (excluding fishing) is 44,000 TJ/yr, when the energy requirement of energy is taken into account.

Most of the variances in the results, are due to methodological reasons. Firstly, the earlier studies did not convert consumer energy inputs back to primary energy inputs - that is, did not take account of the energy requirement of energy. Secondly, as these studies progressed, more and more of the seemingly minor inputs were recognised and taken account of, therefore increasing the estimates.

Riepen (1981) examined energy use in the fishing sector, which had largely been ignored in the above mentioned studies. It was estimated

that the G.E.R. of the fishing sector was about 1,600 TJ/yr. As with the other studies, this study did not take account of the energy requirement of energy, and disregarded some inputs.

7.2.2.2 Patterson and Earle (1984) Study

Due to the incompleteness of the above studies and the inconsistencies of the approaches employed; it was considered necessary to re-analysis energy use in the production sectors.

As can be ascertained from Table 7.3, the Total Energy Requirements (TJ/yr) of the Production Sector were estimated to be 48,599 TJ/yr. The Gross Energy Requirement was 49,925 TJ/yr (this includes inputs such as feed from other sectors in the food system).

Direct energy use accounts for only 28% of the Total Energy Requirements (TER). Fuel (21.6% of the TER) is the main direct energy requirement, with electricity use being comparatively minor (2% of the TER). Fuel which is almost entirely petroleum and diesel is required to provide mechanical energy for tractors, harvestors, road vehicles and other miscellaneous engines. Electricity is required to operate milking equipment, shearing equipment, pumps, lights and to heat water particularly on dairy farms.

Indirect energy use accounts for 72% of the T.E.R. The main indirect energy requirement is the energy embodied in fertilizers, with lesser amounts embodied in the supply of feeds, capital items, service and transport inputs (refer to Patterson and Earle, 1984 for further detailed information about these inputs).

Sheep and beef production requires the most energy (57% of the G.E.R.) required by the production sector. This is primarily because it is the main land use in New Zealand, rather than its energy intensive nature. Dairy farming industry was the other main area of energy use (23% of the G.E.R.). Dairy farming was more energy intensive having an energy intensity ranging from 7.6 to 8.8 GJ/ha, compared with a national mean of 1.2 GJ/ha for beef and sheep production (Smith and McChesney, 1979). Other industries such as cropping, orcharding, market gardening and fishing account for the

Table 7.3. Total Energy Requirements (to/yr) of the Production Sector of the Food System in New Zealand

CLASS	DIRECT				INDIRECT				TOTAL
	Fuel	Electricity	Other	Total	Fuel	Electricity	Other	Total	
Factory Supply Dairy Farms	2,742	934	100	3,776	3,578	255	2,064	5,900	9,676
Town Supply Dairy Farms	642	154	18	814	481	33	274	788	1,602
South Island High Country	122	4	1	127	217	14	107	338	467
South Island Hill Country	308	10	3	322	644	36	334	1,014	1,336
North Island Hard Hill Country	290	10	3	303	1,160	64	570	1,794	2,097
North Island Hill Country	764	26	8	798	2,468	136	1,299	3,903	4,701
North Island Intensive Fattening	517	18	6	541	1,778	115	908	2,801	3,342
South Island Fattening - Breeding	1,315	45	14	1,374	2,105	122	932	3,159	4,533
South Island Intensive Fattening	1,107	38	12	1,157	1,563	97	764	2,424	3,581
South Island Mixed Cropping & Fattening	905	31	10	945	908	61	460	1,429	2,374
Mixed Livestock and Other Farming	864	110	16	990	2,629	319	1,374	4,322	5,312
Cropping	2,085	70	23	2,176	956	56	309	1,321	3,498
Horticulture and Production NEC	675	162	19	856	1,269	71	837	2,178	3,034
Poultry Farming ^c	141	98	10	247	212	28	103	344	590
Pig Farming ^c	121	86	8	215	155	6	30	190	405
Fishing	1,014	9	9	1,031	745	37	237	1,020	2,051
TOTAL (Primary Energy Requirements)	13,612	1,805	260	15,672	20,868	1,450	10,602	32,925	48,599
TOTAL (Consumer Energy Requirements)	12,488	1,172	-	13,660	-	-	-	-	-

a. Data derived from Patterson and Earle (1984)

b. All requirements are expressed in primary energy terms, except where specified.

c. The energy requirements of food, feed is not included. This figure is taken account of in the processing sector analysis, and is not included here as it would lead to double counting when determining the gross energy requirements of the food system.

remainder of the energy use in the production sector (18% of the G.E.R.).

7.2.3 Land Inputs

7.2.3.1 Quantitative Land Requirements of the Production Sectors

The amounts (000 ha) of land required by each production sector, are detailed by Table 7.4, along with the Gross Energy Requirements (TJ/yr) and the Energy Intensities (GJ/yr/ha) of each sector.

The less energy intensive (GJ/yr/ha) beef and sheep sectors require the most land, while the more energy intensive sectors (GJ/yr/ha) require the least amount of land. However, it should be recognised that these large amounts of land required for beef and sheep production are large requirements for low class land (land classes V to VII). Whereas, the small amounts of land required for dairy farming, horticulture and other intensive forms of production, are small requirements for high class land (generally land classes I and II).

7.2.3.2 Land Class Requirements of the Production Sectors

Land can be classified according to how versatile the land is for sustained production taking into account physical limitation; such as soil productivity, erosion features, climate and land gradient. On this basis, the Ministry of Works and Development (1979) classifies, land into eight classes, with Class I land having the less limitations for productive use and Class VIII having the most limitations for productive use. Table 7.5, and Fig. 7.1 further explain and detail the bases of this land classification. Each main class is sub-divided into sub-classes, according to the main limitation on that class of land. These sub-classes are: e(erosion), w(wetness), s(soil) and c(climate). Where two or more kinds of limitations are essentially equal, the sub-classes are given the following priority for recording purposes: e,w,s and then c.

For each production sector, only certain classes of land are suitable for the type of production activities practised by that

Table 7.4: Land Requirements (000ha) and Energy Intensities (GJ/yr/ha) for Production Sectors of New Zealand Food System

Sector	Land Requirements ^a (000 ha)	Gross Energy Requirements ^b (TJ/yr)	Energy Intensity ^c (GJ/yr/ha)
Factory Supply Dairy Farms	1,236	10,197	8.25
Town Supply Dairy Farms	136	1,767	12.99
South Island High Country	3,207	475	0.15
South Island Hill Country	1,850	1,383	0.75
North Island Hard Hill Country	1,309	2,122	1.62
North Island Hill Country	1,963.5	4,750	2.42
North Island Intensive Fattening	876	3,464	3.95
South Island Fattening - Breeding	1,460	4,601	3.15
South Island Intensive Fattening	681	3,625	5.32
South Island Mixed Cropping and Fattening	383	2,396	6.26
Cropping	391	3,592	9.19
Fishing	0	2,051	N.A.
Horticulture and Production NEC	82	3,034	37.00
Mixed Livestock and Other Farming	2,582	5,478	2.12
Pig Farming	19	1,025	53.95
Poultry Farming	8	1,296	162.00
TOTAL (Columns 1&2) Mean (Column 3)	16,183.5	49,599 ^d	2.94

a. Patterson and Earle (1984)

b. Patterson and Earle (1984)

c. Column 2 ÷ column 1 (excluding fishing)

d. G.E.R.'s are not additive.

Class	Cropping Suitability	*General Pastoral & Production Forestry Suitability	*General Suitability
i	High	High	Multiple Use Land
ii			
iii	Medium		
iv	Low		
v	Unsuitable	Medium	Pastoral or Forestry Land
vi			
vii		Low	Catchment Protection Land
viii		Unsuitable	

Increasing limitations to use

Decreasing versatility

* Land use capability classes iv - vii which have wetness as the major limitation and those units in very low rainfall areas or those occurring on shallow soils are normally not suited to production forestry.

Figure 7.1: Land use suitability of class i to viii land (source: MOWD, 1979)

Class I: This is the most versatile multiple-use land with virtually no limitations to arable use. It is highly suitable for the growing of a wide range of cultivated crops, pasture or forests.

It is flat, or nearly flat, land with deep, easily worked soils. These are usually well supplied with plant nutrients and are responsive to applied fertilisers. The climate is favourable for the growth of a wide range of plants and there is little risk of erosion.

Class I land is confined almost entirely to small areas of well-drained soils derived from alluvium, located mostly on the former flood plains of the larger rivers. It occurs throughout New Zealand but is very limited in total area.

Class II: This is very good land with slight limitations to arable use which can be readily overcome by management and conservation practices. The land may be used for cultivated crops, pasture or forestry. Most Class II land is flat or undulating with the most common limitations being wetness, slight textural problems, or shallow soils.

Class II land is more widespread and abundant in New Zealand than Class I land. Soils are derived mainly from alluvium, although some in the North Island have developed on fine-textured volcanic ash.

Class III: This class of land has moderate limitations to arable use which restrict the choice of crops able to be grown and/or make special conservation practices necessary. It may be used for cultivated crops, pasture or forestry.

Class III land is widely distributed throughout New Zealand. It commonly occurs on undulating to rolling country which has a moderate erosion risk when cultivated, on shallow and stony soils of plains and terraces, and in narrow river valleys where runoff from adjacent hills gives rise to wetness limitations.

Class IV: This land has severe limitations to arable use. These limitations substantially reduce the range of crops which can be grown and/or make intensive conservation treatment and careful management necessary. In general, Class IV land is suited only to occasional cropping, but is well suited to pastoral and forestry use.

The most common limitations to use are erosion, shallow, stony and/or low fertility soils, excessive wetness and other effects of climate such as those associated with altitude.

Class IV land is widely distributed throughout New Zealand commonly occurring on undulating to strongly rolling country. It occurs in similar situations as Class III land but the limitations are more pronounced and are therefore more restrictive to cropping.

Class V: This is high producing land which has limitations which make it unsuitable for cropping but which has only slight limitations to pastoral or, in general, forestry use. The most common limitations which preclude arable use are slope, the presence of boulders and rock outcrops, or excessive wetness. Erosion is not a dominant limitation in this class as the land is relatively stable under a permanent vegetative cover. Class V land is limited in its occurrence in New Zealand. It is generally confined to very stable hill country and localised areas of river flats.

Class VI: This is non-arable land which has moderate limitations and hazards under a perennial vegetation cover. Erosion is commonly the dominant limitation on Class VI land. However, it can be minimised by appropriate soil conservation measures. Soil limitations also commonly restrict use but wetness and climatic factors are less dominant limitations.

Class VI encompasses most of New Zealand's good, relatively stable, hill country, but can include stony and shallow soils of fans and terraces.

Class VII: This land is unsuitable for arable use and has severe limitations or hazards under a perennial vegetation. With few exceptions it can only support extensive grazing or erosion control forestry. The limitations to use of Class VII land are similar to those affecting Class VI land but are intensified. Risk of erosion is frequently the dominant limitation making careful conservation management for grazing use necessary. Class VII land can also have severe soil, wetness or climatic limitations. Land of Class VII is widely distributed and includes much of the steeper and more erodible North Island hill country as well as South Island 'high country'. It also occurs, although to a lesser extent, on the shallow, stony and/or low fertility soils of the fans and terraces (including 'pakihi' land).

Class VIII: This land has very severe to extreme limitations or hazards which make it unsuitable for arable, pastoral, or production forestry use. Soil conservation and water management are the main on-site and off-site concerns in the use of this land. It is suitable for catchment protection purposes, which include water management interests, and also for recreational uses.

The most common limitation to use is extreme actual or potential erosion. This may be combined with severe climatic limitations.

Class VIII land is mainly high, mountainous country although it may include very steep slopes and also highly erodible areas at lower altitudes, such as fore dunes.

sector. For example, Dairy Farming is generally practised on Class I and III land, although it can be practised on Class IV land in some circumstances. The productivity of the lower classes of land is insufficient to sustain Dairy Farming, at its present level of intensity. There are some difficulties in establishing what land classes, can sustain the production activities of certain sectors. Firstly, the production activities of a particular sector are somewhat varied in some cases. Therefore, although most of the production activities of a given sector can be sustained on a particular range of land classes, some of the production activities of that given sector may be able to be sustained in lower class land. In such cases, the predominant production activity of a particular sector, is assumed for establishing the suitable land classes of that sector. Secondly, the land classes suitable for a particular production activity, is not only dependent on physical limitations, but on the current technological limits and management practices. In this study, the current use of technology and management practices were assumed. Locational factors can also importantly determine, the land requirements for a given production activity. This is obviously important in Town Supply Dairy Farming, Market Gardening and Poultry Farming, as it is particularly important that such activities be located in close proximity to their markets, in urban areas. Fortunately, most class I and II land which is required by these sectors, is located near population centres, and therefore it is largely unnecessary to specify such locational factors in the model.

By taking all these factors into consideration, and after receiving advice from the Ministry of Works and Development (pers com. Fletcher, 1982), the range of land classes detailed by Table 7.6 were assumed to be suitable for various production sectors. It may be possible that some of these production activities can be practised on land classes, outside the range specified by Table 7.6 however, this is considered unlikely given current technology and the current level of inputs assumed in this model. Class IIc was not considered suitable for most production activities practised in the "Horticulture and Production NEC" sector, because of the climatic factors (sunshine hours, frost-days, temperature ranges) which constrain many horticultural activities on such land.

Table 7.6: Assumed Classes of Land Suitable for Various Production Sectors

Sector	Classes of Suitable Land
Factory Supply Dairy Farms	I-III
Town Supply Dairy Farms	I-III
South Island High Country	VI, VII (South Island)
South Island Hill Country	V, VI (South Island)
North Island Hard Hill Country	VII (North Island)
North Island Hill Country	V, VI (North Island)
North Island Intensive Fattening	I-V (North Island)
South Island Fattening - Breeding	I-V (South Island)
South Island Intensive Fattening	I-V (South Island)
South Island Mixed Cropping and Fattening	I-IV (South Island)
Cropping	I-III
Horticulture and Production NEC	I, IIW, IIE, IIS
Mixed Livestock and Other Farming	I-V
Pig Farming	I-III
Poultry Farming	I-IV

7.2.3.3 Land Constraints on Agricultural and Horticultural Production

There are 27,130,000 hectares of land in New Zealand, of which 16,183,500 hectares (60%) is currently used for agricultural and horticultural production (Department of Statistics, 1981a). Some land currently used for other purposes could be used for agricultural and horticultural purposes (Department of Statistics, 1981b):

- (1) most of the land occupied by cities and towns (370,000 ha), which is predominantly high class productive land.
- (2) Some of the land occupied by national parks, reserves and domains (2,690,000 ha), which is predominantly low class land.
- (3) Some of the land used for forestry production (810,000 ha), which is predominantly lower class land.
- (4) Most of the small amount of high class land used for nurseries, flower growing, stud farming, tobacco farming and other miscellaneous activities.

In addition, there is some idle land, mainly low class land which could be used for agricultural and horticultural production.

Therefore, there are some obvious difficulties in establishing an exact estimate for the amount of land available for agricultural and horticultural production. Particularly, as assumptions have to be made about the amount of land used for competing land uses such as forestry production. However, for the purposes of this study it was assumed that the amount of land available for agricultural and horticultural production, remains the same as it is now - that is, 16,183,500 ha. The Ministry of Works and Development (1979) were requested through their computer based Land Resource Inventory service, to estimate the land available in each land use class and sub-class available for agricultural and horticultural production. This excluded land currently occupied by towns and cities, national parks, forest parks and under exotic forest plantations - these data are presented for both the North and South Island in Table 7.7

7.2.3.4 Matrix Formulation

Each production sector can be sustained on land classes as indicated in Table 7.8. For example, Factory Supply Dairy Farms

Table 7.7: Land Class Availability for Agricultural and Horticultural Production

Land Class	South Island	North Island	Total
Ic	7.5	33.1	40.6
Is	4.7	43.8	48.5
Iw	23.7	73.4	97.1
I Total	36.0	150.3	186.3
IIc	80.0	62.5	142.5
IIe	94.5	64.6	159.1
IIs	196.4	234.7	431.1
IIw	117.8	358.7	476.5
II Total	488.8	720.5	1,209.3
IIIc	170.2	71.3	241.5
IIIe	569.8	359.5	929.3
IIIs	575.6	274.9	850.5
IIIw	87.3	319.6	406.9
III Total	1,402.8	1,025.3	2,428.1
IVc	126.5	39.9	166.4
IVe	569.6	789.7	1,368.3
IVs	668.5	203.2	871.7
IVw	53.8	61.5	115.3
IV Total	1,418.6	1,283.3	2,701.9
Vc	65.9	64.3	130.2
Vs	16.8	22.2	39.0
Vw	29.0	0.0	29.0
V Total	111.6	86.5	198.1
VIc	109.2	99.8	209.0
VIe	2,565.4	3,624.9	6,190.3
VIs	486.6	23.3	509.9
VIw	26.9	22.1	49.0
VI Total	3,188.1	3,979.8	7,167.9
VIIc	218.5	8.1	226.6
VIIe	2,162.0	2,686.7	4,848.7
VIIs	196.8	16.1	212.9
VIIw	27.6	37.0	64.6
VII Total	2,604.7	2,747.8	5,352.6

Notes:

1. Data source: Ministry of Works and Development (1979). New Zealand Land Resource Inventory Computer Retrieval System.
2. This includes all Class I-VIII Land, except land currently occupied by cities and towns, large mines, national parks, forest parks, and under dominant (>60%) exotic cover.

Table 7.8: Matrix for Land Inputs into the Production Sector for the New Zealand Food System Model (1978-79)

Columns Rows	14 71				Constraint
	FDFAR1	FDFAR2	FDFAR3	FISH	
29 X LAND	1,236.0	1,236.0	1,236.0		<16,185.3
30 X LAND1	1,236.0				< 186.3
31 X LANN1					< 150.4
32 X LANS1					< 36.0
33 X LAND2		1,236.0			< 1,209.3
34 X LANN2					< 720.5
35 X LANS2					< 488.8
36 X LA2ES					< 94.5
37 X LA2EN					< 64.6
38 X LA2WS					< 117.8
39 X LA2WN					< 358.7
40 X LA2SS					< 196.4
41 X LA2SN					< 234.8
42 X LAND3			1,236.0		< 2,428.2
43 X LANN3					< 1,025.3
44 X LANS3					< 1,402.8
45 X LAND4					< 2,701.8
46 X LANS4					< 1,418.6
47 X LAND5					< 198.1
48 X LANN5					< 86.5
49 X LANS5					< 111.6
50 X LAND6					< 7,167.9
51 X LANS6					< 3,979.8
52 X LANN6					< 3,188.1
53 X LAND7					< 5,352.6
54 X LANN7					< 2,747.8
55 X LANS7					< 2,604.8

(FDFAR) can operate on some mix of Class I, II or III land - in the model's formulation:

FDFAR1 - indicates that Class I is being used.

FDFAR2 - indicates that Class II is being used.

FDFAR3 - indicates that Class III is being used.

Similar notations are used for the alternative land class uses by the other Production Sectors.

The sum of the usage of land, of a given class, sub-class, or region (North Island or South Island), must not exceed the total availability of that category which is indicated by Table 7.7. That is, for example:

$$\begin{array}{l} \text{FDFAR1} \\ \text{FISH} \end{array} \times \text{LAND} < 16,185.3 \quad (7.3)$$

Such constraints were entered on the right hand side of the matrix (refer to Table 7.8), and were directly abstracted from data referred to in section 7.2.3.1.

7.2.4 Labour Inputs

The labour requirements of each production sector are detailed by Table 7.9. These data were obtained from the various statistical sources, detailed in Patterson and Earle (1984). The labour inputs are expressed in terms of full-time equivalent man-years.

There were no constraints placed on the labour input, although lack of available labour could be considered to be a constraint on agricultural and horticultural production (Beattie 1979). This could particularly be the case when considering the requirement for seasonal labour, in some production sectors.

Table 7.9: Direct Labour Requirements (Full-time equil. man-years/yr) and Labour Intensity (Full-time equil. man-years/yr/(000 ha)) for Production Sectors in the New Zealand Food System

Sector	Labour Requirements (Full-time equil. man-years/yr)	Land Requirements (000 ha)	Labour Intensity (Full-time equil. man-years/yr/(000 ha))
Factory Supply Dairy Farms	37,414	1,236	30.27
Town Supply Dairy Farms	3,346	136	24.60
South Island High Country	822	3,207	0.26
South Island Hill Country	2,088	1,850	1.13
North Island Hard Hill Country	3,723	1,309	2.84
North Island Hill Country	8,670	1,963.5	4.42
North Island Intensive Fattening	7,040	876	8.04
South Island Fattening - Breeding	7,790	1,460	5.34
South Island Intensive Fattening	6,290	681	9.24
South Island Mixed Cropping and Fattening	3,780	383	9.87
Cropping	5,650	391	14.45
Horticulture and Production NEC	10,532	82	128.44
Mixed Livestock and Other Farming	11,320	2,582	4.38
Pig Farming	1,707	19	89.84
Poultry Farming	1,025	8	128.13
TOTAL	111,197	16,183.5	6.87

Data source: Patterson and Earle (1984)

7.2.5 Endogenous Inputs and Outputs

Endogenous inputs and outputs, include inputs and outputs of products which remain within the food system's boundary. Inputs were expressed as negative quantities as they were used by the system, and outputs were expressed in positive quantities as they are produced by the system.

Products produced by the Production Sectors are pre-fixed with the character "P", followed by a numeric subscript indicating the product code number. A full list of these codes are detailed in Appendix E.

The quantities of net inputs and net outputs into each sector were obtained, primarily from the "Data Sheets" contained in Patterson and Earle, 1984. Such data were obtained from a wide variety of sources which are detailed in Patterson and Earle, 1984; primarily from Producer Board Surveys. Readers should refer to Patterson and Earle, 1984 for full details of these sources, and the data analysis methodology.

A matrix representing these inputs and outputs were constructed. A constraint was placed on each product row (>0) meaning that there had to be a net production of each product.

7.2.6 Linking Equations

Each set of land, labour and energy inputs, were expressed by the variable (column) of the type: Name (Land class no.), e.g. FDFAR1, FDFAR2, FDFAR3. Whereas the endogeneous inputs and outputs are expressed by the variable (column) of the type: Name only - e.g. FDFAR. Therefore there is a requirement for the equation of the following type to be written for each production sector: (to essentially, link potential land input data, with endogenous input-output data):

$$\text{FDFAR.FDFAR1} + \text{FDFAR.FDFAR2} + \text{FDFAR.FDFAR3} = \text{FDFAR.FDFAR} \quad (7.4)$$

where all coefficients equal unity, and variables are unknowns.

Re-arranged to be in matrix form:

$$\text{FDFAR.FDFAR1} + \text{FDFAR.FDFAR2} + \text{FDFAR.FDFAR3} - \text{FDFAR.FDFAR} = 0 \quad (7.5)$$

7.2.7 Other Equations and Constraints

An activity bound of < 1 was placed on the variable FISH. It is recommended that a bound equal to the maximum sustainable yield of the New Zealand fisheries should be placed on this variable. However, this is difficult because:

- (1) the lack of reliable data for the maximum sustainable yield for particular fish types,
- (2) it is difficult to estimate the mix of fish types that may be caught in the future.

Nevertheless, it is not expected that the total tonnage of fish caught in the future, on a sustainable basis, will significantly exceed that of the 1978-79 defined bound limit.

TOBACO, allowed for the land requirements of the tobacco growing sector. Tobacco is considered to be able to be grown on Class I South Island Land, Class IIS, Class IIE and Class IIW South Island Land. This obviously, was a simplification as tobacco farming in New Zealand is confined to the Nelson region, not the South Island. If necessary, an allowance can be made for this, but at this stage this refinement is considered largely unnecessary because of the very small requirement of land for tobacco farming. The following equations, allow for the land requirement of tobacco farming:

$$\text{TOBACO.TOBAC1} + \text{TOBACO.TOBAC2} + \text{TOBACO.TOBAC3} + \text{TOBACO.TOBAC4} = \text{TOBACO.} \quad (7.6)$$

where all coefficients equal unity, and variables are unknowns.

$$\text{XLANS1.TOBAC1} = 0.2 \text{ (Class I SI land, 000 ha)} \quad (7.7)$$

$$\text{XLANS2WS.TOBAC2} = 0.2 \text{ (Class IIW SI land, 000 ha)} \quad (7.8)$$

$$\text{XLANS2ES.TOBAC3} = 0.2 \text{ (Class IIE SI land, 000 ha)} \quad (7.9)$$

$$\text{XLANS2SS.TOBAC4} = 0.2 \text{ (Class IIS SI land, 000 ha)}. \quad (7.10)$$

A constraint of $\text{TOBACO} = 1$ is placed on equation 7.6, meaning that tobacco farming production is assumed to remain the same as it was in 1978-1979.

Similar equations could be written allowing for non-agricultural and horticultural production, on land that would be suitable for such production - e.g. for nurseries, flower growing and stud farming. For

these activities land was allocated out of the model, therefore decreasing the overall land constraint (row 29). However, to allow for the "interaction" of non agricultural-horticultural with agricultural-horticultural uses of land, such equations should preferably be written into the model.

7.2.8 Summary Matrix

Table 7.10 summarises the Production Sector Matrix. This matrix could be more efficiently formulated by transferring the energy input matrix to the Production Sectors (72-88), reducing the repetitive input of data in columns 72-88, by about 3 times.

7.3 Processing Sector Matrix

7.3.1 Introduction

The Processing Sectors, were defined as those sectors where biological raw materials are converted into foodstuffs, ready for export and domestic distribution. The Processing Sector Matrix, covered 24 such sectors, which were defined in terms of the New Zealand Standard Industrial Classification (NZSIC), refer to Table 7.11. Readers should refer to the NZSIC (1979), for more precise definitions of the processing sectors.

7.3.2 Energy Inputs

7.3.2.1 Previous Studies

Since 1974 the New Zealand Energy Research and Development Committee (NZERDC), has sponsored a systematic series of surveys aimed at estimating the direct energy requirements of the food processing industries.

The Dairy Processing Industry (i.e. Co-operative Dairy Companies and Milk Processing Plants) were surveyed by Vickers and Shannon (1977). This survey indicated that the direct energy requirements of the Dairy Processing Sector was 11.5 PJ/yr and that 0.4 PJ/yr of direct energy was used in collecting the milk. This survey has recently been

Table 7.10: Production Sector Matrix, for New Zealand Food System Model (1978-79)

Columns Rows		1 13 Primary Energy Inputs	14 71 Production Sectors (Sub-divided in Land Classes)	72 88 Production Sectors	89 Other Sectors	Constraints
1	Primary Energy Inputs	Energy Transformation Matrix (section 7.1)	Energy Input Matrix (section 7.2.2)			=0
2						.
3						.
4						.
5						.
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27	Dolnet	.				
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29	Direct Land Inputs	Land Input Matrix (section 7.2.3)				16,185.3
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31						.
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80	Direct Labour	.				
81	Production Sectors	.				
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96	Endogenous Inputs/ Outputs	Endogenous Inputs/Outputs Matrix (section 7.2.5)				=0
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Table 7.11: Codings and New Zealand Standard Industrial Classifications for Processing Sectors

Code	New Zealand Standard Industrial Classification	
	Number	Name
ABATTO	31112	Other Abbatoirs and Rural Slaughter Houses
AFFEDS	31120	Prepared Animal Feeds
BISCIT	31174	Biscuit Factories
BREAD	31171	Bread Bakeries
BREAK	31162	Prepared Grain Breakfast Foods
BREW	31331	Breweries
CAKEF	31172	Cake Pastry and Pie (other than meat) Factories
CAKEK	31173	Cake and Pastry Kitchens
CANING	31130	Canning and Preserving of Fruit and Vegetables
CDAIRY	31121	Co-operative Dairy Factories
DAIRYF	31124	Factories Manufacturing Dairy Products
COCOA	31190	Cocoa, Chocolate and Sugar Confectionery
CREAMF	31123	Icecream Factories
DRINKS	31340	Soft Drinks and Cordials
FOONEC	31120	Food Products Not Elsewhere Classified
FWORKS	31111	Meat Export Works (Freezing Works)
GRAIN	31161	Grain Milling
OILS	31150	Vegetable and Animal Oils and Fats
PACKER	31113	Meat Packers and Cannerys
PIES	31117	Meat Pies and Puddings
POULTR	31115	Poultry Slaughter Houses
PRFISH	31141	Land Based Fish Factories
PROCES	31122	Milk Processing Plants
SMALLG	31114	Ham, Bacon and Smallgoods
SPIRIT	31310	Distilling, Rectifying and Blending Spirits
SUGAR	31180	Sugar Factories and Refineries
WINE	31320	Wine
XMALT	31332	Malting

repeated, indicating a slight increase in electricity consumption, a marked decrease in oil consumption and a marked increase in natural gas consumption (Vickers and Miller, 1983). No survey has been undertaken of "Factories Manufacturing Dairy Products" (NZSIC Group).

The Meat Export Works and Abbatoirs were surveyed by Pearson and Pilling (1979) and Pilling (1977). These surveys indicated that the direct energy requirements of this sector was 7.0 PJ/yr. This survey was repeated by Downey (1982), although the Abbatoirs were not included, as they were previously found to only use about 0.3 PJ/yr of direct energy. This survey indicated that coal, gas and electricity consumption had slightly increased, and oil consumption had decreased slightly.

Cleland and Earle (1980) surveyed the direct energy requirements of the remainder of the food processing industries. Detailed surveys were undertaken of 13 industrial groupings, which are fully referenced in the above mentioned publication. The direct energy consumption of this group was found to be 5.0 PJ/yr.

Patterson and Earle (1984) conducted a study which aimed to estimate the indirect energy requirements of the food processing sector, drawing on data from those above mentioned surveys and statistical data primarily derived from Carter, Peet and Baines (1981). The study indicated that the total energy requirements (excluding the energy requirements of the biological raw materials) of the processing sector was 34.1 PJ/yr, using average data for the years 1974-1978. The indirect energy requirements were found to be only 17% of the total energy requirements. Packaging was found to be the main indirect energy requirement (5PJ/yr). A more detailed survey of the energy requirements of food packaging similarly estimate a total energy requirement of food packaging to be 5PJ/yr (Soo, Earle and Patterson, 1984).

7.3.2.2 Patterson and Earle (1984) Study

Due primarily to the slightly different approaches employed in the above studies, the differing years surveyed, and the not entirely complete coverage of all sectors, it was decided to re-analyse the

above data employing a consistent methodology and the same base year (1978-79).

The results of this re-analysis are summarised by Table 7.12. As can be ascertained from Table 7.12, it was estimated that the total energy requirement of the food processing sector to be 39.6 PJ/yr for the year 1978-79. Essentially, these results indicate a very similar pattern of energy requirements, as the previous studies, with Co-operative Dairy Factories accounting for 39%; Meat Export works accounting for 22%, and Abbatoirs, Canning and Preserving Fruit and Vegetables, Foods NEC, and Breweries about 4% each. Direct energy requirements were found to account for about 77% of the total energy requirements, with the main direct requirement being for fuel primarily for fuelling boilers. Indirect energy requirements were found to account for 23% of the total energy requirements, with the main indirect requirement being for packaging.

7.3.3 Labour Inputs

The direct labour requirements of the food processing sectors were estimated using data from the Census of Manufacturing (1978-79) (refer to Table 7.13). For almost all sectors this data could be directly abstracted from the Census of Manufacturing (1978-79). In some cases, data were obtained from previous surveys undertaken by the Food Technology Research Centre (Sugar Refineries and Food NEC) and in one case (Casings of Animal Origins) by multiplying the production (\$/yr) by an estimated labour coefficient (full time equivalent person/yr/\$).

There were no constraints placed on labour availability, as there is relative high urban unemployment in New Zealand, in areas where most food processing factories are located.

7.3.4 Endogeneous Inputs and Outputs

Products produced by the Processing Sectors are prefixed with the characters "Pr", followed by a numeric subscript indicating the product code number. A full list of these codes, for the products produced by the processing sectors, are detailed in Appendix E.

Table 7.12: Total Energy Requirements (TJ/yr) of the Processing Sectors of the Food System, New Zealand

CLASS	DIRECT				INDIRECT				TOTAL
	Fuel	Electricity	Other	Total	Fuel	Electricity	Other	Total	
Meat Export Works	6,016	1,533	160	7,708	504	129	406	1,039	8,747
Other Abattoirs and Rural Slaughter Houses	321	68	8	397	40	7	132	178	575
Casings of Animal Origins	16	4	0	21	2	0	2	4	25
Meat Packers and Cannors	135	191	17	343	17	4	26	47	390
Ham, Bacon and Smallgoods	121	67	6	194	77	18	172	266	460
Poultry Slaughter Houses	81	30	3	114	30	7	40	77	191
Meat Pies and Puddings	81	29	3	113	23	7	30	60	173
Co-operative Dairy Factories	13,097	1,273	161	14,532	80	22	793	894	15,426
Milk Processing Plants	260	157	9	425	55	14	132	198	623
Icecream Factories	68	48	5	120	88	19	52	158	278
Factories Manufacturing Dairy Products	570	28	5	604	47	13	77	137	741
Canning and Preserving Fruit and Vegetables	673	54	10	737	242	75	534	850	1,587
Land Based Fish Factories	238	87	10	334	28	8	127	163	497
Vegetable and Animal Oils and Fats	39	12	92	143	523	47	8	577	720
Grain Milling	67	63	5	135	16	5	42	63	198
Prepared Grain Breakfast Food	76	17	2	94	30	10	34	74	168
Bread Bakeries	526	96	13	635	88	20	137	245	880
Cake, Pastry & Pie (other than Meat) Factories	22	17	1	39	10	2	14	26	65
Cake and Pastry Kitchens	51	34	3	88	39	6	45	90	178
Biscuit Factories	105	54	6	164	62	18	61	141	305
Sugar Factories and Refineries	467	38	7	511	29	10	79	117	628
Cocoa, Chocolate and Sugar Confectionery	250	67	7	324	90	28	102	220	544
Foods NEC and Macaroni etc.	711	94	14	819	241	75	252	568	1,387
Prepared Animal Feeds	542	75	11	627	37	7	41	85	712
Distilling and Rectifying Spirits	125	6	2	133	38	5	22	65	198
Wineries	83	24	3	110	229	42	167	437	547
Breweries	573	113	13	699	667	105	312	1,084	1,783
Malting	188	20	3	212	3	0	13	16	228
Soft Drinks and Cordials	84	24	3	110	139	29	144	312	422
TOTALS	25,586	4,323	582	30,485	3,474	732	3,996	8,191	38,676

a. Base data from Census of Manufacturing (1978-79)

b. All requirements are expressed in Primary Energy Terms.

c. The energy requirement of biological raw materials are excluded. These figures are taken account of in the production sector analysis are not included here as it would lead to double counting when determining the total energy requirements of the food system.

Table 7.13: Direct Labour Requirements (Full-time Person Equivalent/yr),
for the Food Processing Sector of the New Zealand Food System,
1978-79

Sector	Direct Labour Requirement (Full-Time Equivalent Person/yr)
Meat Export Works	28,732
Other Abbatoirs and Rural Slaughter House	1,497
Casings of Animal Origins	20 ^b
Meat Packers and Cannerys	347
Ham, Bacon and Smallgoods	2,095
Poultry Slaughter Houses	924
Meat Pies and Puddings	761
Cooperative Dairy Factories	8,270
Milk Processing Plants	1,320
Icecream Factories	599
Factories Manufacturing Dairy Products	406
Canning and Preserving Fruit & Vegetables	4,233
Land Based Fish Factories	1,566
Vegetable and Animal Oils and Fats	732
Grain Milling	835
Prepared Grain Breakfast Foods	172
Bread Bakeries	2,661
Cake, Pastry & Pie (Other than Meat) Factories	535
Cake and Pastry Kitchens	1,501
Biscuit Factories	937
Sugar Factories and Refineries	300
Cocoa, Chocolate & Sugar Confectionery	2,366
Foods NEC and Macaroni etc.	2,868
Prepared Animal Feeds	931
Distilling and Rectifying Spirits	104
Wineries	916
Breweries	1,496
Malting	293
Soft Drinks and Cordials	1,417
TOTAL	68,834

a. Base data from Census of Manufacturing 1978-79

b. Estimate based on production (\$) and an estimated labour/\$ coefficient.

The quantities of net inputs and net outputs of products, produced by each sector, were abstracted from unpublished Input-Output sheets, obtained from the Department of Statistics (1982), and derived from returns from the Census of Manufacturing (1978-79). Only establishments with 10 or more employees are required to submit such returns to the Department of Statistics, so therefore the Input-Output data had to be scaled up to take account of production from establishments of less than 10 employees. This was undertaken by assuming that the input-output mixes of establishments with less than 10 employees was the same as establishments with 10 or more employees; and that the ratio of inputs to outputs (\$) were the same for small (<10) and large (>10) establishments. That is,

$$\begin{aligned} \text{Quantity of Input or Output} \\ \text{of All Establishments} \end{aligned} &= \left[\begin{array}{l} \text{Quantity of Input or Output in} \\ \text{Establishments (>10 employees)} \end{array} \right] \times \\ &\left[\begin{array}{l} \frac{\text{Production in All Establishments (\$)}}{\text{Production in Establishments (> 10} \\ \text{employees (\$)}} \end{array} \right] \quad (7.10)$$

The variables on the right hand side of these equations were obtained from the Census of Manufacturing (1978-79), and the variable on the left hand side is unknown but can be determined by substituting into the formula.

Inputs were expressed as negative quantities as they are consumed by the system, and outputs were expressed as positive quantities as they are produced by the system. A constraint was placed on each production row (20) meaning that there had to be a net production of each product.

7.3.5 Summary Matrix

Table 7.14 summarises the Processing Sector matrix. Both the Energy Input and Labour Input sub-matrices are very dense matrices (<1% non-zero elements). The Endogenous Input-Output Sub-Matrix is fairly sparse, with only a relatively few products being used and produced by any given sector.

Table 7.14: Processing Sector Matrix, for New Zealand Food System Model (1978-79)

Columns	89	90	91		115	S U G A R	Constraint
Rows	A	A	B				
	B	F	I				
	A	E	S				
	T	E	C				
	T	D	I				
	O	S	T				
1 Primary Energy Inputs	Energy Input Matrix (Section 7.3.2)					=0	:
:						:	
:						:	
:						:	
:						:	
:						:	
:						:	
16						=0	
80 Labour						>0	
136						>0	
:	Labour Input Matrix (section 7.3.3)					:	:
:						:	
:						:	
:						:	
:						:	
:						:	
:						:	
:						:	
:						:	
:						:	
:	Endogenous Inputs/Outputs Matrix (Section 7.3.4)					:	:
:						:	
:						:	
:						:	
:						:	
:						:	
:						:	
:						:	
:						:	
:						:	
425						>0	

Land inputs are not included as they are insignificant, and are in any case largely included in the land allowed for urban settlement.

7.4 Export-Import Sector Matrix

This matrix allows for the importing and exporting of products, to and from the food system.

7.4.1 Coding System

Each import is prefixed by the characters "XI" followed by:

- (1) A numeric code if it is a processed product e.g. XI19.
- (2) The character "P", then a numeric code if it is an unprocessed foodstuff e.g. XIP19.

The latter segment of the codes correspond to the product codings used in the production sector matrix and the processing sector matrix e.g. XI19 indicates imports of calves hides as Pr19 is processed calves hides; and XIP19 indicates imports of unprocessed berryfruit as P19 is unprocessed berryfruit. The codes XI1 to XI9, are reserved for imports of foodstuffs which are not produced in significant quantities in New Zealand - vegetable oil seeds, copra, vegetable oils, rice, cocoa beans, raw sugar, coffee bananas and unblended tea.

Each export is similarly coded - that is, each export is prefixed by the character "X" followed by:

- (1) a numeric code if it is a processed product e.g. X19
- (2) the character "P", then a numeric code if it is an unprocessed foodstuff e.g. XP19.

The latter segments of the codes correspond to the product codings used in the production sector matrix and the processing sector matrix.

Readers should refer to Appendix E, for the full list of the codes used in this matrix.

7.4.2 Energy Inputs

Energy inputs are required for transportation systems that are involved in exporting and importing products. These transportation systems include both the:

- (1) Domestic transportation system that transport exports prior to leaving international terminals for overseas destinations, and transports imports from the international terminal to their points of domestic destination (e.g. processing factories and wholesale stores).
- (2) International transportation system that transports exports and imports to and from New Zealand's international terminals.

Energy inputs into the domestic transportation, are taken account in the wholesale transport matrix, and readers should refer to section 8.1.2 for fuller details of these inputs.

Previous studies have focused on the economics of the international transportation system (Chudleigh, 1977; Chudleigh, 1978; Shipping Corporation of New Zealand, 1978; Chudleigh 1979). Results from these studies are summarised and further analysed by Copeland, Horsfield and Chudleigh (1982). These studies have made various estimates of the international transportation costs (\$) of exporting goods from New Zealand. Chudleigh (1979) estimated that this cost was between \$800 and \$900 million for the Calendar year 1977. This estimate lies in about the middle range of the various cost estimates quoted by Copeland, Horsfield and Chudleigh (1982), and is close to the survey year (1978-79) used in this model as the base year. Therefore, this cost estimate was selected as the most appropriate one for the calculation of the energy requirements of exporting products from the New Zealand food system.

This cost estimate (say \$1977 850 million) was backdated to September \$1971, using the Farming Freight Cost Index, from the Monthly Abstract of Statistics. Data from the Input-Output tables (1971-72, 1978-79 provisional) and External Trade Statistics indicates that about 7% of these freight costs are involved in air transport and about 93% in water transport. Therefore, the international transport energy requirements of all exports (not just foodstuffs), was calculated:

Water Transport:

$$0.93 \times \$1971-72 \text{ 456,400,000/yr} \times 31.6 \times 10^6 \text{ J}/\$1971-72$$

(cost estimate) (energy intensity for water
transport from Carter, Peet
and Baines, 1981)

$$= 13.3466 \times 10^{15} \text{ J/yr (1)}$$

Air Transport:

$$0.07 \times \$1971-72 \text{ 456,400,000/yr} \times 70.2 \times 10^6 \text{ J}/\$1971-72$$

(cost estimate) (energy intensity for air
transportation from Carter,
Peet and Baines, 1981)

$$= 2.3894 \times 10^{15} \text{ J/yr (2)}$$

Total: Sum (1) + (2) = $15.736 \times 10^{15} \text{ J/yr}$

Since Food Exports only 25.79% of the total imports and exports, by value, in 1978-79 (External Trade Statistics,) the energy requirement of international transport of exported foods is estimated to be:

$$0.2579 \times 15.736 \times 10^{15} \text{ J/yr} = 4.0593 \times 10^{15} \text{ J/yr}$$

The mean total energy intensity for importing, exporting and re-exporting goods to and from New Zealand is estimated to be:

$$\frac{15.7360 \times 10^{15} \text{ J/yr}}{\$7,319,659,000/\text{yr}} = 1.99 \text{ MJ}/\$$$

The denominator is the total value of imports, exports and re-exports from New Zealand, obtained from the External Trade Statistics. The primary energy requirements (X Coal, X Oil, X Gas, X Elect, X Import, X Capital) of the total energy intensity of 1.99 MJ/\$, were calculated by using data from Carter, Peet and Baines (1981). This energy intensity was used in the Export-Import matrix. However,

it should be recognised that:

- (1) it is a weighted mean estimate, and in any particular case it will vary according to the destination of the product.
Therefore, it is assumed in this model, that the weightings (distances from markets) will not change significantly in time or with change of markets or products exported.
- (2) it is assumed that the energy intensity (MJ/\$) for importing and exporting foods, is the same as that for all imports and exports. This assumption could introduce significant error, as most food products have a low value: volume ratio compared with other exports-imports. Therefore, they should require more transport energy (MJ) per unit of value (\$), as transport energy requirements are to a large extent a function of volume.

Finally, it should be noted, that it is recognised that the use of the above calculated energy intensity is far from satisfactory and could cause misleading results. This situation can only be improved by more detailed research into the actual energy requirements of importing and exporting commodities - the present research results (as summarised by Copeland, Horsfield and Chudleigh, 1982) are far from being adequate either in their detail or accuracy.

7.4.3 Market Levels and Prices

For each export product, the 1978-79 mean overseas market price was abstracted from the 1978-79 External Trade Statistics: Exports published by the Department of Statistics (1980b). The value (\$f.o.b) was divided by the quantity, to obtain a \$/quantity coefficient. Some problems were encountered, as the classification system used in the External Trade Statistics, differed from that used in the Census of Manufacturing which formed the basis of the classification of the products in this model. Also, the measurements used to measure quantities differed somewhat between both classification systems. However, in all cases these problems were resolved, if not by somewhat tedious searching for the appropriate conversion factors.

For each import product, the 1978-79 mean overseas market price was similarly abstracted from the 1978-79 External Trade Statistics:

Imports published by the Department of Statistics (1980a). The value (\$c.i.f) was divided by the quantity to obtain a \$/quantity coefficient. Similar problems were encountered as in the exports, due to the different classification systems used by the Department of Statistics, in the External Trade Statistics and in the Census of Manufacturing.

For each export product, the 1978-79 market in quantity terms were abstracted from the 1978-79 External Trade Statistics: Exports. These market levels, formed the basis of the market constraints placed on the model, in the various runs described in Chapter 9. More research of the market literature and data sources is required to be undertaken, so that more accurate information can be obtained on the long term market for various products and be eventually incorporated into the model.

7.4.4 Matrix Formulation (refer to Table 7.15)

For each export variable, a coefficient of -1 is entered against the corresponding production/processing output indicating that 1 unit is lost to system when exported; and the value (\$) is entered in the DOLLAR and the DOLNET rows, indicating the overseas currency (\$) gained by the system. Hence, in MPS format the entry for the X1 column was:

```
X1 DOLNET 3.5350 DOLLAR 3.5350
X1 PR1 -1.0000
```

Similarly, for each import variable, a coefficient of 1 is entered against the corresponding production/processing output indicating that 1 unit is gained by the system when imported, and the value (\$) is entered in the DOLNET row as a negative value, indicating that overseas currency (\$) has been lost (or forgone) by the system. Hence in MPS format the entry for the XI100 column was:

```
XI100 DOLNET -0.6484 PR100 1.0000
```

Constraints of >0 were placed on each production/processing sector rows (136 ...425) meaning that the production - exports + imports must be greater than zero. Bounds were placed on variables (116-325), meaning that the activity of the export variables cannot be greater than the existing market levels. These bounds restrictions were relaxed in several of the runs (refer to Chapter 9).

The energy requirements of international transport of food exports was assumed to be directly proportional to the value (\$) of the food exports - that is, 1.99 MJ/\$. That is,

DOLLAR	=	0.05000	XCOAL
DOLLAR	=	1.05000	XOIL
DOLLAR	=	0.01000	XGAS
DOLLAR	=	0.07000	XELECT
DOLLAR	=	0.61392	XIMPOR
DOLLAR	=	0.18000	XCAPTL
DOLLAR	=	1.99	XTOTAL
DOLLAR	=	1.99	TOTAL

Row 28, ensures that the sum of all the exports (\$), equals the activity of the variable DOLLAR, by placing a coefficient of -1 in Row 28 corresponding to the variable DOLLAR. Since the import values (\$) are in C.I.F. (Cost including freight) terms, the energy requirement of this transport of international imports is not included as it would lead to double counting.

8 DISTRIBUTION - TRANSPORT, HOUSEHOLD AND CATERING - HOTEL MATRICES

8.1 Distribution and Transport Sector Matrix

8.1.1 Introduction

The distribution and transport sector includes:

- (1) all storage and transportation steps in the food chain from the processing plant's gate, to the household's gate. In the case of non-processed foods, it includes all those storage and transportation steps in the food chain from the first storage step beyond the farm gate, to the householder's gate.
- (2) all transportation steps to and from Catering establishments and Hotel establishments, including the transportation of customers from their points of origin to these establishments.

8.1.2 Energy inputs:

8.1.2.1 Wholesale distribution

Wholesale distribution is defined as the storage and transportation steps in the food chain from the processing plant's gate to the retailer's door. In the case of non-processed foods, it is those storage and transportation steps in the food chain from the first storage step beyond the farm gate to the retailer's door. Patterson and Earle (1982c) undertook detailed surveys of total energy use in the Wholesale Distribution sector (readers requiring further detailed information are advised to refer to this survey):

(1) Total Energy Requirements(TJ/yr)

Patterson and Earle (1982c) estimated the total energy requirements of the Wholesale Distribution sector to be 6,008 TJ/yr, for the year 1980. As can be ascertained from Table 8.1, Groceries Distribution accounted for 36.8% of this energy requirement, followed by Dairy and Related Products (30.2%), Fruit and Vegetables (21.2%), with only minor requirements being estimated for other survey groupings. Most of the energy requirements were for the transport steps (89.4%) as opposed to

Table 8.1: Total Energy Requirements (TJ/yr) of the Wholesale Distribution Sector of the Food System, in New Zealand

Class Classification		Storage			Transport		Total
Class	Products	Electricity	Fuel	Indirect ^a	Fuel	Indirect	
Dairy Related Products	Butter, Cheese, UHT Milk, Yoghurt Eggs, Margarine	108	0	120	566	1018	1812
Grocery Products	Groceries, Biscuits, Confectionery Soft Drinks	31	21	79	650	1429	2210
Fish	Fresh Fish	0	0	1	8	17	26
Foods NEC	Coffee, Tea, Flour, Sugar, Health Foods, Imported Foodstuffs, Dried Fruit.	6	0	9	43	88	146
Fruit and Vegetables	Fresh Fruit and Vegetables	108	16	113	374	665	1276
Meat	Fresh Meat	0	0	0	120	209	329
Refrigerated Products	Frozen Pies and Pastry, Icecream Lines, Fruit Drinks and Frozen Poultry	13	0	14	65	117	209
TOTALS		266	37	336	1826	3543	6008

a. Does not include packaging energy requirements.
Data Source: Patterson and Earle (1984).

the storage steps (10.6%).

It should also be noted that the direct energy requirement of the wholesale distribution of foods, was estimated to be only 35% of the total energy requirements. Most of this direct energy was required for transport fuels, with most of the remainder of the direct energy being for electricity required for lighting, refrigeration and internal transport (forkhoists) in stores. Most of the indirect energy requirements of the wholesale distribution of foods, were the indirect requirements of transportation systems. Carter, Peet and Baines (1981) estimated that the indirect requirements of "Rail Transport" are 71% of the total energy requirements, and the indirect energy requirements of "Road Freight Transport" are 63% of the total energy requirements.

(2) Total Energy Intensities (MJ/kg)

The total energy intensities for the storage steps (S_1 - S_{14}) in the wholesale distribution of foods are outlined by Table 8.2. The most energy intensive storage step was for banana ripening (S_{11}) which required 1.14 MJ/kg. Banana ripening requires extra direct energy for the operation of controlled atmosphere stores, as well as extra indirect energy for the supply of ripening gas and the controlled atmosphere storage equipment. Those storage steps which required refrigeration also had comparatively high storage energy intensities. The storage of Refrigerated and Dairy Products (S_6) had a total energy intensity of 0.64 MJ/kg, the storage of fish (S_2) had a total energy intensity of 0.57 MJ/kg, and the storage of meat (S_{13}) had a total energy intensity of 0.50 MJ/kg.

The total energy intensities for the transportation steps (T_1 - T_{40}), are outlined by Table 8.3. As can be ascertained from Table 8.3 the transportation steps (T_1 - T_{40}) were generally more energy intensive than the storage steps (S_1 - S_{14}). Poor loading factors lead to particularly high energy intensities for the transportation of novelty lines. Whereas, bulk commodity products had better loading factors and therefore lower energy intensities.

It should be noted that usually, a product passed through several storage and transportation steps before arriving at the retail

Table 8.2: Energy Intensities (MJ/kg) for Storage Steps in the Wholesale Distribution of Foods, in New Zealand

Step	Establishment	Direct ^b				Indirect ^a			Total
		Type of Storage	Fuel	Electricity	Total	Buildings, Equipment, Materials	Supply of Direct	Total	
S1	Apple and Pear Marketing Board	Cool Store	0.05	0.18	0.23	0.09	0.14	0.23	0.46
S2	Distribution Depot: Biscuit-Confectionery	Ambient Temperature	0.00	0.17	0.17	0.14	0.09	0.23	0.40
S3	Distribution Depot: Grocery	Ambient Temperature	0.05	0.05	0.10	0.10	0.07	0.17	0.27
S4	Distribution Depot: Refrigerated & Dairy	Refrigerated	0.00	0.33	0.33	0.13	0.18	0.31	0.64
S5	Distribution Depot: Soft Drinks	Ambient Temperature	0.00	0.03	0.03	0.07	0.02	0.09	0.12
S6	Packing House: Fruit and Vegetable	Ambient Temperature	0.04	0.10	0.14	0.11	0.09	0.20	0.34
S7	Produce Market	Ambient Temperature	0.01	0.09	0.10	0.03	0.06	0.09	0.19
S8	Produce Market	Banana Ripening	0.01	0.63	0.64	0.15	0.35	0.50	1.14
S9	Terminal Store	Cool Store	0.05	0.14	0.19	0.15	0.12	0.27	0.46
S10	Warehouse: Grocery	Ambient Temperature	0.06	0.04	0.10	0.09	0.07	0.16	0.26
S11	Warehouse: Grocery	Refrigerated	0.05	0.07	0.12	0.09	0.08	0.17	0.29
S12	Warehouse: Foods NEC	Ambient Temperature	0.00	0.12	0.12	0.12	0.07	0.19	0.31
S13	Wholesaler's Store: Fish	Cold Store	0.00	0.30	0.30	0.10	0.17	0.27	0.57
S14	Wholesaler's Store: Meat	Cold Store	0.00	0.32	- .32	0.08	0.18	0.26	0.58

a. Packaging materials not included

b. Includes internal transport

Table 8.3: Total Energy Intensities (MJ/kg) for Transport Steps in the Wholesale Distribution of Foods in New Zealand

Step	Origin	Destination	Direct	Indirect	Total
T1	Processing Plant	Grocery Warehouse	0.44	0.88	1.32
T2	Processing Plant	Distribution Depot: Soft Drinks	1.19	1.60	2.79
T3	Processing Plant	Distribution Depot: Confectionery-Biscuit	0.35	0.70	1.05
T4	Processing Plant	Distribution Depot: Groceries	0.44	0.88	1.32
T5	Processing Plant	Retail Establishment: Groceries	0.55	1.10	1.65
T6	Processing Plant	Exports Terminal: Groceries	0.22	0.44	0.66
T7	Distribution Depot: Soft Drinks	Grocery Warehouse	0.55	1.10	1.65
T8	Distribution Depot: Soft Drinks	Retail Establishment	3.60	5.66	9.26
T9	Distribution Depot: Confectionery-Biscuit	Distribution Depot: Confectionery-Biscuit	1.20	1.88	3.08
T10	Distribution Depot: Confectionery-Biscuit	Grocery Warehouse	0.22	0.35	0.57
T11	Distribution Depot: Confectionery-Biscuit	Retail Establishment	3.30	5.19	8.49
T12	Distribution Depot: Groceries	Grocery Warehouse	0.44	0.70	1.14
T13	Grocery Warehouse	Grocery Warehouse	0.44	0.70	1.14
T14	Grocery Warehouse	Retail Establishment (Self Delivery)	2.20	2.00	4.20
T15	Grocery Warehouse	Retail Establishment (Truck Delivery)	0.44	0.70	1.14
T16	Distribution Depot: Groceries	Grocery Warehouse	0.44	0.70	1.14
T17	Import Terminal	Grocery Warehouse	0.44	0.70	1.14
T18	Distribution Depot: Dairy and Related	Retail Establishment	1.32	2.16	3.48
T19	Apple and Pear Board Stores	Produce Market	0.48	0.92	1.40
T20	Apple and Pear Board Stores	Export Terminal	0.14	0.28	0.42
T21	Apple and Pear Board Stores	Processing Plant	0.10	0.15	0.25
T22	Packing House: Fruits	Produce Market	0.33	0.60	0.93
T23	Import Terminal	Produce Market	0.28	0.62	0.90
T24	Packing House	Produce Market	0.11	0.17	0.28
T25	Produce Market	Retail Establishment	0.55	0.87	1.42
T26	Produce Market	Retail Establishment (via small distributor)	1.65	2.60	4.25
T27	Wharfside: Fish	Retail Establishment	0.55	0.87	1.42
T28	Processing Plant: Fish	Wholesale Store	0.91	1.44	2.35
T29	Processing Plant: Fish	Retail Establishment	0.91	1.52	2.43
T30	Wholesale Store: Fish	Retail Establishment	0.33	0.52	0.85
T31	Processing Plant: Meat	Retail Establishment	0.44	0.69	1.13
T32	Processing Plant: Meat	Wholesale Store	0.44	0.69	1.13
T33	Wholesale Store: Meat	Retail Establishment	0.55	0.87	1.42
T34	Processing Plant: Foods NEC	Warehouse: Food NEC	0.50	0.99	1.49
T35	Warehouse: Foods NEC	Grocery Warehouse	0.44	0.70	1.14
T36	Import Terminal	Warehouse: Foods NEC	0.50	0.99	1.49
T37	Warehouse: Foods NEC	Retail Establishment	0.44	0.70	1.14
T38	Milk Processing Plant	Household & Retail Establishment	0.63	0.99	1.62
T39	Bakeries: Pies, Cakes, Bread	Retail Establishment	0.44	0.70	1.14
T40	Brewery	Retailing, Catering & Hotel Establishments	0.44	0.70	1.14

establishments. These distribution networks are detailed in Patterson and Earle (1982c) and Patterson and Earle (1984).

8.1.2.2 Retail storage

Retail storage is defined as the storage of foods in retail establishments. This includes the activities of Groceries and Supermarkets (N.Z.S.I.C. Group Nos. 62211 & 62213), Dairies (62212), Butcheries (62214), Greengroceries and Fruiteries (62220), Wine and Spirit Merchants (62231 & 62232) and Others (62215, 62216 & 62219).

(1) Total Energy Requirements (TJ/yr)

Patterson and Earle (1982e) estimated the total energy requirements of the Retail Distribution sector to be 1173 TJ/yr, for the year 1980, which can be increased to 1186 TJ/yr when recent survey data for Wine and Spirit Merchants is included.

As can be ascertained from Table 8.4 the main energy requirement was by the Groceries and Supermarkets group (53.4%), followed by Butcheries (23%), Dairies (17.1%), with the remainder only accounting for a relatively small amount (6.3%). Refrigeration (52 - 79%, depending on the shop type) was found to be the main end-use of energy, followed by lighting (5 - 25%), HVAC (1 - 18%), miscellaneous (1 - 18%) and water heating (1 - 11%).

Most of the total energy requirement was for the direct energy and for the energy required for the supply of this energy (86.3%), with the remainder being for the supply of buildings and equipment (13.7%).

(2) Total Energy Intensities (MJ/kg)

The total energy intensities for the retail storage steps (S_{20} - S_{26}) of foods are outlined by Table 8.5. The most energy intensive steps are the steps which require refrigeration (S_{21} , S_{23} , S_{24}). The ambient storage steps (S_{20} , S_{22} , S_{25} , S_{26}) are generally much lower than the refrigeration steps.

Table 8.4: Total Energy Requirements (TJ/yr) of the Retail Storage Steps in the N.Z. Food System, 1981-82

Establishments	Direct					Indirect		Total
	Fuel	Electricity	Total	Equipment	Buildings	Supply of Direct Energy	Total	
Butcheries	2	149	151	20	17	85	122	273
Dairies	0	111	111	9	22	61	92	203
Greengroceries & Fruiteries	0	18	18	2	7	10	19	37
Groceries & Supermarkets	35	314	349	12	68	204	284	633
Others (Food)	1	13	14	1	3	9	13	27
Wine and Spirit Merchants	0	6	7	0	1	4	6	13
TOTALS	29	611	650	44	118	373	536	1,186

Data source: Patterson and Earle (1982e).

Table 8.5: Total Energy Intensities (MJ/kg) of the Retail Storage Steps in the New Zealand Food System, 1981-82

Step	Establishment	Type of Storage	Direct	Indirect	Total
S20	Supermarkets & Groceries	Ambient	0.33	0.23	0.56
S21	Supermarkets & Groceries	Refrigerated	2.17	0.28	2.45
S22	Dairies	Ambient	0.28	0.19	0.47
S23	Dairies	Refrigerated	1.53	0.23	1.76
S24	Butcheries	Refrigerated	1.29	1.34	2.62
S25	Greengroceries	Ambient	0.22	1.13	1.35
S26	Not Elsewhere Classified	Ambient	0.32	0.22	0.54

Data Source: Patterson and Earle (1982e)

8.1.2.3 Shopping

Shopping is defined as those transportation steps in the food chain undertaken by household members to retail establishments. This usually means a trip from the household to the retail establishment and return. Data presented in this section are drawn from a detailed sample survey of food shopping trips in Palmerston North. An examination of the sample parameters, and other factors, indicate that the Palmerston North sample is probably representative of the national situation. However, the results of this survey need to be verified with other surveys in other centres. Readers interested in further details of this sample survey should refer to Patterson and Earle (1982b).

An important element of the survey methodology used, was that it was recognised that most shopping trips are multi-purpose. Customers were asked to subjectively weigh up what degree of trip purpose on a 0 - 100 scale could be attributed to visiting the shop being surveyed. This percentage (expressed as a proportion), was subsequently used to scale-down the estimates of energy use, so as not to attribute energy used for other trip purposes solely to shopping for food.

(1) Total Energy Requirements (TJ/yr)

The total energy requirement of shopping for foods (excluding that 5% not covered by the survey) are 11,583 TJ/yr (refer to Table 8.6). This total energy requirement can be extended to 12,200 TJ/yr, by assuming the MJ:\$ ratio of the surveyed population is the same for the unsurveyed population.

The direct energy requirement of shopping for food (excluding the 5% not covered) in New Zealand was estimated to be 4.43 PJ/yr, for 1980. This direct energy requirement can be extended to about 4.70 PJ/yr, by assuming the MJ/\$ of the surveyed population is the same for the unsurveyed population. The New Zealand Yearbook (1981) reports that the direct energy requirements of the entire transport sector was 91.04 PJ/yr in 1980. This means that energy used in shopping for food accounts for about 5% of the energy use in the entire transport sector.

The indirect energy requirement of shopping for food in New

Zealand, scaled up to include the 5% not covered by the survey is 7.53/yr, for 1980. This indirect energy requirement accounts for 62% of the total energy requirements, and represents the energy requirements of the transport system infrastructures.

Shopping at Dairies (29%) was estimated to have the highest total energy requirement, followed by shopping at Supermarkets (20%), Groceries (20%), Butcheries (12%), Greengroceries and Fruiteries (9%) and Others (1%).

(2) Total Energy Intensities (MJ/kg)

The total energy intensities for the shopping steps (T_{50} - T_{55}) of the food chain are outlined by Table 8.7.

These energy intensities (MJ/kg) were statistically examined and analysed (for detailed information refer to Patterson and Earle, 1982b). An important statistical determinant of the total energy intensities was found to be the customers sex (F ratio = 9.337, significant at the $p = 0.002$ level). Males were found to have a mean energy intensity for their shopping trips of 19.27 MJ/kg, compared with 11.54 MJ/kg for females. The age of the customer was a quite significant influence in determining the total energy intensity for a shopping trip (F ratio = 1.633, significant at the $p = 0.135$ level). The most important trend was that under 20 year olds, particularly 0 - 9 year olds had comparatively low total energy intensities for food shopping trips. Of all the parameters examined, the day of the shopping trip was found to have the most influence on the total energy intensities for food shopping trips (F ratio = 4.513, significant $< p = 0.001$ level). There was found to be an almost ordered decline in these total energy intensities as the days progressed through the week. That is, shopping trips on Monday had the highest total energy intensity (18.14 MJ/kg), followed by trips on Wednesday (12.8 MJ/kg), Tuesday (11.71 MJ/kg), trips on Thursday (10.06 MJ/kg) and trips on Friday (9.86 MJ/kg). Both the socio-economic status of the customer and the weather had little or no influence in determining the total energy intensities of shopping trips.

Table 8.6: Total Energy Requirements (TJ/yr) of the Shopping for Food in New Zealand

Survey Classification		Direct	Indirect	Total
Class	NZSIC Groups			
Groceries	62211	887	1,442	2,329
Dairies	62212	1,261	2,053	3,314
Supermarkets	66213	1,262	2,030	3,292
Butcheries	66214	557	890	1,447
Fish Shops	66215	18	29	47
Delicatessens	66216	16	26	42
Food NEC	66219	24	39	63
Greengroceries and Fruiteries	66220	403	646	1,049
TOTAL		4,428	7,155	11,583

Table 8.7: Total Energy Intensities (MJ/kg) for the Shopping Steps in the New Zealand Food System, 1981-82

Step	Origin	Destination	Direct	Indirect	Total
T50	Butchery	Household	6.29	10.06	16.35
T51	Dairy	Household	6.29	10.07	16.36
T52	Greengrocery-Fruiteries	Household	2.76	4.41	7.17
T53	Grocery	Household	4.91	7.96	12.87
T54	Supermarket	Household	4.92	7.87	12.79
T55	Other Retail Establishments	Household	5.07	8.13	13.20

8.1.3 Endogenous Inputs and Outputs

Essentially, the Distribution-Transport Sector, enables products to be distributed from processing plant gates or farm gates to the household or point of final consumption. Therefore, the endogenous inputs into this sector are production or processing sector products (P (number), Pr (number)), and the endogenous outputs are household sector inputs (H (number)). For further details of how these endogenous inputs and outputs were included in the matrix, readers should refer to the next section.

8.1.4 Matrix Formulation

The problem to be solved here, is essentially the classical transport (or network) problem, where there is a series of nodes and a series of possible routes between these nodes which run between the origin and the destination (refer to Cooper and Steinberg, 1974 for a fuller explanation of such problems).

The origins in this case are the processing factories and in some cases the farm gate. The destinations are the household, catering establishments and hotel establishments. The nodes are the storage steps (S1 - S₂₆) and the possible routes are the transport steps (T1 -T₅₅). For full details of the actual storage capacities of the storage steps, and the flows along the transport routes readers should refer to Patterson and Earle (1982c). In this case the objective function was either to minimise Q or DOLNET.

The Energy Input Matrix, specifies the primary energy input co-efficients, for each storage and transport step (data were abstracted from section 8.12).

The endogenous output matrix specifies the input of processing/production output required for each alternative distribution route. Each alternative route is indicated by a set of three groups of characters - the first alphabetic character indicates that it is a household input, the next numeric characters indicate the product number and the last characters indicate a coding for the alternative route. Hence, product H1, has the following alternative distribution

Table 8.8: Distribution - Transport Sector Matrix

[illegible]

routes: H1AA, H1AB, H1AC, H1AD, H1AE, H1AF.

The household inputs matrix specifies the household inputs for each alternative distribution route. The constraint at the end of the row indicates the "demand" for each household product.

The transport and storage inputs matrix specifies the transport and storage steps required for each alternative distribution route. Aggregated routes were included to reduce duplicating inputs, where alternative distribution routes had common sets of transport and storage inputs. The aggregate routes were coded according to type of route:

CD1 - CD8, Confectionary distribution routes.

GD1 - GD10, Groceries distribution routes.

FD1 - FD8, Food NEC distribution routes.

FV1 - FV19, Fruit and Vegetables distribution routes.

The transport and storage inputs into each of these aggregated routes are specified in columns 2500--2550 of the transport and storage input matrix.

Linking equations for each transport and storage row, ensure that the sum of each transport and storage input is numerically equal to the column (variable) of the same name divided by - 1,000. Each storage and transport coefficient is expressed in terms of 10 tonnes, and each storage and transport variable is expressed in terms of 10 tonnes.

The Aggregated Route Inputs Matrix, specifies the inputs of aggregated routes into each alternative distribution route. Linking equations ensure that the sum of each aggregated route is numerically equal to the column (variable) of the same name.

Fixed bounds equal to unity were sometimes placed on the columns (variables) HOTELS and CATERERS.

8.2 Household Sector Matrix

8.2.1 Introduction

The household sector includes those activities of the food chain, which take place in households or permanent dwellings. That is, the final preparation and storage of foods, and the essentially non-commercial production of foods from household gardens.

8.2.2 Energy Inputs

Patterson and Earle (1982d) undertook a detailed study of the total energy requirements in the household preparation and storage of foods, and data from this publication is used as a basis to the data presented here.

8.2.2.1 Total Energy Requirements (TJ/yr)

The total energy requirements of the household preparation, storage and production of foods is estimated to be 24.36 PJ/yr, for the years 1980-1981 (refer to Table 8.9).

The direct energy requirements of the household preparation and storage of food is 13.33 PJ per annum. The New Zealand Yearbook (1981) indicates that the direct energy requirement for "domestic" use was 40.30 PJ per annum. Therefore, the direct energy requirements of the household preparation and storage of foods is 32% of this total once all the ancillary services to cooking and food preparation (such as lighting, dishwashing, and refrigeration) have been taken into account.

Electricity was estimated to be the main source of direct energy (80%). Various fuels including oil, gas, coal and wood were estimated to be the source of the remainder of the direct energy (20%). HVAC, lighting, cleaning and general maintenance of the kitchen area, were estimated to be the main end-uses of direct energy (34%). This was followed by range cooking (16%), dishwashing (10%), refrigeration (9%) and other cooking (2%).

The indirect energy requirements of the household preparation, storage and production of foods accounted for 11.03 PJ per annum (45% of the total energy requirements). The energy required for the supply of direct energy is the main indirect energy requirement (70%), although this can only be approximated because the actual mix of fuels

Table 8.9: Total Energy Requirements (PJ/yr) of the Household Preparation and Storage Sector of the Food System

Survey Classification	Energy Requirements	
	(PJ/yr)	(%)
Direct		
Dishwashing	2.25	10
HVAC, Lighting, Maintenance	4.57	19
Other Cooking	0.57	2
Range Cooking	3.76	16
Refrigeration	2.18	9
Total	13.33	57
Indirect		
Buildings	1.01	4
Equipment, Utensils	0.93	4
Materials	0.57	2
Supply of Direct	7.73	33
Total	10.24	43
TOTAL	23.57	100

used is not known with any certainty. Building space (kitchen and dining room areas) accounted for 9% of the indirect energy requirements, followed by equipment and utensils (8%), production of foods from household gardens (7%), and kitchen materials (5%). Kitchen materials included such items as dishwashing detergents, cleaning materials, packaging items and oven bags.

8.2.2.2 Total energy intensities (MJ/kg)

The total energy intensities (MJ/kg) for the household preparation, storage and production of foods, 1980-1981, are detailed by Table 8.10.

Baking was found to be the most energy intensive cooking mode (40.37 MJ/kg), followed by roasting (16.91 MJ/kg), grilling (10.17 MJ/kg), steaming (7.15 MJ/kg), boiling (4.84 MJ/kg), frying-heating (3.02 MJ/kg), deep frying (2.78 MJ/kg) and toasting (1.68 MJ/kg).

Refrigeration had an energy intensity of 4.04 MJ/kg, and the general baseload for kitchen activities had an energy intensity of 6.47 MJ/kg.

The home production of foods was found to have an energy intensity of 12.59 MJ/kg, which generally was much higher than the commercial production of foods (refer to section 7.2.2). Much energy was required to supply the fertilizers, pesticides and equipment required for home gardening.

8.2.3 Endogenous Inputs and Outputs

The inputs of food products into the household sector can be estimated; by subtracting from the total domestic production the Exports and the foods used by the Catering-Hotel Sector, and adding the Imports of foodstuffs used directly by the household. By undertaking such a calculation, the total amount of each food product available for household use was calculated.

The household production of foods (i.e. in household gardens), was found to be 62,420 tonnes/yr, calculated using data from the

Table 8.10: Total Energy Intensities (MJ/kg), for the Household Preparation, Storage and Production of Foods, 1980-1981

Code ^a	Mode/Activity	Direct	Indirect	Total
C1	Baking	40.13	0.24	40.37
C2	Roasting	16.67	0.24	16.91
C3	Grilling	9.93	0.24	10.17
C4	Steaming	6.91	0.24	7.15
C5	Boiling	4.60	0.24	4.84
C6	Frying-Heating	2.78	0.24	3.02
C7	Deep Frying	2.54	0.24	2.78
C8	Toasting	0.73	0.95	1.68
C9	Refrigeration	3.74	0.30	4.04
C10	General Baseload for Kitchen Activities ^b	5.45	1.02	6.47
HOME	Production from Household Gardens ^c	0.00	12.59 ^c	12.59

- a. Variable code used in Matrix formulation.
b. Includes the direct energy requirements of kitchen HVAC, lighting and general maintenance, and indirect energy requirements of kitchen and dining room buildings, general kitchen equipment and materials.
c. Energy required to supply fertilisers, pesticides and garden equipment.
d. Data sources: Patterson and Earle (1982d). Patterson and Earle (1984).

Table 8.11: Total Household Food Production (Tonnes/yr)

Item	Production (tonnes/yr)
Fruit ^a	2,805
Potatoes ^b	25,200
Other Vegetables ^c	34,415

- a. 1% of commercial production (Department of Statistics, per. comm. 1983).
b. 14% of commercial production (Food Balance Sheet, Monthly Abstract of Statistics, Feb. 1983).
c. 21% of commercial production (Food Balance Sheet, Monthly Abstract of Statistics, Feb. 1983).

Department of Statistics (1983) (refer to Table 8.11). It was assumed in this study that all production (outputs) from household production, was consumed (inputs) by households.

8.2.4 Nutritional Outputs and Requirements

8.2.4.1 Nutritional Outputs Considered and Codings

The nutritional elements included in this analysis included:

- (1) Dietary Fibre (FIBRE). Defined as the sum of the polysaccharides and lignin which are not digested by the endogenous secretions of the human gastrointestinal tract (Paul and Southgate, 1978).
- (2) Metabolic Energy (ENERGY).
- (3) Protein (PROT).
- (4) Fats (FAT).
- (5) Calcium (CA).
- (6) Phosphorus (P).
- (7) Magnesium (MG).
- (8) Iron (FE).
- (9) Sodium (NA).
- (10) Zinc (ZN).
- (11) Potassium (K).
- (12) Vitamin A (A). Defined as: $\mu\text{g retinol} + \frac{\mu\text{g } \beta\text{-carotene}}{6}$
- (13) Vitamin B1 (B1) : Thiamin.
- (14) Vitamin B2 (B2) : Riboflavin.
- (15) Niacin (NIACIN): Defined as: $\text{mg nicotinic acid} + \frac{\text{mg tryptophan}}{60}$
- (16) Vitamin B6 (B6).
- (17) Free Folic Acid (FOLIC). Determined by Lactobacillus casei assay.
- (18) Total Folic Acid (TFOLIC). Determined by Lactobacillus casei assay, after treatment with conjugases.
- (19) Vitamin C (C).
- (20) Vitamin D (D).
- (21) Vitamin E (E).

For fuller definitions of these nutritional elements, and for details of the methods of calculation, readers should refer to Paul and

Southgate (1978), which was the main source of data used here.

Only those nutritional elements were considered for which there were both:

- (1) a Recommended Dietary Allowance (RDA) recommended by the National Academy of Sciences (1980).
 - (2) adequate compositional data were available in the food tables (Iodine was excluded for this reason, as this element is not covered by Paul and Southgate (1978) which was the main data source).
- Although there are not RDA's for FIBRE and FAT, these nutrients were considered so as to provide extra information from the modelling process.

The main data source for estimating the nutritional output was Paul and Southgate (1978). Supplementary data sources (refer to methodology section), were used when compositional data could not be obtained from Paul and Southgate (1978).

8.2.4.2 Allowance for Wastes and Loss of Nutrients

Allowance had to be made for wastage of foods and loss of nutrients in kitchen practice. In general (e.g. Paul and Southgate 1978) the food tables, make allowance for the fact that not all of the weight of a food, is edible although it may contain various nutritional elements. For example, lamb chops according to Paul and Southgate (1978), are 18% bone, and therefore only have an edible portion of 82% by weight, although the bone itself contains much calcium.

Allowance is also made by Paul and Southgate (1978), for vitamin degradation during cooking (refer to Table 8.12). These losses detailed by Table 8.12 are "average" values used by Paul and Southgate (1978), which vary quite significantly depending on cooking times and the severity of cooking (e.g. when boiling or frying). In all cases, the losses of vitamins B1, B2, B6 and Folic Acid, are very significant (20-40%). In vegetables, the loss of vitamin C is substantial (40-70%).

Allowance, is also made for general wastage of foods in the household. Unfortunately, there is no specific data, concerning the

Table 8.12: Vitamin Losses During Household Cooking

Foodstuff	Cooking Modes	Vitamin	Loss (%)
Cereals and Cereal products	Boiling	B1	40
		B2	40
		Niacin	40
		B6	40
		Total Folic	50
	Baking	B1	25
		B2	15
		Niacin	5
		B6	25
		Total Folic	50
Eggs	Boiling	B1	10
		B2	5
		B6	10
		Total Folic	10
	Frying	B1	20
		B2	20
		B6	20
		Total Folic	35
Meat	Roasting-Frying -Grilling	B1	20
		B2	20
		Niacin	20
		B6	20
	Stewing-Boiling	B1	60
		B2	30
		Niacin	50
		B6	50
	All Modes	Total Folic	30
		B12	20
		C	20
		E	20
Root Vegetables	All Modes	B1	25
		B2	30
		Niacin	30
		C	40
		B6	40
		Total Folic	50
Leafy Vegetables	All Modes	B1	40
		B2	40
		Niacin	40
		C	70
		B6	40
		Total Folic	30

Data Source: Paul and Southgate (1978)

wastage of foods in the New Zealand Household (pers. com. Davidson, 1982). However, there is some data available for other developed nations. Estimates seem to range between about 5-25% of the total food input into the household kitchen, depending on the actual food (refer to Dowler, 1977; Wenlock and Biss, 1977; Wenlock et al., 1980; Osner, 1982). In this study it was assumed that there was a general wastage figure of 5% for all items, although it is recognised that for most perishable items that is probably an underestimate of the actual wastage. Although, some evidence (pers. com. Harding, 1982) suggests that the advent of home freezers in most New Zealand households may have reduced household wastage of foods. Davidson (pers. com., 1982), similarly suggests that the advent of home freezers and sliced bread may have cut down wastage of bread.

8.2.4.3 Nutritional requirements of the New Zealand population

Recommended Dietary Allowances (RDA), were used as the basis for the calculations of the nutritional requirements of the New Zealand Population. These are recommended by the National Academy of Sciences (1980), as the "average daily amounts of nutrients that population groups should consume over a period of time". The RDA's are estimated to exceed the requirements (except metabolic energy) of most individuals of nearly all in the population groups. It should be recognised that the RDA's are based on meeting the nutritional requirements of United States citizens, and not New Zealand citizens.

The total requirement of each nutrient for the N.Z. Population (1976) was calculated knowing the RDA for each nutrient for each population cohort (National Academy of Sciences, 1980), and the total number in each population cohort (N.Z. Department of Statistics, 1976). As no population cohort data were available for 1978-79, these nutrient requirements had to be scaled up for 1978-79, using the increase in population between 1976 and 1979 (Department of Statistics, 1980d). This assumed that the population age-structure was the same in 1976 and 1979.

Table 8.13 details the total requirement for each nutrient. The total requirement for metabolic energy is estimated to be $10.700 \text{ PJ.yr}^{-1}$, which is approximately 15% of the energy requirement for domestic

Table 8.13: Minimum Nutritional Requirements of the New Zealand Population
1978-1979

Nutritional Element	Quantity.Yr ⁻¹	
Metabolic Energy	10.7001	PJ
Protein	52,077.2	Tonnes
Calcium	990.064	Tonnes
Phosphorus	987.157	Tonnes
Magnesium	344.900	Tonnes
Iron	18.3831	Tonnes
Zinc	15.9634	Tonnes
Vitamin A	945.9	kg
Vitamin B1	1,278.1	kg
Vitamin B2	1,521.4	kg
Niacin	16.8955	Tonnes
Vitamin B6	2.1628	Tonnes
Vitamin B12	3.3358	kg
Total Folic	414.0	kg
Vitamin C	64.3991	Tonnes
Vitamin D	8.167	kg
Vitamin E	9.6086	Tonnes

Note: The total requirement for each nutritional element was estimated on basis of the Recommended Dietary Allowances, as recommended by the National Academy of Sciences (1980); and Population data from the New Zealand Census of Population and Dwelling Vol.2, and the New Zealand Yearbook 1980, respectively published by the Department of Statistics (1976, 1980).

food production (expressed in enthalpy terms). In weight terms, a large amount of Protein (52,077.2 tonnes.yr⁻¹) is required; with smaller amounts of calcium (990 tonnes.yr⁻¹), phosphorus (987 tonnes.yr⁻¹) and magnesium (344 tonnes yr⁻¹); and even smaller amounts of iron, zinc, and the vitamins.

It is recognised that an adequate diet requires other nutritional elements, particularly essential amino acids and dietary fibre.

Amino acid patterns of protein in foods can be specified as according to the suggested FAO and WHO (1973) suggested standard, or egg pattern or casein pattern. However, this would almost certainly lead to computational problems, if such patterns were formulated into the problem. In the case of dietary fibre, there are no authoritative published data on recommended levels of intake and therefore minimum levels could not be specified.

The effects resulting from deficient intakes of the above-mentioned nutrients are well known and documented elsewhere (refer to Reports of the F.A.O./W.H.O. Expert Group Reports Nos. 230, 301, 302, 452, 522, 532; and National Academy of Science, 1980).

It should also be noted, that the over supply of a nutrient can lead to a nutritionally inadequate diet - for example, excessive vitamin A and D intake have been associated with kidney stone formation (F.A.O./W.H.O., 1966). Therefore, it may be necessary to place upper limits on the supply of certain nutrients; although this was not attempted due to the lack of such quantitative data and because in the solution to the models no such high levels of intake were incurred.

8.2.5 Matrix Formulation (Refer to Table 8.14)

The primary energy requirement for each of the household storage and preparation modes (C1 to C10), were specified by rows 1 to 16 (data were directly abstracted from Table 8.10). Similarly, the primary energy requirements of the household production of foods (data were directly abstracted from Table 8.11).

The outputs from the household production, were specified in the column (HOME) in the appropriate rows.

Table 8.14: Household Sector Matrix

Columns		Preparation and Storage Models										Household Products										Catering-Hotel Outputs										Constraints																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																										
Rows		C1		C10	HOME	H1B		H413	Z1B		Z409DF																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															

Each processing sector output (Pr) and production sector output (P), required by a household sector product were indicated by a -1 coefficient in the appropriate row.

Similarly, the household preparation and storages inputs required by a household sector product were indicated by a coefficient 1. Most products required more than one such input - for example, fried beef (H1F) requires inputs of C6 (Fried/heated), C9 (Refrigeration) and C10 (Baseload). Linking equations were included so that the sum of rows C1 to C10, equalled a column (variable) of the same name:- for example:

$$\begin{array}{l} \text{C1.} \quad \text{H1B} \dots\dots\dots \text{C1.} \quad \text{H413} = 1. \text{ C1} \quad (8.1) \\ \text{(co-efficient) (variable) (co-eff.) (var.) (co-eff.) (var.)} \end{array}$$

rearranged to be in matrix format:

$$\text{C1.} \quad \text{H1B} \dots\dots\dots \text{C1.} \quad \text{H413} - 1. \text{ C1} = 0 \quad (8.2)$$

The nutritional outputs of the household products (columns 1700 - 3000) are specified by the coefficients in rows 57 - 78. The minimal requirements for each nutritional output are specified by the constraints for rows 57 - 78 (data were directly abstracted from Table 8.13).

For most of the Linear Programming runs, a bound fixed to or less than unity was placed on the variable (column) HOME, as it was assumed that household production could not be greater than this level.

It should be noted that all coefficients of the household products (H1B....H413) and the household preparation and storage modes (C1....C10) were expressed in terms of per 1000 tonnes of the above mentioned variables.

8.3 Catering-Hotel Sector Matrix

8.3.1 Introduction

This section covers the ex-household consumption of food, in commercial establishments; namely in Catering establishments and

Hotels. In this model, all other final consumption of food is considered to be a household function, although it is recognised that not all food is physically consumed in the household. Hotels (coded HOTELS in the model), include; Licensed Hotels and Motels (N.Z.I.S.C. Group 63212) and Licensed Taverns and Chartered Clubs (N.Z.S.I.C. Group 63150). Catering establishments (coded CATERS in the model) include: Takeaway Food Stores (N.Z.S.I.C. Group No. 63110), Tea, Coffee Houses, Cafes, Unlicensed Restaurants (N.Z.S.I.C. Group No. 63120), Caterers (N.Z.S.I.C. Group No. 63130) and Licensed Restaurants and Cabarets (N.Z.S.I.C. Group No. 63140).

8.3.2 Energy Inputs

8.3.2.1 Catering Industry

Data about the direct energy requirements of Catering establishments, were obtained from Patterson and Earle (1982a). This study estimated that the direct energy requirements, for 1980, of the Catering Industry (CATERS) was 640 TJ/yr expressed in consumer energy terms, or 1028 TJ/yr expressed in primary energy terms. The main direct energy requirement was for electricity (95%) with only a small amount (5%) of fuels, mainly natural gas being used. Cooking was found to be the main end-use of direct energy (ranging from 56 - 69% depending on the establishment type), followed by water heating (10 - 24%), refrigeration (11 - 16%), and miscellaneous uses (5 - 22%).

By using multiple linear regression, it was possible to estimate the energy intensity (MJ/kg) of various cooking and food preparation modes (refer to Patterson and Earle, 1982a for further details). For 33 Catering establishments, in the sample survey, there was a total direct energy consumption figure available (MJ/yr), and throughput data for various cooking and food preparation modes (kg/yr). The analytical problem which arose was to allocate or partition the direct energy figure to several modes (termed the "partitioning" problem in EA - refer to section 1.2.1.4). This problem was resolved by using a variant of the multiple linear regression technique first used by Cleland, Earle and Boag (1981), Rao *et al.*, (1981) and Jacobs (1981). That is, the following equation was solved by multiple linear regression:

$$\sum_{i=1}^{i=j} Y = b_1 \sum_{i=1}^{i=j} (X_1)_i + b_2 \sum_{i=1}^{i=j} (X_2)_i \dots + b_n \sum_{i=1}^{i=j} (X_n)_i \quad (8.3)$$

$Y =$ Direct energy consumption of a Catering Establishment per annum (MJ)

$X_1 \dots X_n =$ throughput per annum for the various cooking and food preparation modes (kg)

$b_1 \dots b_n =$ energy intensity (MJ/kg) for the various cooking and food preparation modes

$i =$ various catering establishments.

The energy intensities (MJ/kg) estimated for the various cooking and food preparation modes are outlined by Table 8.15. The most energy efficient cooking mode was found to be deep frying having an energy intensity of 0.69 MJ/kg, which was primarily considered to be due to the more efficient heat transfer to the cooking load, and the more efficient loading of deep frying vats. The other more traditional cooking methods had much higher energy intensities: heating and frying (12.75 MJ/kg), grilling (12.39 MJ/kg), roasting and baking (8.14 MJ/kg), steaming and boiling (7.98 MJ/kg).

The indirect energy requirement of buildings and equipment used by the Catering Industry was estimated to be 103 TJ/yr by Patterson and Earle (1984). Soo, Earle and Patterson (1984) estimated that the gross energy requirements of packaging used by the Catering Industry to be 142 TJ/yr.

The total energy requirements of the Catering Industry were estimated to be 1273 TJ/yr, using mean values for the years 1980 - 1983 (refer to Table 8.16). Direct energy requirements accounted for 81% of the total energy requirements, with indirect energy requirements accounting for only 19%.

Table 8.15: Direct Energy Intensities (MJ/kg) for 33 Catering Establishments in Palmerston North, Estimated by Multiple Linear Regression

Cooking or Food Preparation - Storage Modes	Estimate Using Multiple Linear Regression
Baked/Roasted	8.14
Grilled	12.39
Heated/Fried	12.75
Steamed/Boiled	7.98
Deep Fried	0.69
Hot Water Added ^b	0.66
Pie Warming	2.00
Hot Water for Cleaning	0.30
Refrigeration	1.15

- a. For further details refer to Patterson and Earle (1982a)
 b. Preparation of coffee, tea, dehydrated soups and other dehydrated products by adding hot water or boiling for a short period in water.

Table 8.16: Total Energy Requirements (TJ/yr) of the Catering Industry 1980-1982

	Consumer	Primary						Total
		Coal	Oil	Elec.	Gas	Captl.	Import	
Direct								
Electricity	608	153.8	76.6	698.6	0	55.3	4.9	989
Gas	32	0.3	1.0	0.6	36.8	0.6	0	39
Sub Total	640	154.1	77.6	699.2	36.8	55.9	4.7	1,028
Indirect	N.A.	49.3	74.6	30.6	3.7	2.7	84.4	245
TOTAL		203.4	152.2	729.8	40.5	58.6	89.1	1,273

- a. Totals may not add-up due to roundings.

8.3.2.2 Hotel Industry

Data about the direct energy requirements of hotels were obtained from Lion Breweries (pers. com. I. Wells, 1982). During the years 1980-81 and 1981-82, Lion Breweries undertook a detailed study of energy use in their hotels, as part of an energy conservation campaign. Data from this monitoring procedure, enabled a national estimate of the direct energy consumption of hotels to be made (for further details refer to Patterson and Earle, 1984). It was found that the direct energy consumption for the Hotel Industry, for the years 1980-81 and 1981-82, was 4,278.3 TJ/yr $\pm$ a standard error of 9.2%. The main end-use of energy in Hotels was found by Lion Breweries to be HVAC (40%), followed by Kitchen Equipment (25%), Plant (15%) Liquor Areas (9%), Accommodation (3%), Staff Areas (4%) and Food Customer Areas (2%).

The indirect energy requirements of buildings and equipment, for the Hotel Industry was estimated using data from the Census of Distribution (1978-79), supplied to the author by the Department of Statistics (1980). The expenditure (\$ 1978-79) on Capital by the Hotel Industry, was converted to 1971-72 terms, by using the M.O.W.D. (1981, pers. com.) construction cost index. This figure, was then multiplied by the appropriate energy intensity (MJ/\$) from Carter, Peet and Baines (1982), so as to obtain the total energy requirements of Capital (buildings and equipment) for the Hotel Industry (55 TJ/yr). There is no available data on the amount of packaging used by the Hotel Industry - however, it is considered to be very small, and therefore can be disregarded.

The total energy requirements of the Hotel Industry were estimated to be 4,333 TJ/yr using mean values for the years 1980-1981 and 1981-1982 (refer to Table 8.17). The direct energy requirements accounted for nearly all (98.7%) of this total.

It could be reasonably argued, that including all the energy use of the Hotel Industry in the food system energy use calculation is misleading as the Hotel Industry provides an accommodation and entertainment function and not solely a food function. Although, this is recognised by the author as a reasonable argument, there appears to be no easily applicable method of partitioning energy use to the

Table 8.17: Total Energy Requirements (TJ/yr) of the Hotel Industry,
1980-81 - 1981-82

	Consumer	Primary						
		Coal	Oil	Elec.	Gas	Captl.	Import	Total
Direct								
Electricity	1,589.2	402.1	200.2	1826.0	0	144.6	12.7	2,854
Gas	926.2	9.3	27.8	18.5	1065.1	18.5	0	1,139
Oil	504.2	37.3	512.2	1.0	0	0	4.5	555
Sub Total	3,019.6	448.7	740.2	1846.0	1065.1	163.1	17.3	4,278
Indirect	N.A.	14.1	20.0	5.1	0.5	0.6	14.9	55
TOTAL		463	760	1851	1066	164	32	4,333

a. Totals may not add up due to roundings

various functions. So, therefore, such a partitioning on the basis of hotel function was not attempted here.

8.3.3 Labour Inputs

The direct labour requirements of the Hotel and Catering Industry were obtained from the Census of Distribution (1978-79), for the year 1978-79. There were 10,211 full-time equivalent persons per annum employed by the Catering Industry; and 19,541 full-time equivalent persons per annum employed by the Hotel Industry.

It should be noted that it can also be reasonably argued that the labour inputs, need to be partitioned as not all labour is provided solely for providing food services. However, the same approach for the same reason was adopted here - that is, the labour requirement was not partitioned.

8.3.4 Endogenous Inputs and Outputs

8.3.4.1 Catering Industry

Data on the inputs-outputs of foodstuffs into Catering establishments, were obtained from Patterson and Earle (1982a). These data from a sample survey of 33 establishments in the Palmerston North area, were scaled up so as to obtain a national estimate for the Catering Industry (refer to Table 8.18).

The approximate volumetric level of sales of each alcoholic beverage sold per annum by the Catering Industry was estimated by the following equation:

$$C_A = P_A \times T_A \quad (8.4)$$

where: T_A = matrix, detailing the sales/yr (1978-79), in volumetric terms, of alcoholic beverages on the total domestic market. (Data sources: Census of Manufacturing 1978-79; External Trade Statistics 1978-79.)

P_A = scalar, representing the % of total sales (expressed as a proportion) by the Catering Industry 1978-79, of alcoholic beverages. (Data source: Census of Distribution, 1978-79.)

C_A = matrix, detailing the sales/yr (1978-79), in volumetric terms of

Table 8.18: Foodstuffs Used by 33 Catering Establishments in Palmerston North (kg/week)

	Roasted or Baked	Grilled	Heated or Fried	Steamed or Boiled	Deep Fried	Warmed	Hot Water Added	Uncooked	Totals	Refrigerated
1. Beef	320	468	129	61					979	979
2. Lamb and Mutton	121	74	39						235	235
3. Pork	61	69	26	21					179	179
4. Sausages			166		431				598	598
5. Hamburger Patties			473						473	473
6. Uncooked Meats								156	156	123
7. Other Meats	27	45							72	72
8. Curry & Spring Rolls					176				176	176
9. Chickens	277		16	9	369				673	673
10. Icecream (Milks)								200	200	200
11. Icecream (Other)								468	468	468
12. Vegetables (Frozen)				136					136	136
13. Vegetables (Other)			101	2,650				972	3,723	
14. Potatoes (Chips)					8,983				8,983	
15. Fruit								725	725	
16. Juices & Concentrates								994	994	994
17. Canned Foods			311		52				363	
18. Fish	65		20	66	1,854				2,008	2,008
19. Flour	89		124		768				982	
20. Bread			91					2,554	1,645	
21. Cakes								701	701	
22. Pies and Pastries						1,249		208	1,458	
23. Hamburger Buns			664						664	
24. Biscuits								15	15	
25. Confectionary								118	118	
26. Alcoholic Beverages								10	10	10
27. Soft Drinks								2,398	2,398	2,398
28. Fats and Oils	37		49		1,323				1,410	
29. Jams, Pickles & Sauces								218	218	
30. Sugar								427	427	
31. Dehydrated Soup							1,362		1,362	
32. Other Dehydrated							244	260	504	
33. Vinegar								20	20	
34. Other Foods (nec)				43					43	
35. Milk and Cream								3,024	3,024	3,024
36. Butter								260	260	260
37. Cheese								250	250	250
38. Yoghurt								33	33	33
39. Coffee							8,272		8,272	
40. Tea							4,664		4,664	
41. Eggs	122		251	31					405	
42. Others	498		38	12				351	900	510
TOTALS	1,521	656	2,505	3,032	13,961	1,249	14,543	13,375	50,946	13,809

a. Totals may not add up because of roundings

b. All weights are expressed on a weight basis at the time of purchase by the caterer. If the weight is greater, weights are expressed in terms of the "made-up" weight of a product - e.g. the "made-up" weight of dehydrated soups.

alcoholic beverages in the Catering Industry (Sales = Outputs, Input = Output as there is assumed to be no wastage).

This equation also assumes that the Catering Industry uses the same mix of alcoholic beverages as is sold in the total domestic market. This obviously is not the case, with probably more wine being sold by Catering Establishments, and less spirits and beer. However, since the Catering Industry only uses 3% (in \$ terms) of the alcoholic beverages sold on the domestic market, the use of this approximating assumption, should not critically affect the results of various runs described in Chapter 9.

8.3.4.2 Hotel industry

The approximate quantity of inputs and outputs of foodstuffs into and from the Hotel Industry can be estimated by substituting in the following equation:

$$H_F = P_F \times C_F \quad (8.5)$$

where:

C_F = matrix, detailing the quantity of inputs and outputs from foodstuffs to and from the Catering Industry 1978-79 (Data source: section 7.1.4.1).

P_F = scalar, representing the Hotel Industry sales (\$/yr, 1978-79) of food, expressed as a proportion of the Catering Industry sales of food (\$/yr, 1970-77). (Data source: Census of Distribution 1978-79).

H_F = matrix, detailing the quantity of inputs and outputs of foodstuffs into and from the Hotel Industry 1978-79 (unknowns, determined by the equation).

The equation assumes that the Hotel Industry, uses the same mix of foodstuffs as the Catering Industry.

The volumetric levels of sales of each alcoholic beverage sold per annum by the Hotel Industry was estimated using the following equation:

$$H_A = P_A \times T_A \quad \text{where:} \quad (8.6)$$

T_A = matrix, detailing the sales/yr (1978-79), in volumetric terms, of alcoholic beverages on the total domestic market (Data source: Census of Manufacturing 1978-79, External Trade Statistics, 1970-79).

P_A = scalar, representing the % of total sales (\$) (expressed as a proportion) by the Hotel Industry (1978-79), of alcoholic beverages. (Data source: Census of Distribution, 1970-79.)

H_A = matrix, detailing the sales/yr (1978-79), in volumetric terms of alcoholic beverages in the Hotel Industry (Sales = Outputs, Inputs = Outputs as there is assumed to be no wastage).

This equation also assumes that the Hotel Industry uses the same mix of alcoholic beverages as is sold in the total domestic market. This appears to be a reasonable assumption as data from the Census of Distribution (1978-79), indicates that 71% of the total sales (\$) of alcohol is by the Hotel Industry.

8.3.5 Nutritional outputs

The 21 nutritional elements included in the Household Sector Matrix, were also included in the Catering-Hotel Sector Matrix (refer to section 8.2.4 for a list and definitions of these nutritional elements). Also, as with the Household Sector Matrix, Paul and Southgate (1978) was the main data source for the nutritional composition of foods. The same secondary data sources as for the Household Sector Matrix, were used here (refer to section 8.2.4). Furthermore, the same allowances for wastes and loss of nutrients were also made, as for the Household Sector Matrix.

8.3.6 Matrix formulation (refer to Table 8.19)

The matrix formulation is based on the variables CATERERS (representing the production-consumption activity of the Catering Industry) and HOTELS (representing the production-consumption activity of the Hotel Industry).

The coefficients in rows 1-16, represent the primary energy inputs; in row 80 the direct labour inputs; rows 136-425 endogenous inputs of products from other sectors particularly and almost exclusively from the processing sectors; and rows 516-625 the outputs.

The outputs are prefixed by the character "Z"; followed by the numeric code representing the product - i.e. the same numeric code used in the foregoing matrices; and followed by a set of characters (<2) representing the cooking mode of the product. For example, Z1G, stands for a Cater Hotel Sector product (represented by the character "Z"), which is beef (represented by 1), which is grilled (represented

Table 8.19: Catering - Hotels Sector Matrix

[illegible]

by the character "G").

The outputs from the Catering-Hotel Sector are linked to the nutritional outputs by equations of the following type:

$$Z1B. CATERERS + Z1B. Hotels = 1. Z1B \quad (8.7)$$

(co-eff.)(var.) (co-eff.)(var.)=(co-eff.)(var.)

rearranged to be in the matrix format:

$$Z1B. CATERERS + Z1B. HOTELS - 1.Z1B = 0 \quad (8.8)$$

The variable Z1B, represents the nutritional output of the Catering-Hotel Sectors. For further details of how the nutritional outputs and requirements were dealt with refer to section 8.2.4.

9 PRELIMINARY RESULTS AND DISCUSSION

9.1 Introduction

Numerous 'optimal solutions' can be generated from the Linear Programming model of the New Zealand food system. It is impossible to detail all of these possible solutions. Therefore, four major runs are detailed here, which should be representative of a range of possible results. However, it should be recognised that these runs can be varied and refined by altering the objective functions, constraints and coefficients. This may become necessary as more data, more options come to hand; or as the analyst's perception of the problem changes.

These sets of coefficient matrices, constraints and objective functions, could form the basis of a series of future 'Scenarios' for the future growth and developemnt of the Food System. 'Scenarios' have recently gained some popularity and currency in long term energy planning (e.g. Harris et al., 1977). A 'Scenario' is a possible, but not necessarily probable, future development path which can be implied from a given set of values and conditions (as reflected in this case by a set of objective functions and constraints). It is neither a forecast of, or prescription for a particular development pathway. Scenario based planning, implies an element of choice and exploration; rather than a simple projection of current trends and values which typifies shorter term planning.

9.2 Run 1: Standard Run

9.2.1 Introduction

A Standard Run was undertaken to provide a "baseline" for comparing subsequent runs, and to provide some means of validating the model. The Standard Run was based on the production-consumption and exporting-importing activities of the 1978-79 food system. Most variables (columns) and rows could be fixed at the 1978-79 levels, although data were not available for all rows and columns.

9.2.2 Objective function

As most rows and columns were fixed, it was to a large extent unimportant which variable (Q, Dolnet) was used as the objective function. However, in this case the maximization of Q (row 24) was used as the objective function.

9.2.3 Constraints

All sectors had fixed activities of unity, which meant that their production-consumption activities were set at 1978-79 levels. This included all production, processing, catering, hotels, and home production sectors. All exports and imports were fixed at the 1978-79 levels.

All foods in excess of exports were assumed to be available for household consumption.

The land class inputs were set as free rows, as no data, were available on the actual land class inputs into production activities.

The labour inputs and energy inputs, and the nutritional outputs were also set as free rows. By comparing the values generated by the model for these rows, with actual values provides some basis for validating the model. However, unfortunately as only approximate actual values are available, this validation can only remain approximate. Furthermore, the model assumes structural optimality which may not be the case in reality.

9.2.4 Results

9.2.4.1 Objective Function and Total Energy Requirements (refer to Tables 9.1 & 9.2)

The objective function value for the General Model was 56,235 Q (i.e. hydro-electricity-equivalents. TJ. yr⁻¹), and -14,763 Q for the Distribution-Transport Model; therefore making a sum total of 41,472 Q.

Table 9.1: Primary Energy Requirements of Run1 - General Model

Primary Energy Requirements	Q(TJ)	$\Delta H(TJ)$
Direct		
Coal	5,081	18,989
Oil	12,823	26,363
Gas	1,801	3,527
Electricity	21,228	21,228
Wood	117	622
Imported	236	534
Capital	958	1,804
Sub-Total	42,244	73,067
Indirect		
Coal	902	3,372
Oil	9,210	18,936
Gas	190	373
Electricity	2,444	2,444
Wood	0	0
Imported	5,135	11,630
Capital	1,493	2,810
Sub-Total	19,374	39,565
TOTAL	61,618	112,632

Table 9.2: Primary Energy Requirements Runs 1&3 - Distribution Model

Primary Energy Requirements	Q(TJ)	$\Delta H(TJ)$
Direct		
Coal	286	1,068
Oil	5,712	11,744
Gas	0	0
Electricity	1,029	1,029
Wood	0	0
Imported	48	110
Capital	42	79
Sub-Total	7,117	14,030
Indirect		
Coal	266	994
Oil	5,041	10,364
Gas	39	77
Electricity	1,157	1,157
Wood	0	0
Imported	695	1,573
Capital	448	843
Sub-Total	7,646	15,008
TOTAL	14,763	29,038

This represents the net energy gain by the food system, and could be represented by the following equation:

$$Q_{\text{net energy}} = Q_{\text{gain (General + Transport Model)}} - Q_{\text{lost (General + Transport Model)}}$$

Q_{gain} equals the energy gained from trading food system products (\$), for energy embodied in imported fuel and merchandise (41.04 MJ/\$, weighted mean). Q_{gain} numerically equals 117,853 Q. Q_{lost} equals the energy used by the food system in producing food system products for domestic consumption and export. Q_{lost} numerically equals 76,381 Q.

Details of the primary energy requirements for the General Model and Transport Model, are respectively outlined by Tables 9.1 & 9.2. In total, the primary energy requirement is 76,361 Q.yr⁻¹, of which 61,618 Q.yr⁻¹ is required by the General Model and 14,763 Q.yr⁻¹ is required by the Distribution-Transport Model. This represents a total of 141,670 TJ.yr⁻¹ (H).

Direct energy requirements (Q) account for 64.62% of the total, with indirect energy requirements (Q) accounting for 35.38%. The largest primary energy requirement was for oil (42.92%, Q) followed by hydro-electricity (33.05%), then coal (8.56%), imported goods (8.00%), capital (3.85%), natural gas (2.66%) and wood (0.15%).

It should be noted that, the total primary energy requirement (Q) represents 30.15%, of the total primary energy requirements of the New Zealand economy (refer to Table 9.3).

9.2.4.2 Export Earnings (\$ 1978-79)

The gross export earnings were \$3,170 million, expressed in 1978-79 dollars (f.o.b.). The net export earnings were \$2,871 million, expressed in 1978-79 dollars (f.o.b. - c.i.f.). The net export earnings included the gross earnings minus expenditure on the imports of foodstuffs. By including expenditure for imports of oil and goods required by the food system the net figure is further reduced to \$2,355 million. These import-export (\$) figures, are numerically equal to the 1978-79 earnings, since all imports and exports were fixed to the

Table 9.3: Total Energy Requirements of N.Z. Economy, 1978-79

	$\Delta H(\text{PJ yr}^{-1})$	$Q(\text{PJ yr}^{-1})^a$
Direct		
Coal	75 ^b	20.07
Oil	175 ^b	85.12
Natural Gas	47 ^b	24.00
Electricity	70 ^b	70.00
Wood	20 ^c	3.78
Indirect:	114 ^d	50.33
Total	501	253.30

Data Sources:

- a. Conversion coefficients for converting ΔH to Q , obtained from section.
- b. Departments of Statistics (1980).
- c. Crude estimate based on data from Patterson (1979).
- d. Carter, Peet and Baines (1980, for 1978).

1978-79 level in this run.

9.2.3.4 Direct Labour Requirement

The direct labour requirement was 170,176 man-year equivalents.yr⁻¹

However, it should be noted that as with all other runs, this figure does not include the labour requirements involved in fishing, transport-distribution and in the household because of the lack of data. Furthermore, the indirect labour requirements are also not included because of the total lack of data in this area.

9.2.4.4 Direct Land Requirements

The direct land requirements for the food system was 16,185,300 ha.yr⁻¹. Since the total land area in New Zealand is 26,910,000 ha, the direct land area used by the food system is approximately 60.14% of the total land area. It should be noted that there is considered only to be a very small indirect land requirement, and therefore it is not important to include this in the model. For example, the indirect land requirement includes the land required to grow the wood for fence battens, and the wood required in buildings used in the food system.

9.2.4.5 Product Mixes and Structure of the Food System

The production of the New Zealand food system, is characterised by the large production of beef and sheep meat and wool; and dairy products. Most of this production is exported. Arable farming, pig and poultry farming, and horticultural production mainly supply the domestic market. Overall, 44% of the food production by value is exported (Patterson and Earle, 1984). Most of the final consumption of food takes place in the household (85%), compared with only 15% in ex-household situations (Catering Establishments, Hotels) (Department of Statistics, 1979b).

9.2.4.6 Nutritional outputs

The nutritional outputs, in this run were calculated on the basis, of "food available for local consumption". This is the same basis used in the construction of the New Zealand Food balance sheet (Department

of Statistics, 1979a). All food that is not used for exporting, is assumed to be available for local consumption.

On this basis, there is an adequate supply of all nutritional elements, except Folic Acid and Vitamin D - that is, the RDA was exceeded in all cases except for Folic Acid and Vitamin D. It should also be noted that there was also found to be inadequate intakes of those nutritional elements in all other runs, which suggests that there is actually an inadequate dietary intake of these nutritional elements in the New Zealand diet. This is confirmed by further evidence:

(1) data from Birkbeck's (1977) National Diet Survey, indicates that intakes of Folic Acid, are 45.65% below The R.D.A.

(2) evidence (Harding, 1983, pers. com.) suggests that R.D.A. for Vitamin D is based on American conditions; whereas in New Zealand conditions less Vitamin D dietary intake may be acceptable, due to greater Vitamin D synthesis from the precursor due to greater exposure to sunlight.

9.3 Run 2: Minimisation of Q

9.3.1 Introduction

The aim of this run was to determine the "least energy cost" diet, given the nutritional requirement of the population, land use and other constraints, and minimal imports of foodstuffs. Previous studies (Leach, 1976; Pimentel, 1980), have focused on using energy input: output ratios, or energy input: protein output ratios, as general measures of food production energy efficiency. In doing so, they have not taken account of all the nutritional outputs required to provide a nutritionally adequate diet. Therefore, the aim of Run 2 is to provide some insight into what constitutes an energy efficient diet - that is, what is the least energy (Q) required to provide a diet which meets the minimal dietary requirements for each nutritional element as recommended by the National Academy of Sciences (1980).

It should be noted that such an approach has been attempted, in an unpublished work by Rehkugler (1976), quoted by Fluck and Baird (1980). Although full details of Rehkugler's (1976) work are not available; it appears that the model used very approximate estimates for the energy

requirements (based on data from Hirst, 1973), and probably used enthalpy measurements which do not take account of energy quality. Despite the "preliminary" nature (to quote Rehkugler, 1976) of this work, the findings are relevant and provide a useful basis for comparison with this study:

- (1) Nutrient constraints can be met with minimum energy demand by the consumption of large quantities of relatively few food items.
- (2) If variety of foods in the daily menu and reasonable restrictions on food qualities are introduced as constraints, more foods are introduced into the optimum solution with a resulting higher energy demand and lower energy efficiency.
- (3) As the level of nutrients needed in the diet increased, the energy efficiency decreased and total energy required to supply the diet increased. The higher nutrient quality diet demands more energy inputs into our food systems.
- (4) Cereal products and fresh vegetables are energy efficient foods and to minimise energy demands on our food system should be introduced first into our daily diet. Dairy products and meats are the next most important food items to be introduced into the diet to provide the higher level nutrient demands at a minimised energy cost to our food system.

9.3.2 Objective Function

The objective function for Run 2, was the minimisation of Q (row 24). The energy requirement of importing the same amount of goods and foodstuffs required from overseas, was not included. All energy input values (on row 24) were expressed as positive, rather than as negative values as used in other runs. That is, the objective function was to minimise the energy inputs (Q).

9.3.3 Constraints

9.3.3.1 Nutritional Requirements

For Run 2, the nutritional requirements for Metabolic Energy, Protein, Calcium, Phosphorus, Magnesium, Iron, Zinc, Vitamin A, Vitamin B1, Vitamin B2, Niacin, Vitamin B12, Vitamin C, and Vitamin E were used (refer to Table 8.13). This excluded T Folic, Vitamin B6 and

Vitamin D, which are also included in Table 8.13. These last three nutritional elements were excluded because they led to computational problems - that is, solutions could not be consistently obtained when specifying constraints for these nutritional elements, because "degenerative" sequences easily developed in the iterations -inversion process whereby very large numbers resulted which lead to the storage capacity of the computing system being exceeded.

However, it should be recognised that the use of 14 nutritional constraints, significantly exceeds the number of constraints used in most other food optimisation problems (refer to Anderson, 1975). Furthermore, there is strong evidence to suggest that the current intakes of Vitamin D, Folic Acid and Vitamin B6 are below the R.D.A. Firstly, data from Birkbeck's (1977) National Diet Survey, indicates that the intakes of Folic Acid and Vitamin B6 are respectively 45.65% and 20.56% below the R.D.A. Secondly, it is considered that the Vitamin D dietary intake is probably below the R.D.A., which is based on American conditions (pers. com. Harding, 1983). This is because it is considered that this dietary deficiency, is probably compensated for by greater Vitamin D synthesis in New Zealand, due to the greater exposure of New Zealanders to sunlight. In addition the absolute amounts of these nutritional elements which are required are very small in the case of Vitamin B6 (2.1628 tonnes c.f. 52,077.2 tonnes for Protein), and minute in the case of Vitamin D (8.167 kg) and Folic Acid (414.0 kg). Hence, in absolute terms the quantities of these nutritional elements are not large and therefore could be supplied by "natural" or "artificial" (Vitamin Tablets) means with little more expenditure of energy.

9.3.3.2 Land Constraints

For Run 2, the full set of land area constraints were specified (refer to section 7.2.3). In total, this included 28 constraints, specifying the limited amounts of each class of land available and their location (South Island and North Island). This total amount of land could not exceed 16,185,300 ha, which is equal to the amount of land used in 1978-79 for agricultural and horticultural production.

9.3.3.3 Export-import constraints

No exports were allowed (i.e. export columns were set to zero), and limited imports were allowed. The imports which were allowed included $XI170 \leq 0.0024$ (Food Emulsifiers), $XI207 \leq 5.5383$ Molases), and $XI \leq 130.00$ (Raw Sugar). These limited imports had to be included, so that a feasible solution could be obtained.

9.3.3.4 Other constraints

Fish production was limited to $FISH \leq 1$, limiting fish production to no more than the 1978-79 level of production. Similarly, home production of fruit and vegetables was limited to no more than the current production ($HOME \leq 1$). Land equal to the current land required for Tobacco production, was allocated for that usage. Non-negativity constraints were placed on all variables.

9.3.4 Results

Direct comparison of the results from Run 2 (Minimisation of Q), and Run 1 (Standard Run), are not always valid; because essentially Run 2 is only concerned with the domestic component of the food system, whereas Run 1 is concerned with the entire system including the Import-Export components. It is very difficult because of computational and methodological reasons (primarily the partitioning problem), to allocate land, labour and energy requirements to the domestic component of the food system. However, it should be noted that approximately 44% of the food (sales value (\$) at processing, production sector boundaries) is exported (Patterson and Earle, 1984). Therefore, as a "rule of thumb", approximately 66% of the land, labour and energy inputs can be allocated to the domestic system.

9.3.4.1 Objective function and total energy requirements (refer to Tables 9.4 and 9.5)

The objective function value for the General Model was $12,438 \text{ Q.Yr}^{-1}$ (i.e. hydro-electricity equivalents TJ.yr^{-1}) and $8,496 \text{ Q.Yr}^{-1}$ for the Distribution-Transport Model; therefore making a sum total of 20,934

Table 9.4: Primary Energy Requirements of Run 2 - General Model

Primary Energy Requirement	Q(TJ)	Δ H(TJ)
Direct		
Coal	756	2,826
Oil	3,776	7,763
Gas	122	239
Electricity	2,750	2,750
Wood	22	119
Imported	38	87
Capital	117	220
Sub-Total	7,581	14,004
Indirect		
Coal	196	733
Oil	2,659	5,466
Gas	29	57
Electricity	433	433
Imported	1,247	2,824
Capital	291	548
Sub-Total	4,855	10,061
TOTAL	12,438	24,065

Table 9.5: Primary Energy Requirements of Run 2 - Distribution Model

Primary Energy Requirement	Q(TJ)	H(TJ)
Direct		
Coal	142	531
Oil	2,868	5,896
Electricity	490	490
Imported	24	55
Capital	20	38
Sub-Total	3,544	7,008
Indirect		
Coal	146	544
Oil	3,545	7,288
Gas	23	45
Electricity	654	654
Imported	341	772
Capital	242	456
Sub-Total	4,951	9,759
TOTAL	8,496	16,767

Q.Yr⁻¹. This compares with 76,381 Q.Yr⁻¹ for the Standard Run (Run 1), although Run 1 includes agro-food production for export (44% of the total production by sales value (\$)). Therefore, partitioning energy inputs (Q) on a sales value (\$) basis, the energy inputs (Q) into domestic food production approximately equals 42,800 Q.Yr⁻¹ which can be reduced by just under half for the optimum value i.e. to 20,934 Q.Yr⁻¹. The greatest potential for energy input (Q) reduction, by re-structuring the system, is in the General Model rather than the Distribution-Transport Model. The General Model reduced from 61,618 Q.Yr⁻¹ to 12,438 Q.Yr⁻¹ (by 80%), whereas the Distribution-Transport Model reduced only from 14,763 Q.Yr⁻¹ to 8,496 Q.Yr⁻¹ (by 42%).

Direct energy requirements (Q) account for 53.15% of the total, with indirect energy requirements (Q) accounting for 46.85%. In Run 2 (Min Q), much more reliance is placed on indirect energy requirements (46.85%), compared with only 35.38% in Run 1 (Standard Run). The largest primary energy requirement was for Oil (51.73%), followed by hydro-electricity (25.60%), then imported goods (10.34%), coal (7.66%), capital (3.29%), natural gas (1.22%) and wood (0.18%). The greatest contrast with Run 1 (Standard Run) is the greater use (8.81% more) of Oil in Run 2, and the lesser use (8.25% less) of hydro-electricity. This is because the hydro-electricity usage could be substantially reduced in the production, processing and consumption sectors; but oil usage could not be reduced by as much by reducing transport inputs.

9.3.4.2 Optimal diet

The optimal diet is detailed by Table 9.6. Large quantities of cereals and horticultural products (particularly fresh fruit) form the basis of the optimal diet. There is also a substantial quantity of refined sugar. Cereal consumption in this diet is about 2.5 times the current production, and horticultural products consumption is about twice the current production. Particularly large quantities of most fresh fruits and onions are used, notably with apple consumption being about 6 times the current consumption. There is some production and consumption of dairy products, although at about 1/10 of current production, and some usage of small amounts of meats. There is no consumption of fish products.

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Table 9.6: Optimal Diet Solution for Run 2 - General Model

Q	Objective Function	Quantity		Units
		12,438.33		TJ (n ₁ (m ₂))
H171	Flour		280.71	000 tonnes
H172	Flour - Self Raising	(3.64)	4.97	000 tonnes
H173	Flour - Other	(19.16)	27.43	000 tonnes
H178	Breakfast Cereals - Wheat	(8.61)	0.14	000 tonnes
H179	Bran and Pollard	(9.35)	70.86	000 tonnes
H18F	Edible Offals	(17.48)	8.09	000 tonnes
H204	Sugar-Refined	(41.51)	57.23	000 tonnes
H206	Sugar - Golden Syrup		0.97	000 tonnes
H36	Preserved Hams	(0.86)	0.03	000 tonnes
H39	Meat Paste	(0.24)	0.02	000 tonnes
H140	Meat Tongues - Canned	(0.37)	0.05	000 tonnes
H400	Apples - Fresh	(59.94)	368.72	000 tonnes
H402	Citrus Fruit - Fresh	(29.90)	45.42	000 tonnes
H403	Kiwifruit - Fresh	(7.55)	38.19	000 tonnes
H404	Pears - Fresh	(7.19)	29.26	000 tonnes
H405	Stonefruit - Fresh	(25.45)	69.41	000 tonnes
H408F	Onions - Fried	(69.59)	142.59	000 tonnes
H41	Animal Fat - Pig		1.30	000 tonnes
H412	Grapes - Fresh	(2.01)	75.20	000 tonnes
H42	Edible Tallow	(0.01)	2.39	000 tonnes
H44	Meat Preps - Meat Extracts	(0.02)	0.01	000 tonnes
H66	Milk-Treated	(40.41)	6.14	x10 ⁶ litres
H68	Icecream Mixture	(50.56)	0.11	000 tonnes
H70	Condensed Milk and Cream	(3.24)	0.001	000 tonnes
H71	Evaporated Milk and Cream		0.02	000 tonnes
H72	Butter	(60.12)	31.18	000 tonnes
H73	Wholemilk Powder	(0.02)	6.40	000 tonnes
H74	Spray Skim Milk Powder		23.64	000 tonnes
H75	Roller Skim Milk Powder		0.30	000 tonnes
H76	Buttermilk Spray Milk Powder		2.61	000 tonnes
H77	Buttermilk Roller Milk Powder		0.45	000 tonnes
H78	Milk Powder Products		3.40	000 tonnes
H79	Anhydrous Milk Fat	(0.05)	2.30	000 tonnes
H7G	Pig - Grilled	(34.14)	1.19	000 tonnes
H80	Cheese - Hard	(5.37)	10.79	000 tonnes

The values in parenthesis, are the approximate 1978-79 household consumption of these products. This does not include consumption in catering establishments or hotels. Furthermore, the quantities indicated here, were not necessarily prepared by the cooking modes used in the optimal solution.

This represents a similar but not entirely identical diet, as the optimal diet determined by Rehkugler (1976) for the United States food system. As in Rehkugler's (1976) study cereals predominated the diet, although in this case fresh fruits (rather than fresh vegetables) tended to predominate the diet. Unlike Rehkugler's (1976) study, sugar consumption was an important element of the optimal solution obtained here, providing a cheap source of metabolic energy. Also, unlike Rehkugler's (1976) study, some consumption of dairy, and to a much lesser extent, meat products were required. The small amount of meat products appear necessary for providing almost all the Vitamin B12 requirement in the diet. Finally, like Rehkugler's (1976) study, and like suggestions from other studies, fish products are greatly "energy inefficient" sources of nutritional elements whether it be metabolic energy, protein or other nutritional elements.

The optimal diet could be altered by introducing constraints to restrict the probably unacceptable inputs of some products (particularly flour). This will have the effect of introducing less energy efficient (Q) food products into the diet, and therefore increasing the objective function value.

9.3.4.3 Nutritional outputs

Table 9.7 details the nutritional outputs obtained from Run 2, along with values for the RDA, and actual nutritional outputs calculated from data from Birkbeck (1977). The RDA were exceeded for 14 nutritional outputs with the notable exception being Vitamin D, Folic Acid and Vitamin B6. Furthermore, although there is no RDA for Dietary Fibre an intake of nearly 50g/person per day was obtained, which is considered adequate.

Table 9.8 details the sources of each nutritional output. Cereals formed the basis of the diet being the main source of Dietary Fibre (72.2%) Metabolic Energy (45.2%), Protein (68.3%), Calcium (44.6%), Phosphorus (70.4%), Magnesium (83.3%), Iron (83.6%), Zinc (82.7%), Potassium (40.6%), Vitamin B1 (80.1%), Niacin (91.7%), Vitamin B6 (76.2%) and Folic Acid (78.6%). The main function of Dairy Products was to supply Calcium (42.9%) and vitamins, particularly Vitamin D (95.0%).¹ Fruit and Vegetables also played an important role in

1. This assumes fortified dairy products, as detailed in Paul and Southgate (1978). For New Zealand most Vitamin D is not derived from dietary intake, being produced by photosynthetic means (refer to section 9.2.4.6).

Table 9.7: Nutritional Outputs for Run 2 - General Model

Nutritional Outputs		Values		
		Optimal	Recommended ^a Minimum	Actual ^b
FIBRE	Tonnes	55,492.8	—	—
ENERGY	TJ	10,700.1	10,700.1	12,641.3
PROT	Tonnes	63,651.2	52,077.2	92,086.9
FAT	Tonnes	89,256.3	—	—
CA	Tonnes	1,076.1	990.1	921.5
P	Tonnes	1,789.9	987.2	—
MG	Tonnes	576.2	344.9	—
FE	kg	18,734.8	18,383.1	19,630.0
NA	Tonnes	590.3	—	—
ZN	kg	16,996.1	15,963.4	12,400.0
K	Tonnes	3,004.7	—	—
A	kg	945.9	945.9	—
B1	kg	1,928.6	1,278.1	1,114.3
B2	kg	1,521.4	1,521.4	3,442.0
NIACIN	kg	29,054.4	16,895.5	21,541.3
B6	kg	1,879.5	2,162.8	1,718.1
B12	g	4,541.7	3,358.9	5,118.5
FOLIC	kg	170.5	—	—
TFOLIC	kg	347.7	414.0	—
C	Tonnes	68.9	64.4	99.6
D	g	289.8	8,167.2	—
E	kgs	9,608.6	9,608.6	—

a. From Table 8.13.

b. Approximate Dietary Intake calculated from Birkbeck's (1976) National Diet Survey.

Table 9.8: Sources of Nutritional Output for Run 2 - General Model

Nutritional Output	Major Sources (%)
Dietary Fibre	Cereals (72.2), Fruit and Vegetables (27.8)
Metabolic Energy	Protein (10.1), Fat (30.9), Carbohydrate (59.0)
Protein	Cereals (15.2), Fruit and Vegetable (26.8) Dairy Products (16.2), Refined Sugar Product (8.6). Cereals (68.3), Dairy Products (22.1), Fruit and Vegetables (7.0).
Calcium	Cereals (44.6), Dairy Products (42.9)
Phosphorus	Cereals (70.4)
Magnesium	Cereals (83.3)
Iron	Cereals (83.6)
Zinc	Cereals (82.7)
Potassium	Cereals (40.6), Fruit and Vegetables (40.3), Dairy Products (18.0)
Vitamin A	Edible Offals (60.0), Dairy Products (38.3) Fruit and Vegetables (2.7)
Vitamin B1	Cereals (80.1)
Vitamin B2	Dairy Products (37.5), Cereals (33.9), Meats (15.2) Fruit and Vegetables (13.4).
Niacin	Cereals (91.7)
Vitamin B6	Cereals (76.2)
Vitamin B12	Meats - Edible Offal (75.2), Dairy Products (24.8)
Folic Acid	Cereals (78.6), Fruit and Vegetables (14.2)
Vitamin C	Fruits and Vegetables (96.3)
Vitamin D (note a)	Dairy Products (95.0)
Vitamin E	Fruit and Vegetables (77.6), Cereals (13.9), Dairy Products (8.5).

- a. For fortified dairy products from Paul and Southgate (1978)
In New Zealand most vitamin D is obtained from photosynthetic sources,
not dietary sources (refer to section 9.2.4.6).

supplying vitamins particularly Vitamin C (96.3%) and Vitamin E (77.6%). A relatively small amount of Meats (9.38 tonnes) mainly being Edible Offals (8.09 tonnes), supplied most of Vitamin A (60.0%) and the Vitamin B12 (75.2%) requirements.

The major change in the diet from the existing diet is the change, from meat to cereals as the main protein and metabolic energy source. The main sources of protein in the current diet are animal protein (45.2 - 50.2%, depending on age-sex cohort, Birkbeck, 1977), dairy products (17.8 - 21.0%) and vegetable protein (31.6 - 35.2%). Cereals only accounted for between 1.4 and 3.2% in the same survey. Whereas, in Run 2 the use of cereals as a protein source increased to 68.3%; the use of meats as a protein source virtually disappeared; the use of dairy products as a protein source increased slightly, and the use of fruit and vegetables as a protein source decreased. The main source of Metabolic Energy in the current diet is Fat (41.1 - 43.3%, depending on age-sex cohort; Birkbeck, 1977), followed by Carbohydrate (38.4 - 39.7%), Protein (13.5 - 14.3%) and Ethanol (1.8 - 6.4%). Whereas, in Run 2 Carbohydrates (59.0%) primarily derived from cereals and to lesser extent refined sugar, provides the main source of metabolic energy; rather than fat derived from meat. The use of protein, fats and ethanol all reduce as metabolic energy sources in Run 2, with ethanol usage dropping to zero.

9.3.4.4 Exports-Imports

One of the main aims of Run 2 was to reduce, the direct imports of foodstuffs, and completely restrict exports. However, some imports of foodstuffs are necessary, as New Zealand does not produce some essential foodstuffs (XI170, Food Emulsifiers; XI207, Molasses; XI6, Raw Sugar). The optimum solution required the importation of 79,987 tonnes of Raw Sugar, 2.4 tonnes of Food Emulsifiers and 5,538 tonnes of Molasses. The cost of these imports of foodstuffs was \$1978-79 18.72 million (C.I.F.). No energy requirement (Q) was associated with the importing of these products, so therefore they are considered in Run 2 to be essentially "free" inputs. However, even if an energy requirement (Q), say of 41.04 TJ/\$10⁶ were used, this is not expected to significantly affect the results as this only amounts to 768 TJ. Another approach, could be to set up a notional sugar beet industry, to

locally produce sugar - this would involve detailed costing and estimation procedures beyond the scope of this study.

Although there is restricted imports of food in Run 2, imports of oil, materials and capital equipment are required. The cost of the oil is \$1978-79 37.62 million (C.I.F.) and the cost of materials and capital equipment are \$1978-79 40.10 million (C.I.F.).

9.3.4.5 Direct Labour Requirements

The direct labour requirement was 47,505 man-year equivalents, yr^{-1} . This is only 26.7% of the labour requirements of Run 1 (Standard Run).

9.3.4.6 Direct Land Requirements

The direct land requirement for Run 2 was 1,386,600 $\text{ha} \cdot \text{yr}^{-1}$, which is only 8.57% of the total land in food production in 1978-79 (refer to Table 9.9 for details). All of this direct land requirement is for high grade, productive Class I and Class II land - in fact nearly all of the Class I land and all of the Class II land is required. By using some more land (about an estimated 16,000 ha using data from Harris et al., 1979), to provide a local supply of sugar from sugar beet, it would be possible to produce enough food to supply the New Zealand population, on about 9% of the total land used for food production in 1978-79 (or about 5% of the New Zealand total land area). This would require all Class II land and some Class III land, and leave large areas of lower class productive land for other productive purposes.

9.3.4.7 Structure of the Food System

Table 9.10, details the sector activities for the food system for Run 2 (an activity of 1 = the sectors 1978-79 production). The cropping sectors activity increases by 2.48 times, and the horticultural sector's activity increases by 2.05 times. Factory supply dairy farms are at only 0.14 times the 1978-79 production which is about the level of Town supply dairy farms for 1978-79. There is a very small amount of sheep and beef farming (South Island Intensive Fattening). The processing sectors are substantially reduced with no processing of fruit and vegetables, some production from Co-operative

Table 9.9: Direct Land Requirements for Run 2 - General Model

Land Class	Area (000 ha)	
	Optimal	Available
I (Both Islands)	177.3	186.3
II (Both Islands)	1,209.3	1,209.3
II (South Island)	77.6	411.2
IIIE (South Island) ^a	2.0	92.5
All Class (Both Islands)	1,386.6	16,105.3

a. For Tobacco Farming.

Table 9.10: Food System Structure for Run 2 - General Model

Sector	Sub Sector	Activity ^a
CROP		2.48
	CROP2	2.48
FDFARM		0.14
	FDFAR1	0.01
	FDFAR2	0.13
HORT		2.05
	HORT1	2.05
SIFAT		0.11
	SIFAT2	0.11
CDAIRY		0.14
FWORKS		0.13
GRAIN		1.37
SUGAR		0.40

a. The activity = 1, for the sectors 1978-79 production.

Dairy Companies (0.14) and some production from Freezing Works (0.13). However, grain milling production is increased (1.37), and sugar refining is at 0.40 times the 1978-79 level.

There is no fish production, and very little meat production, indicating that such production is energy inefficient (or inoptimal), when all nutritional outputs are taken into consideration. This confirms previous findings from studies which have only singularly considered the energy efficiency of providing energy, protein or weight outputs (Leach, 1976; Pimentel and Pimentel, 1979).

It should also be noted that there is no Home Production of fruit and vegetables, no ex-household consumption (Catering Establishments, Hotels), and very little cooking of foods.

9.4 Run 3: Maximisation of Q (Net Energy Yield)

9.4.1 Introduction and Background

Like Run 2, Run 3 is based on the Net Energy Concept. Run 2, aimed to minimise net energy loss from the system, taking account of only domestic food demand. Run 3, introduces the dynamics of international trade, which implies a whole series of choices and trade-offs between using food for domestic consumption or for external trade. The criteria (or objective function) being used here, is that of overall net energy gain. Energy is necessarily lost to the system when it is required to be used to produce food for domestic consumption; but it is gained in the trading process - usually in much larger amounts. Only small amounts of energy are required for producing foods for exports, but in return these foods can be exchanged for oil and energy intensive goods, therefore allowing the system to gain net energy. Net energy gain from trade or from internal primary energy sources) provides the basis for physical growth of the New Zealand economy. Hence, the importance of net energy gain from trading foods, and the rationale for using net energy gain as the objective function for Run 3.

9.4.2 Objective Function

The objective function for Run 3, was the maximisation of net energy gain, by the food system, given by the following equation:

$Q_{\text{net energy}} = Q_{\text{gain}}(\text{General+Transport Model}) - Q_{\text{lost}}(\text{General+Transport Model})$

Q_{gain} equals the energy gained in the trading of food system products (\$), for energy embodied in imported fuels and merchandise (41.04 MJ/\$, weighted mean). Q_{gain} is therefore, directly proportional to the variable DOLNET (net value of agro-food products exported). Q_{lost} equals the energy used by the food system in producing food system products for domestic consumption and export.

9.4.3 Constraints

9.4.3.1 Domestic Food Consumption Constraints

For Run 3, the household consumption rows were fixed at the 1978-79 consumption levels. The columns for the Catering Industry (CATERS) and the Hotel Industry (HOTELS), were set at the 1978-79 activities. By setting the domestic food consumption at 1978-79 levels, optimal solutions were relatively easily obtained (1166 iterations & 420.35 CPU seconds for the General Model; 389 iterations & 237.82 CPU seconds for the Transport Model). Whereas, by using nutritional constraints to determine domestic food demand, the problem was much more difficult to solve (up to 6,000 iterations for the General Model), and degenerative sequences frequently developed in such runs.

9.4.3.2 Land Constraints

For Run 3, the full set of land area constraints were specified (refer to section 6.2.3). In total, this included 28 constraints, specifying the limited amounts of each class of land available and their location (South Island and North Island). The total amount of land could not exceed 16,185,300 ha, which is equal to the amount of land currently used for agricultural and horticultural production.

9.4.3.3 Export-Import Constraints

There are obvious constraints on the market levels for almost all agro-food products, determined by a mix of political-economic factors. It is very difficult to fix exact limits on the market levels, essentially because of their indeterminate and variable nature. In view of this difficulty, the approach here was to set the market levels at twice the existing limits, and then to vary these constraints so as to test the impact of restricting markets on the other variables in the model. However, it should be recognised that market levels at twice the existing level are "optimistic", particularly for dairy and meat products.

It was found to be necessary to place some constraints on the export-import levels because:

(1) where the import value (\$) of a product was less than the export value (\$), the problem became unbounded, as products could be imported then exported indefinitely, so increasing the objective function. In Run 3, such products which had import values (\$) less than the export values (\$), were not allowed to be exported.

(2) the problem became essentially unsolvable, as "degenerative" computational sequences readily developed, if no export-import constraints were imposed on the problem.

9.4.3.4 Other Constraints

Fish production was limited to $FISH \leq 1$, limiting fish production to no more than the 1978-79 level of production. Similarly, home production of fruit and vegetables was limited to no more than the 1978-79 level of production ($HOME \leq 1$). Land equal to the current land required for Tobacco production, was allocated for that usage. Non-negativity constraints were placed on all variables.

9.4.4 Results

9.4.4.1 Objective Function and Total Energy Requirements

The objective function value for the General Model was 129,000 Q (i.e. hydro-electricity equivalents. TJyr⁻¹) and -14,763 Q for the

Distribution-Transport Model; therefore making a sum total of 114,237 Q. That is, the net energy gain of the food system was 114,237 Q for Run 3, compared with 41,472 Q for Run 1 (Standard Run). This high net energy gain, was gained by nearly doubling net export receipts from the Standard Run, with only a relatively small increase in the energy requirements of the food system (100,566 Q c.f. 76,381 Q) (refer to the next section , for further details concerning the net export receipts).

Details of the primary energy requirements for the General Model and the Distribution Model are respectively outlined by Tables 9.11 & 9.2. In total, the primary energy requirement is 100,566 Q, of which 85,303 Q is required by the General Model and 14,763 Q is required by the Distribution-Transport Model. This is equivalent to 75.8% of the primary energy requirement of the 1978-79 New Zealand economy, which represents a very large increase in the energy requirements of the agro-food sector. However, this is more than offset, by the even larger amounts of net energy gained by large increases in export receipts.

Direct energy requirements (Q) account for 59.87% of the total, with indirect energy requirements (Q) accounting for 40.13%. The largest primary energy requirement was for Oil (44.98%, Q) followed by hydro-electricity (29.75%), Imported Goods (9.94%), Coal (8.96%), Capital (3.89%), Natural Gas (2.35%) and Wood 0.12%).

9.4.4.2 Export Earnings (\$1978-79) Refer to Table 9.12)

The gross export earnings (DOLLAR) were \$5,432 million, expressed in 1978-79 dollars (f.o.b.). The net export earnings (DOLNET) were \$5,234 million, expressed in 1978-79 dollars (f.o.b. - c.i.f.). The net export earnings (DOLNET) included the gross earnings (DOLLAR) minus expenditure on imports of foodstuffs. By including expenditure for imports of oil and goods required by the food system the net figure is further reduced to \$4470 million, expressed in 1978-79 dollars. This final net figure is 1.9 times the 1978-79 export earnings expressed in 1978-79 constant dollar terms.

Table 9.11: Primary Energy Requirements of Run 3 - General Model

Primary Energy Requirements	Q(TJ)	H(TJ)
Direct		
Coal	7,172	26,803
Oil	17,993	36,993
Gas	2,070	4,054
Electricity	24,358	24,358
Wood	125	662
Imported	279	631
Capital	1,095	2,061
Sub-Total	53,092	95,562
Indirect		
Coal	1,283	4,796
Oil	16,488	33,898
Gas	258	505
Electricity	3,379	3,379
Imported	8,974	20,326
Capital	2,329	4,384
Sub-Total	32,711	67,288
TOTAL	85,803	162,850

9.4.4.3 Direct Labour Requirements

The direct labour requirement was 270,803 man-years equivalents.yr⁻¹. This is 1.6 times the labour requirements for Run 1 (Standard Run).

9.4.4.4 Direct Land Requirement

The direct land requirement for Run 3 was 16,185,300 ha.yr⁻¹, which is the maximum allowable - that is equal to the 1978-79 area in food production.

Table 9.13 outlines the land use patterns for Run 3. Class I land is mainly used for horticulture (121,760 ha), with smaller areas being used for beef and sheep farming (34,000 ha), pig farming (19,000 ha), dairy farming (9,540 ha) and tobacco farming (2,000 ha). Class II land is mainly used for dairy farming (888,270 ha), with lesser areas being used for beef and sheep farming (488,800 ha) and cropping (154,710 ha). Class III land is used for dairy farming (1,695,200 ha) and sheep and beef farming (733,000 ha). Nearly all Class IV, V, VI and VII land is used for beef and sheep farming, except for a very small amount of Class IV land used for poultry farming (8,000 ha).

9.4.4.5 Structure of the Food System

For Run 3, the main structural feature of the food system was the increased production of the Dairy, Beef/Sheep and Horticultural sectors, so to maximise export earnings and hence net energy gain. This was achieved for greater usage of the higher classes of land, by utilizing currently idle land and by utilizing land currently used for cropping. Cropping production decreased due to imports of wheat at 2.18 times the current imports (i.e. 87,268 tonnes c.f. 31,758 tonnes for 1978-79).

Production from both Co-operative Dairy Companies (CDAIRY) increased and Freezing Works (FWORKS), and production from the horticultural sector (HORT) increased by 1.48 times. This enabled exports far in excess of current exports from these sectors (refer to Table 9.12) Excepting wheat the imports of all foodstuffs remained at approximately the 1978-79 levels.

Table 9.12: Exports for Run 3 - General Model

Product		Quantity (Tonnes)	
		Optimal	1978-79 Exports
X1	Beef	395,885	213,000
X2	Veal	18,700	9,350
X3	Mutton	161,368	92,900
X4	Lamb	526,833	315,450
XP 6	Wool	482,992	262,771
XP 10	Barley	24,491	12,245
XP 18	Apples	167,720	83,860
XP 21	Kiwifruit	18,737	9,886
X 301	Fish - Frozen	20,274	20,274
X 72	Butter	301,406	166,559
X 73	Wholemilk Powder	83,436	55,593
X 74	Spray Skim Milk Powder	239,852	119,926
X 76	Buttermilk - Spray	20,542	10,271
X 78	Milk Powder Products	18,360	9,180
X 79	Anhydrous Milk fat	36,480	26,159
X 80	Cheese - Hand	110,409	63,366
X 82	Casein - Acid	70,408	45,246
X 83	Casein - Rennet	12,881	7,126
X 84	Caseinates	23,556	14,980

Table 9.13: Direct Land Requirements of Run 3 - General Model

Land Class	Production Sector	Area (000 ha)
I	HORT	121.76
	SIFAT	34.00
	PIG	19.00
	FDFAR	9.54
	TOBAC	2.00
II	SIFAT	488.80
	FDFAR	399.47
	TDFAR	166.32
	CROP	154.71
III	FDFAR	1,695.60
	SIFAT	733.00
IV	SIFAT	1,418.60
	XIFAT	1,274.99
	POULT	9.00
V	SIFAT	111.60
	XIFAT	86.50
VI	XHILL	3,979.80
	SHILL	2,734.00
VII	XHHILL	2,747.80

The increased production of the horticultural sector had to compensate, for no home production of horticultural products. This is due to the energy inefficiency of home production of such products referred to in section 8.2.

Fish production reached its upper limit, despite the apparent energy in-efficiency of this sector revealed in Run 2.

All of the processing sectors which essentially supply the domestic market, remained at about the 1978-79 levels of production.

9.4.4.6 Household Sector

Two conflicting factors should be taken into consideration when selecting the optimal method of cooking. Firstly, cooking methods such as baking, roasting and grilling are less energy efficient (MJ/kg), compared with cooking methods such as steaming, boiling, frying-heating and deep frying (refer to Table 8.10). However, secondly baking and roasting are less destructive of vitamins, than boiling and frying cooking methods (refer to Table 8.12). The results from Run 3, indicate that the first factor (energy efficiency) outweighed the second factor (vitamin conservation); because the more energy efficient but more vitamin destructive methods of cooking (boiling and frying) were selected as being optimal (refer to Table 9.14).

Only very small amounts of the cooked foods were baked (1,000 tonnes), roasted (3,500 tonnes) or steamed (400 tonnes). Most cooked food was boiled (669,700 tonnes), fried-heated (467,900 tonnes) or deep fried (143,000 tonnes). A significant proportion of the foods remained uncooked (659,000 tonnes), with the "non-cooking" obviously being preferred where possible as it is the most energy efficient mode as well as being the less vitamin destructive.

9.4.4.7 Nutritional Outputs

The same set of nutritional outputs were obtained as for Run 1 (Standard Run), as the same data were used for determining the household demand for foods. There was an adequate supply of all nutritional elements, except for Folic Acid and Vitamin D. The reasons

Table 9.14: Household Cooking, Food Preparation and Storage Modes
for Run 3 - General Model

Mode		Activity ($\times 10^6$ tonnes)
C1	Baking	0.001
C2	Roasting	0.035
C3	Grilling	-
C4	Steaming	0.0004
C5	Boiling	0.6997
C6	Fry-Heating	0.4679
C7	Deep Frying	0.1430
C8	Toasting	-
C9	Refrigeration	1.444
C10	Baseload	2.006

why there was an inadequate supply of these nutritional elements are fully discussed in section 9.2.4.6 (Run 1).

9.5 Run 4: Maximisation of Net Export Earnings

9.5.1 Introduction

Run 4 is analogous to Run 3, as it aims to maximise net export earnings (\$), this time enumerated in terms of economic returns (1978-79 constant dollar terms), instead of energetic returns. The purpose of this run is to provide a contrast between using economic and energetic criteria. It is argued elsewhere in this study, that energy is a better measure of absolute scarcity than monetary measurements, and therefore is a more appropriate numeraire to use particularly in long term analyses (refer to section 6.1.4 and later in Chapter 10).

9.5.2 Objective Function

The objective function for Run 4, was to maximise net export earnings (DOLNET - row 25). DOLNET, represented the gross export earnings, minus the value of imported foodstuffs, oil and merchandise required by the food system. All values were expressed in terms of 1978-79 constant dollars.

9.5.3 Constraints

9.5.3.1 Nutritional Requirements

For Run 4, the nutritional requirements for Metabolic Energy, Protein, Calcium, Phosphorus, Magnesium, Zinc, Vitamin A, Vitamin B1, Vitamin B2, Niacin, B12, Folic Acid, Vitamin C and Vitamin E were used (refer to Table 8.13). This excluded Vitamin B6, Vitamin D and Iron.

The inclusion of these last 3 nutritional requirements, lead to computational problems, the same as those referred to in Run 2 (Minimisation of Q). Furthermore, as with Run 1, 2 & 3, solutions could not be found when including the Vitamins B6 and D (refer to section 9.3.2.1 for a fuller discussion of these problems).

9.5.3.2 Land Constraints

For Run 4, the full set of land area constraints were specified (refer to section 7.2.3). In total, this included 28 constraints, specifying the limited amounts of land available and their location (South Island and North Island). This total amount of land could not exceed 16,185,300 ha which is equal to the amount of land used in 1978-79 for agricultural and horticultural production.

9.5.3.3 Export-Import Constraints

As with Run 3, exports were allowed up to twice existing levels; and imports could be at any level (refer to section 9.3.2.3 for a fuller discussion of the reasons for setting such constraints).

9.5.3.4 Other Constraints

Fish production was limited to $FISH \leq 1$, limiting fish production to no more than 1978-79 levels of production. Similarly, home production of fruit and vegetables was limited to no more than the 1978-79 levels of production ($HOME \leq 1$). Land equal to the current land required for Tobacco production, was allocated for that usage. Non-negativity constraints were placed on all variables.

9.5.4 Results

9.5.4.1 Objective Function and Export Earnings

The gross export earnings (DOLLAR) were \$5,885 million, expressed in 1978-79 constant dollar terms (f.o.b.). This figure is reduced to \$5,142 million (DOLNET) when the cost of oil imports (\$230 million), food imports (\$41 million) and merchandise imports (\$472 million) are deducted.

This compares with the gross export earnings of \$2871 million for 1978-79, and net export earnings of \$2,355 for 1978-79 (refer to Run 1). This high level of export earnings, is primarily achieved by increased exports of dairy and sheep/beef products (refer to Table 9.15). There is also increased exports of Apples and Kiwifruit. The

Table 9.15: Exports for Run 4 - General Model

Product		Quantity (Tonnes)	
		Optimal	1978-79 Exports
X1	Beef	426,000	218,000
X2	Veal	18,700	9,350
X3	Mutton	185,800	92,900
X4	Lamb	630,900	315,450
XP6	Wool	487,498	262,771
X116	Veges-Frozen-Other	5,173	4,485
X117	Fruit-Frozen-Berry	2,869	2,785
X125	Corn-Canned	2,540	1,580
X128	Veges-Other-Canned	3,423	1,711
X301	Fish-Frozen	26,115	20,274
X52	Canned-Beef	3,262	1,631
X72	Butter	333,118	165,559
X73	Wholemilk Powder	90,609	55,593
X74	Spray Skim Milk Powder	239,853	119,926
X76	Buttermilk-Spray Powder	20,542	10,271
X78	Milk Powder Products	18,360	9,180
X79	Anhydrous Milk fat	52,317	26,159
X80	Cheese-Hand	126,732	63,366
X82	Casein-Acid	72,145	45,246
X83	Casein-Rennet	13,208	7,126
X84	Caseinates	24,145	14,780
X89	Apple Juice	$2,193 \times 10^6$	1.097×10^6
X95	Frozen Veges-Mixed	5,492	2,746
XP10	Barley	24,491	12,245
XP11	Maize	20,471	58,037
XP12	Field Peas	4,365	5,059
XP18	Apples	167,720	83,850
XP21	Kiwifruit	19,763	9,882
XP22	Pears	3,167	1,584
XP32	Honey	4,957	2,479
XP35	Eggs	31,447	?
XP9	Oats	9,468	48.6

net export earnings are further increased by reduced (c.f. 1978-79) imports of foodstuffs, particularly raw sugar (30,453 tonnes c.f. 202,742 tonnes). Although there is a marked increase in the imports of Bran and Pollard from virtually nil in 1978-79 to 23,375 tonnes.

9.5.4.2 Total Energy Requirements and Net Energy Yield

The net energy yield for the General Model was 133,724 Q (i.e. hydro-electricity equivalents. TJ yr⁻¹), and -7057 Q for the Distribution-Transport Model; therefore making a sum total of 126,667 Q. This is an even higher net energy gain than that obtained in Run 3 (114,237 Q). This is because, the domestic consumption was determined by the nutritional requirements outlined by Table 8.13, rather than the 1978-79 patterns of consumption of foodstuffs.

Details of the primary energy requirements for the General Model and Distribution Model, are respectively outlined by Tables 9.16 & 9.17. In total, the primary energy requirement is 78,251.9 Q, of which 71,195.2 Q is required by the General Model, and 7056.7 Q is required by the Distribution-Transport Model. This represents a total of 155,889.8 TJ.yr⁻¹(H).

Direct energy requirements (Q) account for 64.41% of the total, with indirect energy requirements (Q) accounting for 35.59%. The largest primary energy requirement was for Oil (48.07%, Q) followed by Hydro-electricity (24.92%), Imported goods (11.25%), Coal (10.06%), Capital (4.01%) and finally Natural Gas (1.60%).

9.5.4.3 Direct Labour Requirements

The direct labour requirement was 274,360 man-year equivalents.yr⁻¹. This compares with 170,176 man-year equivalents for 1978-79 (Run 1).

9.5.4.4 Direct Land Requirements

The direct land requirement for Run 4 was 16,185,300 ha.yr⁻¹, which is equal to the land in food production in 1978-79.

Table 9.1⁸ outlines the land use patterns for Run 4. Class I land

Table 9.16: Primary Energy Requirements of Run 4 - General Model

Primary Energy Requirements	Q(TJ)	$\Delta H(TJ)$
Direct		
Coal	6,601.0	24,667.5
Oil	16,797.8	34,535.0
Gas	1,061.0	2,078.0
Electricity	15,914.3	15,914.3
Wood	67.8	358.9
Imported	238.3	539.7
Capital	718.4	1,352.1
Sub-Total	47,398.6	79,445.5
Indirect		
Coal	1,091.9	4,080.5
Oil	15,624.3	32,122.3
Gas	182.1	356.6
Electricity	2,833.3	2,833.3
Imported	1,844.9	18,886.4
Capital	2,220.1	1,178.7
Sub-Total	23,796.6	62,457.8
TOTAL	71,195.2	141,913.3

Table 9.17: Primary Energy Requirements of Run 4 - Transport Model

Primary Energy Requirements	Q(TJ)	$\Delta H(TJ)$
Direct		
Coal	119.8	447.5
Oil	2,437.8	5,073.7
Gas	0	0
Electricity	376.8	376.8
Wood	0	0
Imported	20.8	47.1
Capital	15.5	29.1
Sub-Total	3,000.7	5,974.2
Indirect		
Coal	105.1	392.7
Oil	2,965.1	6,096.1
Gas	16.2	31.7
Electricity	502.9	502.9
Imported	262.9	595.4
Capital	203.8	383.5
Sub-Total	4,056.0	8,002.3
TOTAL	7,056.7	13,976.5

is mainly used for dairy farming (155,300 ha) with a small amount being used for sheep and beef farming (36,000 ha). Class II land is used for dairy farming (606,900 ha), sheep and beef farming (488,800 ha) and horticulture (100,100 ha). Class III land is used for dairy farming (1,517,100 ha) and sheep and beef farming (911,100 ha). Nearly all Class IV, V, VI and VII land is used for sheep and beef farming, except for a very small amount of Class IV land used for poultry farming (5,000 ha).

9.5.4.5 Structure of the Food System

The structure of the system is based upon the production of large amounts of dairy and beef/sheep products for export, and a domestic consumption of horticultural and dairy products.

Factory supply dairy farming (FDFARM), increased by 1.84 times, compared with 1978-79. The production by beef and sheep farming is similarly increased (refer to Table 9.18). There is no cropping sector (CROP), although there is significant production of arable crops as part of beef and sheep farming activity. Horticultural production is increased by 1.22 times over the 1978-79 level. Fish production remains at the 1978-79 level, with nearly all fish production being exported.

The processing sector is quite different to the 1978-79 structure. Production from Abbatoirs (ABATO) is at zero, with little or no meat in the diet, and production from most sectors having a large input of sugar (BISCIT, BREW, CAKEF, CAKEK, COCOA, FOONEC, CREAMF, DRINKS, PIES, SPIRIT, WINE and MALT) were also reduced to zero or near zero levels. The poultry processing sector's (POULT) production is virtually zero, due to most poultry products being exported. Production from other sectors is quite variable, compared with 1978-79 levels, being generally below 1978-79 levels, excepting for the dairy processing sectors (DAIRY, DAIRYF), oil processing (OILS) and the meat processing sectors (FWORKS, PACKER).

There was no home production of fruit and vegetables, and no ex-household consumption (i.e. no final consumption in catering establishments and hotels).

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Table 9.18: Direct Land Requirements for Run 4 - General Model

Land Class	Production Sector	Area (000 ha)
I	FDFARM	150.3
	SIFAT	36.0
II	FDFARM	606.9
	SIFAT	488.8
	HORT	100.1
III	FDFARM	1,517.1
	SIFAT	911.1
	TOBAC	2.0
IV	SIFAT	1,418.6
	XIFAT	1,278.2
	POULT	5.0
V	SIFAT	111.6
	XIFAT	86.5
VI	XHILL	3,978.8
	SHILL	2,734.0
VII	XHHILL	2,747.8

Table 9.19: Nutritional Outputs for Run 4 - General Model

Nutritional Outputs	Values		
	Optimal	Recommended ^a Minimum	Actual ^b
FIBRE	48,060.1		
ENERGY	10,700.1	10,700.1	12,641.3
PROT	75,145.6	52,077.2	92,086.9
FAT	155,916.4	-	-
CA	1,800.7	990.1	9,215.0
P	1,936.2	987.2	-
MG	2,274.8	344.9	-
FE	13,957.9	18,383.1	19,630.0
NA	3,339.5	-	-
ZN	15,963.4	15,963.4	12,400.0
K	3,606.1	-	-
A	1,959.0	945.9	-
B1	4,710.8	1,278.1	1,114.3
B2	2,688.0	1,521.4	3,442.0
NIACIN	17,016.5	16,895.5	21,541.3
B6	1,589.7	2,162.8	1,718.1
B12	5,139.2	3,358.9	5,118.5
FOLIC	150.1	-	-
TFOLIC	414.0	414.0	-
C	64.4	64.4	99.6
D	2,655.9	8,167.2	-
E	9,608.6	9,608.6	-

a. From Table 8.13

b. Approximate Dietary Intake Calculated from Birkbeck's (1977) National Diet Survey.

9.5.4.6 Nutritional Outputs

Table 9.19 details the nutritional outputs obtained from Run 4, along with values for the RDA, and actual nutritional outputs calculated from data from Birkbeck (1977). The RDA's were exceeded for 14 nutritional outputs with the notable exception being Iron, Vitamin B6 and Vitamin D. Furthermore, although there is no RDA for Dietary Fibre an intake of 43g/person/day was obtained, which is considered to be satisfactory.

These nutritional outputs were supplied almost entirely from processed dairy and horticultural products, with very small amounts of fish and beef (refer to Table 9.19).

9.6 Discussion

9.6.1 Review of the Main Empirical Results and Implications

Similar dietary patterns emerged in all Runs, and in variants of these Runs not reported upon in Chapter 9. The pattern was one of large consumption of cereal products, for supplying primarily dietary fibre, metabolic energy, protein, trace elements and some vitamins (B1, Niacin, B6 and Folic Acid). These cereals were supplemented with comparatively large amounts of mainly fresh fruit and vegetables for primarily vitamin C and E supply. Dairy products were required in significant amounts primarily for vitamin A, B2 and D supply. A very small amount of meat (mainly edible offals) were required for vitamin A and B12 supply. Essentially, the same pattern emerged, with a few variations, irrespective of whether net energy gains or net dollar returns to the economy was used as the numeraire. Therefore, both in terms of energetics and economics, the 'optimal' use of energy, results in the above described diet. These results, therefore, confirm the findings of Rehkugler's (1976) preliminary study and other less rigorous studies (e.g. Green, 1978), that meat and fish are "inefficient" sources of food, from an energy-nutrition viewpoint. Only consumer preference, can justify the inclusion of such products in the diet.

Nevertheless, meat, fish and some dairy production, is justified

in terms of achieving trading goals. As previously discussed the export of such products provides net energy gains to the New Zealand economy, thus providing an important primary energy source for physical growth of the economy. Or expressed in terms of conventional economic wisdom, provides for net dollar returns to the New Zealand economy, therefore providing for what many economists (McLean, 1978) consider to be the cornerstone for any growth in the New Zealand economy.

Therefore, under "optimal" conditions meat, fish and to a lesser extent dairy products, have little or no part in providing food in the New Zealand diet. The only function, for such food production under "optimal" conditions, is as a trading commodity. That is, a trading commodity to exchange for imports of oil and energy intensive goods. This leads to another policy option which needs to be explored - is it preferable in terms of "economic" and "energetic" optimality to grow crops (forestry or arable) on lower class land for conversion to primary energy sources and leave the higher class land for the more "optimal" use of growing crops for food consumption)? In essence, lower class land is indirectly being used as a primary energy source (via the trading process), so therefore using such land indirectly for an energy source does not differ in function from the present use.

Also, it should be noted, that with increasing oil costs, the amount of net energy that can be gained from export foods from low class land production, is declining. So, prospectively if not now, this option of growing crops could provide a more efficient primary energy source, than pastoral farming on this land (Baines and Peet, 1982 found this to be the case when comparing ethanol production for primary energy with pastoral production which could be traded for primary energy).

The finding that meat and dairy products are not "optimal" sources of food, could have some implications in terms of the viability of such products for export. Resource constraints (particularly energy constraints) could force consumers in other countries to reduce inputs of such foods from their diets, as the cost of these foods consequently increase. Therefore, in the long run, the market for such commodities may well decrease. These are essentially "luxury" goods in terms of nutritional economy, and therefore they probably have a high elasticity

of demand, meaning that their demand will probably decrease in direct accordance with price increases.

In re-iteration, the findings of these preliminary Runs do indicate, what represents "optimal" patterns of food production in the New Zealand food system. A literal interpretation of the results leads to the conclusion that meat and dairy products should be exported to maximum levels, so to maximise net energy yield. However, this interpretation could be misleading, as it is based on short term demand patterns for these products. It seems likely if meat and dairy products are "inoptimal" sources of food for New Zealanders (both in energetic and economic sense); that they are also likely to be "inoptimal" sources of food for overseas markets. Therefore, in the long run it does seem likely as energy and physical resource constraints become more apparent, and costs consequently rise, that the overseas markets for these products will decrease. Consequently, it is recommended that further studies critically review the long-term effects of sustaining meat and wool production on lower class land. In the future, it may be preferable to grow crops for primary energy production on lower class land, or adapt farming regimes for growing crops on lower class land instead of meat production (e.g. by terracing). This would obviously involve a complete "rethink" of current agricultural practices undertaken on lower class land.

Finally, these preliminary results indicates that the diets determined in these Runs, very much conform with those advocated by dieticians and nutritionists (e.g. Shorland, 1980). That is, those diets which are "energetically" and "economically" optimal, are also those advocated for health reasons. This again adds weight to the argument that such diet with high cereal, fruit and vegetable intakes, may well in the long term replace diets based on products which New Zealand has traditionally exported. Similarly, cooking of foods (where non-cooking is possible) and the processing of fruit and vegetables were not "optimal" in most Runs. This is also in accordance with the recommendation of many dieticians and nutritionists. Such options are merely economic and energetic "luxuries".

9.6.2 Efficiency and Optimality

As discussed in sections 6.1.3.1 and 6.1.3.2, the most efficient option is not necessarily (in fact hardly ever) the most optimal. Most food energy studies have focused, on net energy ratios (metabolic energy out/energy in), which are simply measures of efficiency. Although it is argued in section 6.1.3.2, that such ratios are of little value in resolving energy-food use problems they are tabulated (Table 9.20) for comparative reasons. As can be ascertained from Table 9.20 the efficiency (metabolic energy out (ΔH)/energy in (Q)), ranges between 37.7 - 51.1% depending on the Run. It should be noted that the reciprocal of this efficiency is equivalent to the quality coefficients ($Q/\Delta H$) investigated in Part A. This means, that the energy embodied in food supply is a comparatively high quality energy output, having coefficients ranging between 2.65 $Q/\Delta H$ and 1.96 $Q/\Delta H$ depending on the Run.

It is difficult to compare the above efficiencies ($\Delta H/Q$) with efficiencies ($\Delta H/\Delta H$), because the latter set of efficiencies used in the literature are in ΔH terms for the denominator. As is extensively discussed in Part A, this is considered to be an incorrect way of "adding up" energy values, as no account is taken of the different energy qualities of the different energy sources.

9.6.3 Limitations and Problems

9.6.3.1 Practical Computational Problems

Models with coefficient matrices of the size used in this study are not easy to solve. Practical limits to the memory storage available on the Prime computer meant that some models could not be solved. Other models could not be solved due to degenerative sequences developing in the iteration process, which meant that large numbers were generated. Another initial practical problem encountered by using the Sciconic package was that matrices of more than 200 columns could not be solved because of a programming "bug" in the software package. In addition to these practical computational problems, large matrices were found to have much longer solution times. Larger models required more CPU seconds to be solved; and hence the monetary cost of processing

Table 9.20: Energy Ratios for Various Runs of the New Zealand Food System Model

Runs	Energy Ratio for ^a Domestic Food Supply	Energy Ratio for Energy ^a Gain from Export
Run 1	0.3771	1.54
Run 2	0.5111	Not applicable
Run 3	0.3771	2.1359
Run 4	Can it be calculated	2.6187

- a. Metabolic Energy Out (ΔH)/Energy In for Producing Food for Domestic Consumption (Q) partitioning on value(\$) basis.
- b. Energy gained from Exports (Q)/Energy In for Producing Agro-Food Products for Exports and Domestic Consumption (Q).
- c. Q = hydro-electric equivalents ($n_1(m_2)$), ΔH = enthalpy change

was more. Furthermore, it was generally less easy to undertake interactive changes to the model.

Therefore, because of these practical computation problems, the model was sequentially solved using two sub-models (refer to section 6.3.6). As discussed in section 6.3.6.5 the sum of these separately determined optima should approximately equal the global optimum. More efficient (in terms of CPU seconds) solutions were obtained by using this method.

However, it is recommended that in the future development of this model that greater emphasis be placed on overcoming these practical computational problems. It is important that these computational problems be overcome, so that the use of the model becomes more "user friendly", and hence more useful as a policy formation tool.

9.6.3.2 Fixed Proportionality Assumption

This is one of the few assumptions, but nevertheless one of the more restrictive assumptions, used in this model. As discussed in section 6.3.1.2., this assumption is not totally unrealistic, as the nature of many production and processing activities do require that:

- (1) certain outputs (e.g. meat and wool from farms, meat and meat by-products such as hides) be in direct proportion to each other.
- (2) certain inputs be in direct proportion to each other, because of formulation requirements.

However, it is conceivable that in some instances, for example, only one product from a processing sector is required to fulfill a nutritional requirement; but the model formulation requires that if this is to be produced so must all the other products from that processing sector be produced in direct proportion to the 1978-79 production. It may be in fact possible, to produce this product, independently of other production from that sector, but this is not allowable because of the way the model is formulated. Despite, all this, this problem is rarely considered to be important because usually processing sectors produce products of similar nutritional composition, and therefore they can usually all 'contribute' to fulfilling the nutritional requirement.

Nevertheless, if this fixed proportionality assumption is considered to be too restrictive, it is recommended that sectors be further disaggregated into groups of similar products. The advantage of doing this, has to be weighed up against the large amounts of time required to calculate the inputs required for all these disaggregated groups of products.

9.6.3.3. Changes of Physical Coefficients Over Time, With Improved Technology

The coefficients for this model, are based on 1978-79 technological standards. The effect of improved technology over time, on the energy efficiency of a process is discussed in section 3.8.2. Essentially, technology improves towards an asymptote representing the minimum theoretical energy requirement for that process (assuming that labour and other physical inputs remain constant). A similar process operates with labour and land requirements for a process. That is, over time with improved management-technological standards, the land and energy efficiency of a process improves towards an asymptote representing the minimum possible land and labour requirement (assuming that other resource inputs remain constant).

Therefore, with higher standards of efficiency and productivity, the coefficients for any sector do decrease, and this possibility is not allowed for in a coefficient matrix based on 1978-79 technological standards. Another possibility that is not allowed for is the possibility of different mixes of land, labour and energy being required by a particular sector. In Economics, this is represented by Isoquant Curves, which shows the combination of two inputs required to produce a given quantity of output. A schematic representation of Energy-Labour isoquant curves is given by Fig 9.1. In essence, only one point on one of these curves represents the coefficients used in time static models. Therefore, an improvement to this model would be to include an equation to represent the isoquant curve(s), or at least an approximation of these curves. This would be theoretically possible, although the collection of data required to obtain this equation, would require much more research. Consequently, this problem of only representing one point on the isoquant curve, will for all

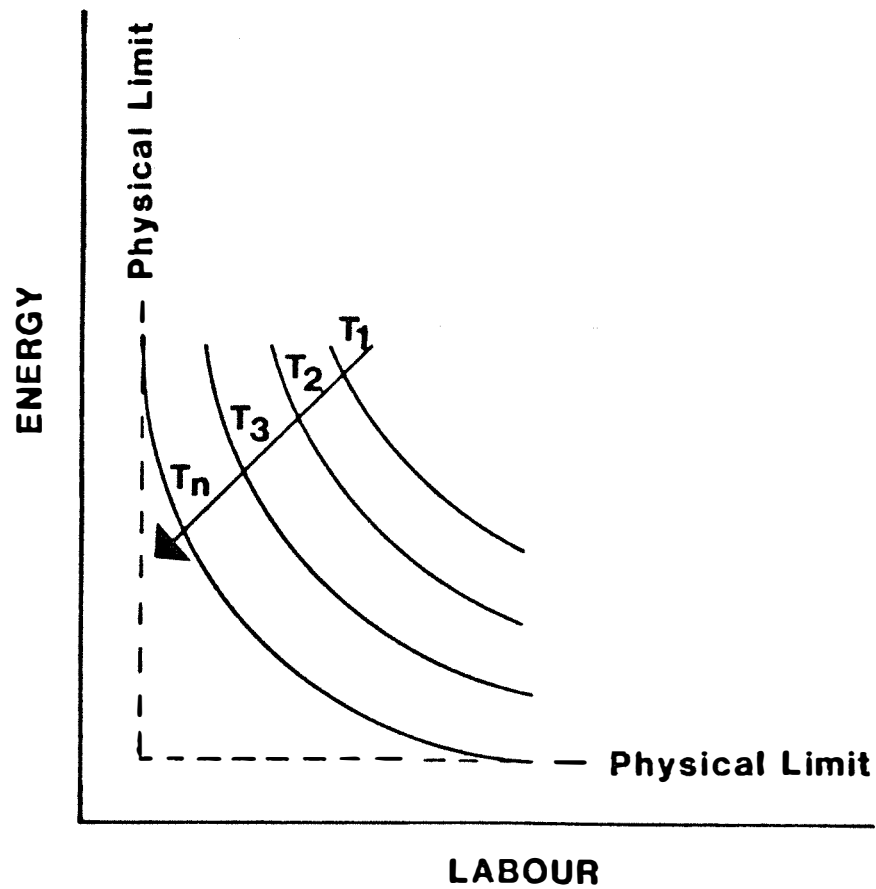


Figure 9.1: Schematic isoquant curves for energy-labour inputs with improved technology-management, where T_1 , T_2 , T_3 represent time periods approaching T_n .

intents and purposes usually remain, because of the potential limitations of collecting data.

For long term analyses, as discussed in section 3.9, it is also preferable that coefficients that represent long-term levels of technology should be used (that is, points on the curve tn). In the case of energy, that is not so difficult, as a lower thermodynamic limit can be calculated (assuming land, labour and other inputs remain constant). However, in the case of land and labour the analytical problem becomes more difficult, especially when it is considered that levels of land and labour efficiency are dependent on levels of energy inputs and efficiency.

Therefore, in reiteration, the assumption of certain coefficients which represent only one level of efficiency and only one mix of inputs; represents a quite restrictive assumption on the use of a coefficient matrix, which is not easily overcome.

9.6.3.4. Changes in Economic Coefficients and Constraints Over Time

One of the advantages of using physical coefficients and constraints, is that they do not fluctuate as widely as economic coefficients and constraints. In the long run, as discussed above, all physical coefficients (energy, land, labour) tend towards a minimum requirement. Physical constraints such as land area and nutritional constraints, for all intents and purpose remain constant. Therefore, despite the analytical problem encountered in using physical coefficients and constraints, they provide a more constant framework for analysis.

Oppositely, economic coefficients and constraints are very variable, especially when examining problems with long time horizons. For example, market levels change, the oil price increased tenfold within a year, and prices and cost of foodstuffs change with the vagaries of the market place. Consequently, much uncertainty is introduced in analyses which use economic variables. Hence, the approach in this study was to construct a model which only used economic variables when absolutely necessary. In this way, it was not

difficult to formulate a model of most of the food system, in physical terms. The only major exception was the import-export sector, which was inextricably related to economic variables such as market prices/costs and market levels. However, not unexpectedly the use of economic variables in the import-export sector, introduced the most uncertainty into the analysis.

9.6.3.5 Conclusion

In summary, the modelling process encountered practical computational problems, was restricted to some extent by the fixed proportionality assumption, but its major set of problems were associated with the uncertainty associated with coefficients and constraints. This uncertainty can be reduced by using physical variables where possible, instead of economic variables which have much more uncertainty associated with them, particularly over longer time horizons. Sensitivity analysis (refer to section 6.3.7) can be of some value in overcoming uncertainty problems, especially when the likely degree of uncertainty is known. The degree of uncertainty is more likely to be definable and known for physical variables, rather than economic variables. Hence, the obvious utility of using physical variables where possible.

9.6.4 Extensions and Improvements of Coefficient Matrices

As discussed in section 9.3.4, the coefficients could be updated, to take account of improvements in technology/management, of the time horizon of the study. This is much easier (but still difficult) when the model is formulated in physical terms.

The indirect coefficients for labour and land, have not been included in the existing coefficient matrices; and labour coefficients have not been included for all sectors.

As discussed in section 9.3, other production-processing sectors, could be included so as to represent possible future production-processing options. For example, sugar beet production, with processing to sugar could be introduced. Or the various biomass options for primary energy production could be introduced.

Finally, it is recommended that sensitivity analysis and parametric programming be undertaken, so as to test the effect of changes in coefficients and constraints (refer to sections 6.3.2.5 and 6.3.7).

9.6.5 Uses of the Linear Programming Model of the New Zealand Food System

9.6.5.1 Long Term Planning Model

The intended use of this model was as a long term planning model. Hence, the model was formulated using physical variables rather than economic variables, as physical variables do not vary significantly over time, and in the long run tend towards physical limits. Most long term models (e.g. the "Limits to Growth Model", Meadows et al., 1972) are simulation models rather than optimisation models.

Linear programming models particularly when used for short term planning purposes, are considered to be prescriptive models - that is, they determine a "blueprint" for restructuring a system given a set of variables, constraints, restrictions and objective criteria (Sharpe and Roy, 1980). While this approach may be correct, for short term planning and scheduling, it is considered to be incorrect for long term planning when many of the policy objectives, and to a lesser extent the coefficients and constraints are not clearly defined or have a high degree of uncertainty associated with them. Therefore, this LP model of the New Zealand food system, has not got a prescriptive function, but rather it should have an instructive function - that is to provide insight and information about the nature of the system to the policy formulator.

Optimisation models, have the advantage over conventionally used simulation models, in that they can sharply focus on the direct implications of optimising certain policy objectives (or combinations of policy objectives). Simulation models, extrapolate on current trends or relationships, most often on sub-optimal paths, therefore losing resolution which is available for optimisation models. Furthermore, it should be noted that this model is not considered to be predictive, at least not in any direct sense. However, indirectly some Runs are

considered to be indicative of future trends. For example, those Runs which use net energy as the objective function, should lead to results which may indicate future food system structures. This is because in the long run, due to depletion of high grade energy resources structures which use less net energy or gain more net energy will become favourable. This indicative use of optimisation models has been used by others in relation to agro-food systems (e.g. Chen and Wensink, 1977; Penn and Irwin, 1977). Penn and Irwin (1977), "simulated" energy restriction on the United States food and fibre system, using I-O optimisation models. Such an approach seems to lie somewhere between the classical optimisation and simulation approaches, embodying elements of both.

Finally, in the context of long term planning, the coefficient matrix can provide some basis for projective models. For example, horticulture output could be say doubled in anticipation of this growth say in the next decade, and the effects of this change can be tested by the model (assuming say economic optimality, which would not be an unreasonable assumption given current planning wisdom). Such an approach could be useful in long term energy planning, where projective scenarios have gained some popularity in recent years (e.g. Harris et al., 1977). However, for such projective scenarios Goal Programming or Multiple Objective LP could be more useful, so objectives other than economic ones could be considered (both these approaches are extensions of conventional LP - refer to Lee, 1972 for further information on Goal Programming).

9.6.5.2 Other Uses and Short Term Planning

Other uses (mainly of an unintended nature) of the model include:

(1) Short Term Economic Planning I-O Linear Programming models are widely used in economic planning (refer to Philpott, 1975). This model can be used for these purposes giving relatively detailed information of product flows, export-import patterns, land-use patterns, labour and energy requirements etc., in the agro-food sector. Previous LP models (Philpott, 1975) of the NZ Economy have been more broad brushed, not giving this degree of detail for the agro-food sector. Conventional economic objectives, such as the maximisation of Output (\$) would probably be used if the model was to be used for economic planning

purposes. However, as mentioned above because of the variability in economic variables over time, it is not advisable to prescriptively use this model, except for very short time horizons.

(2) Short Term Energy Planning The coefficients matrix could be used for short-term demand projections, of agro-food sectors - this would not involve the use of LP.

(3) Agricultural and Food Policy Formulation Although the model was originally formulated for investigating the energetic nature of the food system, the model could be used to more specifically investigate land-food-agricultural policies. Again, these models would tend to reflect economic criteria, rather than explicitly energetic criteria.

9.6.6 Final Evaluation of the Linear Programming Model of the NZ Food System

The objective for Part B was achieved, in that a logical construct was established for investigating the optimal use of energy resources in food systems. This is a marked improvement on previous methods of analysis which relied on simple energy efficiency ratios (usually metabolic energy output or protein output, per primary energy input). Other physical constraints such as land area and quality limitations could also be incorporated into the model; therefore, establishing a broader physical model to examine the optimal use of physical resources in food systems. Energy however, is the primary physical resource which "drives" all activity in the food system. Moreover, energy unlike material resources, is absolutely depletable due to the Second Law of Thermodynamics. Therefore, energy is the correct numeraire to use in evaluating optimality in any such physical system.

In this specific application of this optimisation methodology to the New Zealand food system, problems were encountered which included: practical computational problems, problems in physical coefficients changing over time, and the more critical problem of economic coefficients changing more dramatically and less predictably over time. The methodology can only remain to be indicative and a short term prescriptive technique, unless these "time" related problems are resolved.

10 FINAL REVIEW AND DISCUSSION

10.1 Mathematical and Linear Modelling in Energy Analysis

10.1.1 Nature of Mathematical Models

'Models' or 'Constructs' are an integral part of everyday life. Human beings interact with others and the environment, according to systems of perceptions of reality, or conceptual models. These models can be represented by combinations of words, pictures, physical bodies or any number of symbolic entities. A mathematical model is simply such a representation which uses mathematical symbols and notations.

One of the strengths of mathematical models, is that many variables can be represented in a simultaneous manner. Conceptual models can only successfully deal with a few variables. The human mind cannot understand the dynamics of many variables interacting in a simultaneous manner. Another advantage of mathematical models, is that they are 'impartial' and depend on mathematical logic; rather than intuition or subjective assessment. As Forrester (1973) points out, the intuitive answer or assessment is not always the correct one - that is, large scale systems often act in a 'counterintuitive' manner.

Nevertheless, despite the apparent advantages of mathematical modelling, there are some very serious limitations and pitfalls in their use. Firstly, it should be noted that not all problems, can be correctly assessed or resolved in terms of the mathematical logic of models. Many macro-level problems are what Cartwright (1973) terms as "metaproblems" - that is, many of the variables cannot be quantified, and the exact nature and number of variables are not known with any known precision. Often mathematical modelling techniques are incorrectly applied to metaproblems. This is particularly so in Economic models where only part of the total problem complex is addressed, while maintaining that the entire problem complex is being addressed. Also, mathematical modelling tends to lead to a rigid, dogmatic method of analysis where the analyst totally believes in the mathematical model, to the extent that further research is not seen as necessary as the "problem has been solved" - Kaplan (1964) terms this

phenomenon as a 'premature closure' of ideas.

In conclusion, mathematical models are useful for understanding complex systems consisting of many variables - that is, they are instructive tools. However, they can also be incorrectly applied to metaproblems, and lead to a false sense of scientific rigor.

10.1.2 Linear Modelling in Energy Analysis

The use of mathematical modelling in Energy Analysis, is limited mainly to the use of simulation models (Odum and Odum, 1979), and Input-Output models (Wright, 1974). The use of classical linear Models (Regression and Linear Programming), has been virtually non-existent (refer to section 1.2.2). The purpose of this thesis was to explore the use of Linear Modelling techniques for application in Energy Analysis.

Linear models are the most simple form of mathematical models, being restricted by the Linear Assumption. Clearly, very few - if any, real world systems are totally linear. This is particularly true of natural systems, such as 'natural' food production systems (Ehrlich et al., 1973). Nevertheless, Linear Models are comparatively easy to apply and understand. Firstly, it is easier to represent a system by a series of linear equations, than by a system of second order non-linear equations. Secondly, it is easy to understand the mathematics of linear systems and to compute answers. Computer programming packages of most applications of Linear Modelling are readily available. However, despite all of these apparent advantages of Linear Models, the disadvantages are serious. Linear models are very much simplifications, and can easily evolve into simplistic mental blocks. Most Linear Models - even more so than other models, must be critically evaluated before the results of the modelling process are accepted or used.

Nevertheless, Linear Models do offer a 'higher level' of analysis than can be gained from 'conceptual' models, despite the above stated limitations of mathematical and linear modelling. It was suspected that many of the methodological problems in Energy Analysis existed because previous methods of analysis had been confined to the conceptual level. Macro-level systems cannot readily be understood on

this level. Therefore, as Energy Analysis, by definition, focuses on the macro-level, mathematical modelling should be suited for application in Energy Analysis. Linear Modelling provided an easy access point for the beginning of this exploration.

10.1.3 Review of Linear Modelling Application in this Study

A general equation was derived for explaining the concept of energy quality of sources and uses, on a quantitative basis. The validity of the general equation could be tested by using essentially conventional linear regression analysis techniques. The approach was instructive as it required a conceptual as well as a quantitative assessment, with both modes of analysis benefiting from the other. The Linear Assumption, in this case, was not considered to be restrictive, and a non-linear approach would not add further to improving the analysis. Regression analysis was also proposed as a method for resolving the partitioning (in some cases) and the boundary problems associated with Energy Analysis. In these cases, the Linear Assumption probably will subtract from the value of the analysis, with non-linear regression analysis in most cases being the correct approach.

Linear Optimisation (Linear Programming) was used to address the question of 'energy efficiency' in Food Systems. Previous studies had only focused on simple energy efficiency ratios, which were of limited value. For example, the energy required per unit of metabolic energy output, or protein output was commonly used. It was not surprising that the use of these simple ratios received widespread criticism (Edwards, 1976; Fluck and Baird, 1980). By using a 'systems approach' the question of 'energy efficiency' could be more comprehensively analysed. The main value of this approach was to provide a methodology for examining the optimal or efficient use of energy resources in systems (particularly food systems), and to provide specific information on what constitutes the optimal use of energy resources in the New Zealand food system. Such information could not be gained from simple ratios or from conceptual level analysis, which has previously dominated this field of study. Therefore in conclusion, despite the author's cautionary notes (in sections 10.1.1 and 10.1.2), Linear Modelling has been found to have some useful applications in Energy Analysis. However particularly in the Linear Programming

application, the use of non-linear equations could in some cases lead to more correct results.

10.1.4 Future Applications of Mathematical and Linear Modelling in Energy Analysis

Modelling, is obviously an important tool for understanding the nature of large scale systems. Therefore, there is a place for mathematical modelling in Energy Analysis, as Energy Analysis is about the energetics of large scale systems. However, mathematical modelling should not fall into the 'traps' of economic modelling, and of economic modellers. Mathematical models of large scale problems can only be descriptive or instructive, and rarely if ever predictive or prescriptive. The complexities of macro-level systems make reliable prediction unlikely and usually very inexact, particularly over longer time horizons. Prescription (as often presupposed by economic modellers) is no more than a tautological statement of a set of values and notions about the future.

It is difficult to identify areas for future applications of mathematical modelling in Energy Analysis. Potentially, with added caution, there are many Economic Modelling techniques which may well find a place in Energy Analysis - e.g. time-series analysis. The applications in this study have been 'time static', and there could be a requirement for more simulation models (Linear or Non-Linear). However, modellers should be cautioned against literal interpretation of such models - it is dangerous to assume that such models are predictive.

The scale of future models, is a point that should be addressed. There is a case, particularly if models are to be used for instruction or description, rather than prescription or prediction; that the models remain of a small scale. Extra data, as in the case of Part B of this thesis, can lead to an overlarge model which provides much data, but little user interaction. If the models were to be used for prescriptive purposes there is the case for more detail; so that a detailed 'prescriptive' plan can be derived.

Specifically, in terms of improving and extending the models,

detailed in this study, it is suggested that the:

(1) Linear Regression Model be extended to cover more input and output classes; and that theoretical rather than empirical data be used.

This could lead to an approach based on theoretical thermodynamics.

(2) Linear Programming Model be extended to cover other sectors in the Economy which compete with the resources used by the food system.

Particularly, the forestry sector which competes with the food system for land use. There is also much room for improving the data used for some sectors in this model. The model could also be simplified so as to improve user accessibility.

10.2 Further Developments of Energy Analysis

10.2.1 Resolution of Methodological Problems

There have been many methodological problems which have been identified in the literature - the most commonly cited being the boundary problem, the valuation problem and the partitioning problem (refer to section 1.2.1.4 for a full discussion). It has been argued that regression analysis potentially provides a means of resolving, at least elements of these three main methodological problems facing Energy Analysis (refer to section 5.4 for full details). Most importantly, a means of resolving the energy quality problem was presented in Part A, although it has recognised limitations and assumptions. There is little doubt that non-linear modelling will probably lead to a further understanding of these problems, than the linear approach attempted in this thesis.

Many of the methodological problems associated with Energy Analysis, are held in common with Economics:

(1) The problem of inter-temporal allocation of resources. How does one derive a logical basis for allocating 'stock' resources between different generations, as for all intents and purposes, these 'stock' resources can only be used once.

(2) The problem of externalities. Should some 'cost' factor be incorporated in energy coefficients, to allow for the polluting effects of some processes?

(3) The partitioning (cost allocation) problem. Various 'solutions' to this problem have been proposed both in Economics and Energy Analysis,

but none have gained universal acceptance.

There are a further set of methodological problems in Energy Analysis, which result from the use of energy coefficients (MJ/kg). Often it is falsely assumed that these coefficients are constant and therefore provide a stable basis for evaluating systems. However, these coefficients depend on a number of factors and assumptions. A logical means of dealing with these factors needs to be established - a discussion leading to tentative suggestions for further research is detailed in section 10.2.2.

10.2.2 Resolution of Methodological Problems Associated with Energy Coefficients

10.2.2.1 Assumptions Underpinning Energy Coefficients

The following set of assumptions underpin the derivation of any energy coefficient:

- (1) Technological Assumption As is indicated by Figs 3.8 - 3.10, the energy coefficients (MJ/kg), tend towards a thermodynamic minimum with improvements in technology and management, assuming all other things remain equal.
- (2) Labour Assumption All energy coefficients (MJ/kg), assume a certain level of labour input. The Labour-Energy trade-off is outlined by Fig 9.1.
- (3) Land Assumption (Particularly in the case of Food Production) All energy coefficients (MJ/kg) assume a certain level of land input. The effect of using less land can be compensated for by using more labour or energy, which is often the case in labour and energy intensive systems when land area and quality availability is very limited.
- (4) Grade of Ores of Materials and Energy Inputs As the best ores are exploited, mineral ores or 'energy' ores (oil shales) are exploited, with greater inputs of energy and other resources. At a particular point in time, it becomes more efficient to recycle material resources, rather than exploit virgin ores. So, in the long run the energy and labour requirements of producing a material approaches this point where recycling becomes most efficient. This point does not exist for energy resources, as energy resources cannot be recycled.
- (5) Rate of Production Each energy coefficient (MJ/kg), assumes a

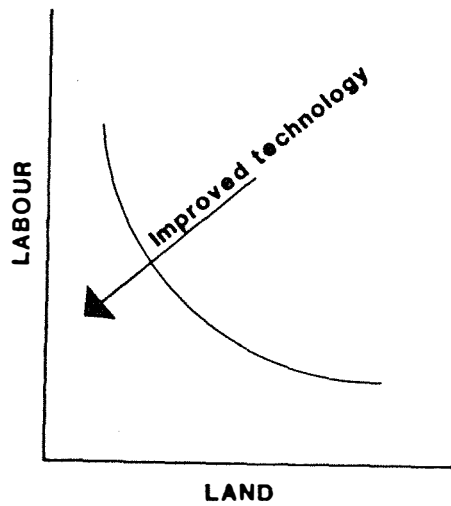


Figure 10.1: Schematic isoquant for the labour-land trade-off

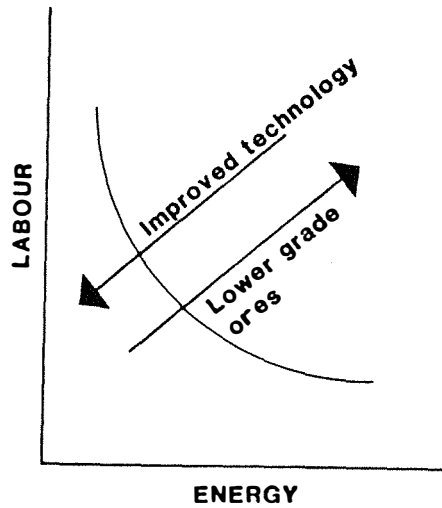


Figure 10.2: Schematic isoquant for the labour-energy trade-off

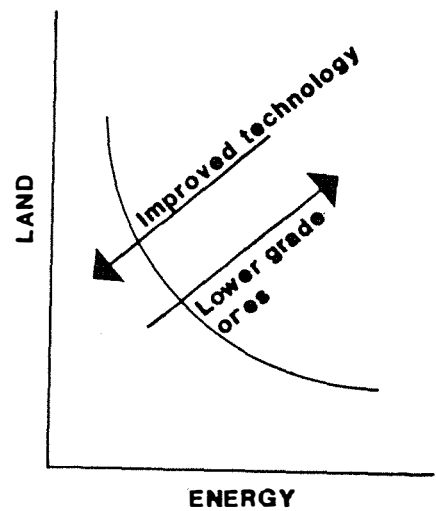


Figure 10.3: Schematic isoquant for the land-energy trade-off

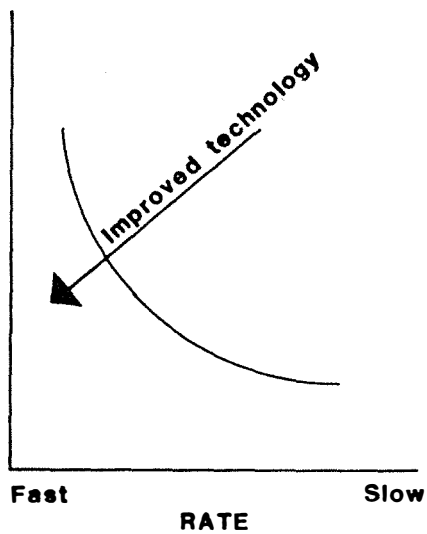


Figure 10.4: Schematic isoquant for the labour-time trade-off

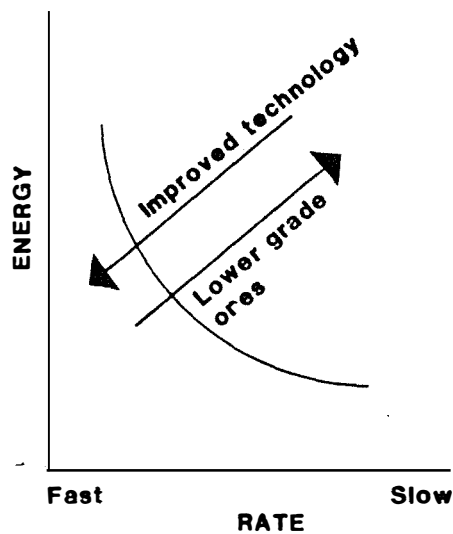


Figure 10.5: Schematic isoquant for the energy-time trade-off

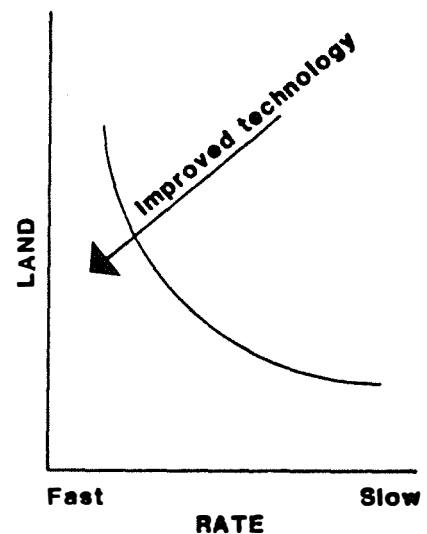


Figure 10.6: Schematic isoquant for the land-time trade-off

certain rate of production. Despite the lack of rigorous study in this field, there is much evidence which indicates that an increased rate of production increases the energy coefficient (MJ/kg) of a process (refer to Slessor, 1978 Chapter 9). There is also a similar hypothesized relationship between rate of production and land coefficients, and rate of production and labour coefficients. Quite simply, the faster the production, the less efficient the process; hence the requirement for more labour or land energy. It should be also noted, that theoretical thermodynamic limits assume infinite time availability - in the 'real' world such time availability does not exist.

10.2.2.2 Towards a Production Function, Based on Physical Inputs

It is possible to hypothesize a production function, incorporating all of the above factors and assumptions:

$$Q_0 = F(\text{rate, Labour, Land, Energy})$$

$$\begin{array}{ccc} \cdot & & \cdot \\ \cdot & & \cdot \\ \cdot & & \cdot \end{array}$$

$$Q_n = F(\text{rate, Labour, Land, Energy})$$

where: Q_n = production given current technology, management and grades of ores.

Q_0 = production given the most efficient technology management and long run level of ores (for 'energy' ores this equals the solar flux, and for 'material' ores this equals the point of recycling - refer to section 10.2.2).

Similar production functions, incorporating energy as a fundamental resource have been hypothesized by Slessor (1978), and are based on the Douglas-Cobb production function which considered only 'Labour' and 'Capital'. In Economics, the contribution of Labour, Capital and other Inputs to the Output, are quantified. The Inputs in the above production function also need to be tested and quantified.

The information in these production functions, can be summarised by a series of isoquant curves, which outlines the trade-offs between each of these factors of production, assuming all other things being equal (Figs 10.1 - 10.6).

10.2.2.3 Towards an Entropy Theory of Production, Based on Thermodynamics

Energy Analysis has been widely accused of being an "Energy Theory of Value". However, while acknowledging that energy is the fundamental resource that "drives" all systems, and the only resource which is absolutely depletable, the author does not subscribe to an "Energy Theory of Value". It is instead hypothesized that there are four fundamental physical resource inputs, into economic systems (time, labour, land, energy) as hypothesized in the above Production Function. The nature of the availability of these four resource inputs is of critical importance:

- (1) time, is constantly available, but if production processes are to be speeded up more resource inputs of labour, land or energy are required- which are all ultimately reducible to energy equivalents.
- (2) labour, is constantly available over time, given demographic stability, but it does depend on indirect inputs of land and energy resources - which are both ultimately reducible to energy equivalents.
- (3) land, is finite and constant over time given sustainable cultivation practices and geological stability, and is only dependent on inputs of energy over geological time periods.
- (4) energy, when used is degraded in quality and therefore is absolutely depletable (Second Law of Thermodynamics).

Proponents of an "Energy Theory of Value", suggest that all inputs of time, labour and land should be reduced to energy terms. Although this may be possible, it is suggested that more information is retained by considering four fundamental resource inputs in a more generalised "Physical Theory of Production". Ultimately, what may well emerge is a Theory of Value/Production based on an amalgamation of all these physical factors of production. However any such theory should emphasize the entropic nature of systems, and the inter-relationships between these fundamental resource inputs which are governed by the Second Law of Thermodynamics. Within such a construct 'Energy's' importance is fundamental, but not all-important.

Any entropy theory of production, will draw on elements of Energy Analysis, but must be also based on classical thermodynamics. Although the union of Energy Analysis and Classical Thermodynamics, has been proposed in the past surprisingly the two disciplines have not

converged. Many of the concepts of thermodynamics are difficult to apply to macro-level systems. However, if Energy Analysis is going to work towards a more generalised theory of entropy, and become less empirical and more theoretical; this union is necessary.

10.2.3 Economics and Energy Analysis Reconsidered

The relative roles of Economics and Energy Analysis, in resource allocation decisions have been widely discussed and debated in the literature. Both disciplines, are implicitly concerned with scarcity, values, time horizons, and in many ways a common set of methodological problems:

(1) Scarcity Economics approaches the problem of scarcity, from a market perception of scarcity. Scarcity in Economics is relative not absolute. That is, relative to human wants and needs. It is argued the market mechanism will overcome all scarcity. Thermodynamic limits to scarcity are not acknowledged by Economics. Energy Analysis approaches to the problem of scarcity, from a physical (entropic) perception - scarcity is absolute when viewed through a construct of entropy. Further, the efficiency of economic processes are limited by theoretical thermodynamic limits.

(2) Values The question of "value" is not implicitly addressed by Energy Analysis. By definition, Energy Analysis, is objective (refer to definition in Introductory section). Whereas, Economics is concerned with assessing human wants and needs which are dependent on value systems.

(3) Time Economics is concerned with an assumed "time preference" for present consumption. The question of time preference is not addressed by Energy Analysis. "Time preference" is a values preference, and as Energy Analysis is "values free", Energy Analysis is therefore not concerned with such preferences (or values). The practice of discounting by Economists, has been widely criticised by Energy Analysts as an arbitrary way of imposing a time value on economic decisions.

(4) Methodological Problems Some of the fundamental methodological problems are common to both disciplines. For example, the problem of inter-temporal allocation of "stock" (non-renewable) and "flow" (renewable) resources. Both disciplines are unable to take account of the needs of future generations. The problem of externalities is also

common to both disciplines (often called the boundary problem in Energy Analysis). The problem of partitioning (or allocation of joint costs) is also common to both disciplines.

In reiteration, Economics is more implicitly concerned with current values (as perceived and measured through the market system) - but only the values of the human consumers. Whereas, Energy Analysis makes no assumptions or does not deal with human values. Energy Analysis is more implicitly concerned with absolute scarcity (entropic scarcity). Therefore, a point for further development could be for an amalgamation of the two disciplines with both disciplines gaining from the strengths of the other.

Energy Analysis more inherently deals with scarcity and physical limits, Economics with values - economics is advantaged by its long history which has afforded it a large body of theory. In contrast, Energy Analysis is a young discipline and possible resolutions to many of its methodological problems are only just beginning to emerge. However, whatever body of theory emerges, it should be realised that both disciplines are only "tools" of the decision makers.

Traditionally, theories of productions are one area, as detailed in sections 10.2.3 and 10.2.4, where the two disciplines could emerge. The use of energetic variables in production function, is more important than the classical use of Labour, Capital and Land, as energetic availability is absolute, whereas these other inputs are dependent on energetic inputs.

10.3 Conclusions

The application of two Classical Linear Modelling techniques were generally successful. In particular, Regression Analysis provided a basis for solving a general equation, so as to determine the energy quality coefficients of energy sources and uses. Preliminary applications of this technique for the New Zealand situation, indicate that hydro-electricity is the highest quality energy resource, followed by natural gas, oil, coal and then wood. The energy quality of end-uses of energy can also be ranked in this way. Linear Programming provided a means of assessing the 'optimal' use of energy resources in

food systems. An application for the New Zealand food system indicated that the most optimal diet (minimising primary energy inputs) consisted of mainly cereals, fresh fruit and vegetables and some dairy products.

The application of these Linear Modelling techniques in Energy Analysis is only preliminary and exploratory. However, they should provide a basis for more advanced modelling applications (non-linear), and application to other systems. If Energy Analysis is to advance beyond its current status, more advanced modelling techniques will have to be applied in order to understand the complex nature of the macro-level systems which are often studied in Energy Analysis. It was concluded that such models should be instructive rather than predictive or prescriptive; and used in a critical not routine manner.

Finally, it was concluded that Energy Analysis provided a more correct basis for assessing absolute scarcity of resources, than Economics. Whereas, Economics provide a basis for evaluating consumer values. Therefore, as resource allocation fundamentally involves determining the use of scarce resources in terms of optimising consumer welfare (values), elements of both disciplines are required in the resource allocation process. Hence, there is a case for the emergence of the two disciplines. Furthermore, it was concluded that despite the primacy of energy in productive processes, it is also critical to incorporate other physical resources (labour, land, time) into this emergent discipline.

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APPENDIX A:

Estimation of the Quality of Energy Sources
and Uses (a copy of a paper published in the
journal Energy Policy 11:4 346-359)

Estimation of the quality of energy sources and uses

M.G. Patterson

In energy analysis and energy planning it is usual for conventional enthalpy based statistics and data to be used. This has led to difficulties, as these statistics and data do not reflect the qualities or grades of the different forms of energy. To help overcome these difficulties, a regression technique has been developed which enables all forms of energy to be converted to common quality equivalents. In particular this should improve the evaluative scope and potential of energy analysis, and in general it should aid the use of physical measurements of energy in energy planning and policy formulation procedures. Uses of the data derived from this technique, the limitations and some possible extensions of this technique are discussed.

Keywords: Energy analysis; Energy quality; Regression analysis

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Energy analysis (EA)¹ and other macro-level techniques that use physical measurements of energy have tended to use enthalpy (ΔH) measurements. In particular, this has led to much criticism of EA, because of its consequent inability to deal with energy of different *grades* or *qualities*.² Unfortunately, enthalpy (ΔH) measurements only measure the heat content of energy forms, and they do not necessarily make any distinction between low grade energy sources, such as incident solar energy, and higher grade energy sources, such as oil or natural gas. Therefore, there is a general requirement for a physical measurement of energy that takes account of the *actual* energy quality of different forms of energy. Such a requirement is of particular importance in terms of developing EA as an acceptable evaluative technique.

Methodology

Refer to the Appendix for definitions of: *primary energy inputs*; *effective energy outputs*; *quality of primary energy inputs*; *quality of effective energy outputs*; *intrinsic quality*; and *quality equivalents*.

Energy accounting procedures

The first step is to identify all primary energy inputs and all effective energy outputs of the economy or system. The second step is to *link* all primary energy inputs to all effective energy outputs by constructing a number of pathway flow diagrams. These pathways should collectively cover all energy transformations and uses in the economy. However, there can be some degree of overlap between pathways, ie the pathways need not be mutually exclusive. Each pathway can have multiple inputs and multiple outputs, which can overcome the partitioning problem³ often associated with such energy accounting procedures. The third step is to estimate the gross energy requirements (GER) of each pathway. The GER includes the direct energy inputs and the indirect energy inputs of each pathway, expressed in enthalpic values (ΔH). As a general principle, it is recommended that the IFIAS conventions of energy accounting be used in determining the GER of each pathway.⁴

Regression equations and solutions

The supply and use of energy in any given economy can be represented by the following general equation:

¹A comprehensive coverage of EA is given by the December 1975 special issue of *Energy Policy*, Vol 3, No 4, which contains 7 articles on this topic.

$$m_1 \sum_{i=1}^{i=j} (Y_1)_i + m_2 \sum_{i=1}^{i=j} (Y_2)_i + \dots m_n \sum_{i=1}^{i=j} (Y_n)_i \quad (1)$$

$$= n_1 \sum_{i=1}^{i=j} (X_1)_i + n_2 \sum_{i=1}^{i=j} (X_2)_i + \dots n_n \sum_{i=1}^{i=j} (X_n)_i$$

where Y = effective energy output of an end-use class (ΔH_{output})

X = primary energy input (ΔH_{input})

m = quality coefficient for an effective energy output (quality equivalents/ ΔH_{output})

n = quality coefficient of a primary energy input (quality equivalents/ ΔH_{input})

i = energy supply-use pathways.

The effective energy outputs ($Y_1, \dots, Y_n$) and the primary energy inputs ($X_1, \dots, X_n$) are known. The quality coefficients of the effective energy outputs ($m_1, \dots, m_n$), and the quality coefficients of the primary energy inputs ($n_1, \dots, n_n$) are not known and they can be determined by multiple linear regression.

To determine these coefficients, one coefficient must arbitrarily be given a value equal to unity. For example, coefficient n_1 can be given a value of 1, and then by rearrangement the general equation now reads:

$$\sum_{i=1}^{i=j} (X_1)_i = n_2 \sum_{i=1}^{i=j} (X_2)_i + \dots n_n \sum_{i=1}^{i=j} (X_n)_i + \quad (2)$$

$$m_1 \sum_{i=1}^{i=j} (Y_1)_i + m_2 \sum_{i=1}^{i=j} (Y_2)_i +$$

$$\dots m_n \sum_{i=1}^{i=j} (Y_n)_i$$

where $n_1 = 1$

This equation is now in a form that can be solved by multiple linear regression. The left-hand-side expression is equivalent to the 'Y' variable used in conventional regression equations, and the right-hand-side expressions are equivalent to the 'X' variables used in conventional regression equations.

The coefficients which result from the solution of this regression equation, only have meaning relative to $n_1 = 1$. That is, they are expressed in multiples of n_1 . In this study such multiples are termed 'quality equivalents'. It is recommended that the regression equation be solved several times by in turn assigning values of unity to each coefficient ($m_1, \dots, m_n, n_1, \dots, n_n$). In this way the general robustness of the model, and the validity of this procedure can be tested.

As a general principle, it is advisable that as many pathways as possible be used in the regression procedure. This should increase the variability in the data set, and hence lead to more accurate solutions of the regression. In particular, it is advisable that each primary energy input class be linked to each effective energy output class by one pathway each (that is, $X_n \times Y_n$ pathways should result from this).

Statistical analysis of solutions

To test the statistical validity of any given set of solutions (ie a particular model) generated by this technique a number of statistical tests should be undertaken.⁵

²G. Leach, 'Net energy analysis - is it any use?', *Energy Policy*, Vol 3, No 4, 1975, pp 332-334.

³The partitioning problem refers to the problem where there is only one energy input figure available, and this figure needs to be allocated to outputs of the system. The IFIAS recommended a number of possible criteria for partitioning, all of which are fundamentally arbitrary.

⁴International Federation of Institutes for Advanced Study, *Energy Analysis Workshop on Methodology and Conventions*, IFIAS, Stockholm, 1974.

⁵For a more complete range of statistical tests of regression models readers should refer to the appropriate literature. See N.R. Draper and H. Smith, *Applied Regression Analysis*, 2 ed, Wiley, New York, 1981.

F test. Usually in regression analysis this is the most important test, as it indicates the overall statistical validity of the model. That is, how adequately the solutions to the regression equation 'fits' the actual data set. The *F* ratio for a model is calculated by most programme packages used in regression analysis. The level of significance (*p*) can be calculated by using standard *F* distribution tables.

t test of coefficients. The *t* ratios for each coefficient are also calculated by most programme packages used in regression analysis. The *t* ratio of a coefficient is simply the estimated coefficient divided by its standard deviation. The level of significance (*p*) of each *t* ratio, and hence the statistical accuracy of each coefficient estimate, can be calculated by using standard *t* distribution tables.

Examination of residuals. An examination of the residuals for each pathway should be undertaken. Those pathways which have the highest standardized residuals conform least to the regression model. If at all possible, it is advisable that the model be reconstructed to eliminate such pathways. Various residual plots are outlined in statistical texts⁶ and are outputted by most programme packages used in regression analysis.

Other statistics. Various other statistics and statistical tests can be undertaken to test a model. For example, the Durbin-Watson statistic can be calculated to test the model for autocorrelation. It may also be useful to calculate partial *F* ratios for each coefficient, so as to estimate their contributions to the overall level of significance of the model.

Recommended methods of model selection and improvement

It is recommended that the maximum number of models be generated by giving each coefficient in turn a value of unity. These basic models should form the basis of the model selection and improvement procedures.

The simplest approach is to choose the basic model which has the highest *F* ratio, provided the model makes good physical sense. For example, it is meaningless to use a model where a coefficient is negative, as this is a physical impossibility.

A more complicated and instructive approach is to 'experiment' with the models so as to maximize the level of significance (*p*) of the model. The aggregation and, where possible, the disaggregation of variable classes ($X_1, \dots, X_n, Y_1, \dots, Y_n$) should form the basis of this 'experimentation'. The original classifications may not necessarily be the 'best' way of classifying the inputs ($X_1, \dots, X_n$) and outputs ($Y_1, \dots, Y_n$) in terms of their energy qualities. It is not only more statistically valid to maximize *p*, but it can also be more instructive to the analyst. This is because such reclassification may give some insight as to the physical and technical reasons why it is best to classify inputs and outputs in a particular way.

When aggregating various inputs or outputs it is recommended that those classes with the lowest *t* ratios for their coefficients be added together first. By doing this the more insignificant coefficients can be eliminated from the model, while also increasing the likelihood of increasing the *F* ratio of the model. Eventually, an optimum aggregation of inputs and outputs should be reached, where the level of significance (*p*) of the model cannot be improved. Statistically, this model best explains the use of energy in the economy or system, in terms of *energy quality*, and should make good physical and technical sense.

⁶For example, Draper and Smith, *op cit*, Ref 5.

Central hypothesis and model building

The central hypothesis that is being tested by this regression technique is that for a given economy or system all *inputs* ($X_1, \dots, X_n$) and all *outputs* ($Y_1, \dots, Y_n$) have *intrinsic quality coefficients*.

This hypothesis will hold true in any system or economy where the outputs are proportional⁷ to the inputs. Evidence and experience strongly indicate that this hypothesis holds true in all economic systems.⁸ Therefore, it is not so much a matter of proving this central hypothesis, but of building a model which best explains this central hypothesis.

To elaborate with an example, the simplest way to model an economy is to set up a model where all inputs are classified into one class and all outputs into another. Although this model may be statistically significant, it may not be the best model in terms of maximizing its statistical validity and instructiveness. The problem for the analyst is to disaggregate these two classes, so as to obtain this best model. This requires a good understanding and knowledge of the statistical testing procedures, and a good understanding of the nature of the system being modelled.

An application for an energy efficient New Zealand economy

To demonstrate the use of this technique, a regression model of a notional⁹ New Zealand economy which uses the most energy efficient technology currently available will be used (see Table 1). There is some allowance made for operational inefficiencies which inevitably occur in any real situation. Since the data derived from this technique were to be used for a long-term planning exercise, it was considered appropriate to use data which would reflect long-run rather than short-run quality coefficients.¹⁰

Inputs and outputs considered

The *primary energy inputs* considered in this example are:

- *Hydroelectricity*. This refers to hydroelectricity at the point of generation, before transmission.
- *Natural gas*. This refers to natural gas as it lies in the gas well.
- *Oil*. This refers to oil products as they are imported in their various degrees of refinement, or indigenous oil as it lies in the oil well.
- *Coal*. This refers to coal as it lies in the ground.
- *Wood*. This refers to wood as it leaves the forest.

The *effective energy outputs* considered in this example are:

- *Electrical output*.¹¹ This class includes all energy use in all end-use processes where there is an absolute requirement for the direct use of electricity. Other energy sources can only be used directly, after they have been up-graded to electricity. These end-use processes include the operating of electronic equipment such as computers, and various electrical appliances and machines such as electrically powered refrigeration units.
- *High grade transport*. This refers to the use of energy by relatively long-range, route flexible and high powered road vehicles (that is, the modern car which is an important end use of energy in the New Zealand economy). This does not include other forms of road transport which are more limited in their range, route flexibility and/or power output. High grade transport directly uses high grade

⁷Multiple linear regression assumes linear proportionalities. For non-linear proportionalities non-linear multiple regression should be used.

⁸Time series data and international comparisons strongly indicate that dollar outputs (\$) are linearly proportional to primary energy inputs in economic systems. On this basis it is not unreasonable to assume that effective energy outputs will be proportional to primary energy inputs in economic systems.

⁹A regression model based on actual energy use in the New Zealand economy has also been successfully constructed.

¹⁰Historical evidence demonstrates that the energy efficiency of a given process or technology approaches a thermodynamic limit: A. Decker, *Report of 9th TNO Conference on Energy Accounting*, Rotterdam, 1976; IFIAS, *Workshop on Energy Analysis and Economics*, Report No 9, Stockholm, 1975. Therefore, in the long run, for a given economy a set of long run quality coefficients will be approached.

¹¹The system boundary ends at the point where electrical energy is delivered to the end-use appliance. This is because the mean end-use efficiency of end uses in this class is very difficult to estimate accurately.

Table 1. An energy efficient New Zealand economy: assumed technologies and operational efficiencies.

Pathway	Supply technology	Efficiency ^a (%)	Distribution technology	Efficiency ^a (%)	End-use technology	Efficiency ^a (%)
Coal → Electrical output	Conventional power station	26	Current transmission system	90	Current electrical and electronic technology	b
Oil → Electrical output	Conventional power station	32	Current transmission system	90	Current electrical and electronic technology	b
Gas → Electrical output	Conventional power station	30	Current transmission system	90	Current electrical and electronic technology	b
Wood → Electrical output	Power station fired by wood	12	Current transmission system	90	Current electrical and electronic technology	b
Hydro → Electrical output	Conventional hydro-electricity generation (dam; water turbine)	b	Current transmission system	90	Current electrical and electronic technology	b
Coal → High grade transport	Gasification. Catalytic conversion to methanol	47	Current distribution system for liquid fuels	100	Internal combustion engine	30
Oil → High grade transport	Oil refinery	92	Current distribution system for liquid fuels	100	Internal combustion engine	25
Gas → High grade transport	Catalytic conversion to methanol	59	Current distribution system for liquid fuels	100	Internal combustion engine	30
Wood → High grade transport	Gasification. Catalytic conversion to methanol	43	Current distribution system for liquid fuels	100	Internal combustion engine	30
Hydro → High grade transport	Conventional hydro-electricity generation (dam, water turbine), current electricity transport system, electrolytic equipment	72	Included in the supply column	–	Internal combustion engine with storage battery	37
Gas → Low grade transport	Current gas supply technology	b	Pipeline	90	Internal combustion engine	27
Wood → Medium grade transport	Gasification	43	Pipeline	90	Internal combustion engine	27
Coal → Medium grade transport	Gasification	47	Pipeline	90	Internal combustion engine	27
Coal → Industrial heat	Current coal mining technology	b	Current distribution system	100	Industrial boilers and furnaces	70
Oil → Industrial heat	Oil refinery	90	Current distribution system for liquid fuels	100	Industrial boilers and furnaces	75
Gas → Industrial heat	Current gas supply technology	b	Pipeline	90	Industrial boilers and furnaces	75
Wood → Industrial heat	Current silvicultural technology and management	b	Current distribution system	100	Industrial boilers and furnaces	33
Hydro → Industrial heat	Conventional hydro-generation (dam, water turbine)	b	Current transmission system	90	Heat pumps (30%), resistance heaters (70%)	160
Coal → Water heating	Current coal mining technology	b	Current distribution system	100	Enclosed burner, water heating cylinder	50
Oil → Water heating	Oil refinery	90	Current distribution system for liquid fuels	100	Enclosed burner, water heating cylinder	65
Gas → Water heating	Current gas supply technology	b	Pipeline	90	Gas water heating cylinder	65
Wood → Water heating	Current silvicultural technology and management	b	Current distribution system	100	Enclosed burner, water heating cylinder	33
Hydro → Water heating	Conventional hydro-generation (dam, water turbine)	b	Current transmission system	90	Heat pumps	200
Coal → Space heating	Current coal mining technology	b	Current distribution system	100	Enclosed burner	49
Oil → Space heating	Oil refinery	90	Current distribution system for liquid fuels	100	Enclosed burner	57
Gas → Space heating	Current gas supply technology	b	Pipeline	90	Enclosed burner	64
Wood → Space heating	Current silvicultural technology and management	b	Current distribution system	100	Enclosed burner	35
Hydro → Space heating	Conventional hydro-generation (dam, water turbine)	b	Current transmission system	90	Heat pumps	250
Coal → Cooking	Current coal mining technology	b	Current distribution system	100	Conventional coal fired range	20
Oil → Cooking	Oil refinery	90	Current distribution system for liquid fuels	100	Conventional oil fired range	20
Gas → Cooking	Current gas supply technology	b	Pipeline	90	Conventional gas fired range	30
Wood → Cooking	Current silvicultural technology and management	b	Conventional distribution system	100	Conventional wood fired range	13
Hydro → Cooking	Conventional hydro-electricity generation (dam, water turbine)	b	Current transmission system	90	Conventional electric range	44

^aEnthalpic (ΔH) efficiency of direct energy flows. Enthalpic (ΔH) efficiencies are also implied in indirect energy flows.

^bEither input or output is outside study boundary. Therefore, no enthalpic (ΔH) efficiency can be calculated.

fuels such as gasoline, methanol, hydrogen and diesel.

- *Medium grade transport.* This refers to the use of energy by road vehicles which have a shorter range and less power output than those in the above category. In the New Zealand situation, this specifically refers to the use of compressed natural gas in vehicles designed to run on gasoline. With the discovery of the Maui natural gas field, a small yet significant proportion of vehicles in New Zealand have been converted to operate on compressed natural gas.
- *Industrial heat.*¹² This refers to the use of energy in industrial situations in producing medium to high temperature heat.
- *Water heating.*¹³ This refers to the use of energy in heating water to medium temperatures, primarily in the household situation.
- *Space heating.* This refers to the use of energy in heating space to medium temperatures, primarily in the household situation.
- *Cooking.*¹⁴ This refers to the use of energy in heating food, primarily in the household situation.

Pathways considered

Theoretically, by linking each of the five primary energy inputs to each of the seven effective energy outputs by one pathway each, 35 (5×7) pathways can be considered. Consideration of all these pathways should facilitate the solving of the regression equations by increasing the variability in the data set.

For some of these 35 links there are several possible pathways that can be considered. For example, high grade transport can be derived from coal in the following ways (to name but a few):

- (1) Coal ^{gasification} → Methanol ^{Mobil process} → Gasoline
- (2) Coal ^{gasification} → Methanol
- (3) Coal ^{hydrogenation} → Crude oil → Gasoline, diesel

In a situation like this, the criteria used to narrow the alternatives to one option is *the most energy efficient pathway (in enthalpy terms) possible in terms of current technology*. Therefore, in the above example option (2) should be chosen.

Some primary energy inputs can be converted more efficiently (in enthalpy terms) to high grade transport energy rather than to medium grade transport energy. For example, crude oil can be converted more efficiently to gasoline and diesel (high grade transport energy) than to compressed methane (medium grade transport energy). In a situation like this, the medium grade options were eliminated from consideration because, even in enthalpy terms, they constituted an inefficient use of the energy resource.

Therefore, by applying these selection criteria a list of 33 energy supply use pathways were considered for analysis:

- (1) Coal → Electricity generation → Transmission → Electrical output
- (2) Oil → Electricity generation → Transmission → Electrical output
- (3) Gas → Electricity generation → Transmission → Electrical output
- (4) Wood → Electricity generation → Transmission → Electrical output
- (5) Hydroelectricity → Electricity generation → Transmission → Electrical output
- (6) Coal → Methanol → High grade transport
- (7) Oil → Gasoline, diesel → High grade transport

¹²The GERs of supplying the materials for the final step of these pathways are not included. For example, the GER of supplying foodstuffs for household cooking is not included in the study boundaries.

¹³*Ibid.*

¹⁴*Ibid.*

- (8) Gas → Methanol → High grade transport
- (9) Wood → Methanol → High grade transport
- (10) Hydroelectricity → Hydrogen → High grade transport
- (11) Gas → Compressed natural gas → Medium grade transport
- (12) Wood → Methane → Medium grade transport
- (13) Coal → Methane → Medium grade transport
- (14) Coal → Industrial heat
- (15) Oil → Industrial heat
- (16) Gas → Industrial heat
- (17) Wood → Industrial heat
- (18) Hydroelectricity → Electricity generation → Transmission → Industrial heat
- (19) Coal → Water heating
- (20) Oil → Water heating
- (21) Gas → Water heating
- (22) Wood → Water heating
- (23) Hydroelectricity → Electricity generation → Transmission → Water heating
- (24) Coal → Space heating
- (25) Oil → Space heating
- (26) Gas → Space heating
- (27) Wood → Space heating
- (28) Hydroelectricity → Electricity generation → Transmission → Space heating
- (29) Coal → Cooking
- (30) Oil → Cooking
- (31) Gas → Cooking
- (32) Wood → Cooking
- (33) Hydroelectricity → Electricity generation → Transmission → Cooking

The model constructed in this example only had one effective output per pathway, although having several primary energy inputs per pathway. A more complex model could have several energy outputs and several energy inputs per pathway.¹⁵ For example, each pathway could be considered to have one main energy output and various waste heat outputs. Coefficients for different grades of waste heat, that could be converted to effective outputs by the use of the appropriate technology, could be estimated using this technique. Also, in situations where there is a partitioning problem, several outputs could be considered for one pathway.

¹⁵It could be more difficult to obtain solutions to the regression when multiple outputs are considered. Generally this will mean there will be less variability in the data set, and therefore more pathways will need to be considered to obtain significant results. It is also expected that in some instances considering multiple outputs could lead to the problem of correlation between variables.

¹⁶New Zealand Ministry of Energy, Energy data files, Wellington, New Zealand, 1978–81.

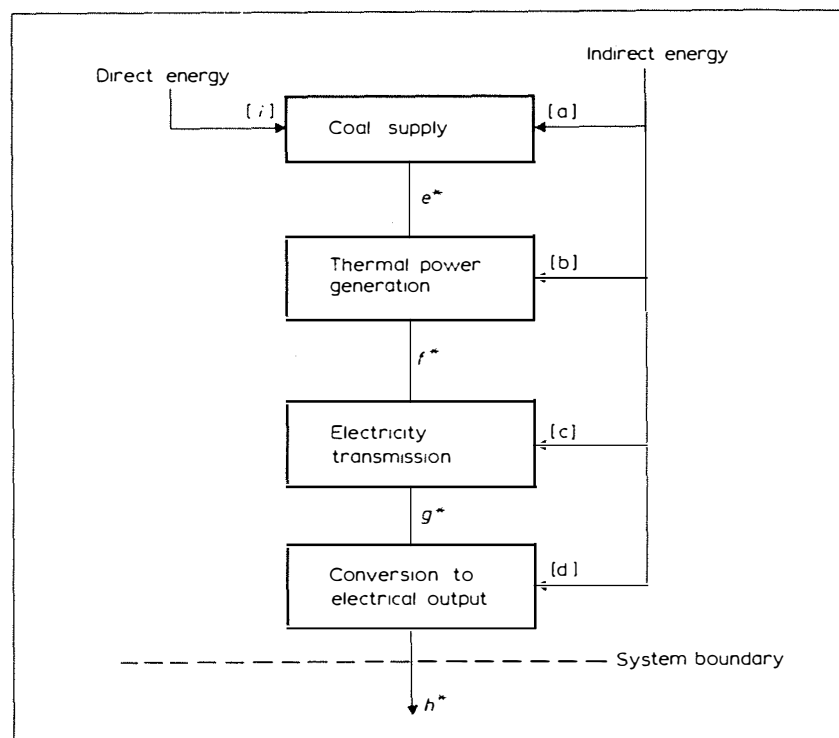
¹⁷New Zealand Ministry of Energy, *Goals and Guidelines: An Energy Strategy for New Zealand*, Wellington, New Zealand, 1978, (particularly the energy flow diagram on the inside back cover).

¹⁸A.J. Carter, N.J. Peet, and J.T. Baines, *Direct and Indirect Energy Requirements of the New Zealand Economy*, Department of Chemical Engineering, University of Canterbury, Christchurch, New Zealand, 1980.

Data collection and data set

The GER of the 33 pathways were estimated using data from various statistical and literature sources. The process method of energy accounting formed the basis of these estimations. Flow diagrams for each pathway were drawn to aid in these estimations (see Figure 1). Data about the efficiency of the main flows were obtained from various publications of the New Zealand Ministry of Energy,^{16,17} for pathways currently operating in New Zealand. Literature data were used to estimate the efficiencies of main flows, for pathways which are not currently operating in New Zealand. The indirect energy requirements were estimated using data from a recently completed input-output based energy analysis of the New Zealand economy.¹⁸

From these data the GER of each pathway was estimated, and normal-



* Conversion ratio of main flow
| GER of input in primary energy terms.

Figure 1. Method of calculating the gross energy requirements (GER) of pathway 1.

$$GER = \left(\frac{[a]}{e^*} + \frac{[i]}{e^*} + \frac{[b]}{f^*} + \frac{[c]}{g^*} + \frac{[d]}{g^*} \right)$$

ized to be expressed in terms of 1 MJ of effective output. This normalization process had the effect of improving the versatility of the data set. In a normalized data set, experience has demonstrated that, statistically, it is unimportant what variable is used as the equivalencing unit. However, it does assume that the relative demand of each output of each pathway is the same. Nevertheless, in both this and other cases examined this assumption has not been found to be critical, as the magnitude of the estimated coefficients do not significantly change when the outputs are weighted according to different relative demands.

Finally, a data set was constructed using data obtained from the data collection and analysis procedure (see Table 2).

Results

Table 3 outlines the results of regression, where the estimated coefficients are expressed in terms of hydroelectricity equivalents per MJ of input or output, ie where n_i is arbitrarily given a value equal to unity. The F ratio for this model is 14.93 which is significant at the $p = 0.001$ level. The estimates of coefficients are all significant at the $p = 0.01$ level.

By arbitrarily giving the other coefficients values equal to unity, the following F ratios were obtained for these models:

$$\begin{aligned} n_2 &= 1, F \text{ ratio} = 13.43, \text{ gas equivalents} \\ n_3 &= 1, F \text{ ratio} = 10.75, \text{ oil equivalents} \\ n_4 &= 1, F \text{ ratio} = 8.00, \text{ coal equivalents} \end{aligned}$$

Table 2. Data set: gross energy requirements of energy supply-use pathways in an energy efficient New Zealand economy.

Pathway	Primary energy inputs (MJ) ^a					Effective energy outputs (MJ) ^{a,b}						
	X ₁ Hydro	X ₂ Gas	X ₃ Oil	X ₄ Coal	X ₅ Wood	Y ₁ Electrical output	Y ₂ High grade transport	Y ₃ Medium grade transport	Y ₄ Industrial heat	Y ₅ Water heating	Y ₆ Space heating	Y ₇ Cooking
Coal → Electrical output	0.03	0.01	0.10	4.56	0.00	1	0	0	0	0	0	0
Oil → Electrical output	0.04	0.03	3.83	0.31	0.00	1	0	0	0	0	0	0
Gas → Electrical output	0.04	3.84	0.17	0.04	0.00	1	0	0	0	0	0	0
Wood → Electrical output	0.03	0.01	0.52	0.02	9.39	1	0	0	0	0	0	0
Hydro → Electrical output	1.14	0.01	0.08	0.04	0.00	1	0	0	0	0	0	0
Coal → High grade transport	1.86	0.13	1.05	8.00	0.00	0	1	0	0	0	0	0
Oil → High grade transport	0.36	0.17	5.64	0.60	0.00	0	1	0	0	0	0	0
Gas → High grade transport	0.36	6.09	0.89	0.20	0.00	0	1	0	0	0	0	0
Wood → High grade transport	1.99	0.13	1.30	0.59	7.75	0	1	0	0	0	0	0
Hydro → High grade transport	3.98	0.14	0.93	0.21	0.00	0	1	0	0	0	0	0
Gas → Medium grade transport	0.15	4.57	0.84	0.33	0.00	0	0	1	0	0	0	0
Wood → Medium grade transport	1.06	0.25	1.35	0.42	9.40	0	0	1	0	0	0	0
Coal → Medium grade transport	0.93	0.23	1.03	9.42	0.00	0	0	1	0	0	0	0
Coal → Industrial heat	0.04	0.01	0.07	1.51	0.00	0	0	0	1	0	0	0
Oil → Industrial heat	0.02	0.02	1.50	0.13	0.00	0	0	0	1	0	0	0
Gas → Industrial heat	0.03	1.57	0.06	0.02	0.00	0	0	0	1	0	0	0
Wood → Industrial heat	0.03	0.03	0.18	0.03	3.03	0	0	0	1	0	0	0
Hydro → Industrial heat	0.57	0.01	0.03	0.01	0.00	0	0	0	1	0	0	0
Coal → Water heating	0.02	0.00	0.08	2.10	0.00	0	0	0	0	1	0	0
Oil → Water heating	0.02	0.02	1.73	0.15	0.00	0	0	0	0	1	0	0
Gas → Water heating	0.03	1.81	0.07	0.02	0.00	0	0	0	0	1	0	0
Wood → Water heating	0.03	0.03	0.18	0.03	3.03	0	0	0	0	1	0	0
Hydro → Water heating	0.58	0.01	0.06	0.02	0.00	0	0	0	0	1	0	0
Coal → Space heating	0.01	0.06	0.10	2.16	0.00	0	0	0	0	0	1	0
Oil → Space heating	0.03	0.03	1.97	0.17	0.00	0	0	0	0	0	1	0
Gas → Space heating	0.04	1.84	0.07	0.02	0.00	0	0	0	0	0	1	0
Wood → Space heating	0.03	0.03	0.17	0.03	2.86	0	0	0	0	0	1	0
Hydro → Space heating	0.46	0.01	0.05	0.01	0.00	0	0	0	0	0	1	0
Coal → Cooking	0.14	0.04	0.25	5.28	0.00	0	0	0	0	0	0	1
Oil → Cooking	0.07	0.07	5.62	0.48	0.00	0	0	0	0	0	0	1
Gas → Cooking	0.10	5.16	0.07	0.20	0.00	0	0	0	0	0	0	1
Wood → Cooking	0.08	0.08	0.46	0.08	7.69	0	0	0	0	0	0	1
Hydro → Cooking	2.09	0.04	0.11	0.03	0.00	0	0	0	0	0	0	1

^aExpressed in enthalpy (ΔH) terms; 1 kWh = 3.6 MJ.

^bNormalized so that all effective outputs equal unity.

- $n_5 = 1$, F ratio = 6.08, wood equivalents
 $m_1 = 1$, F ratio = 7.30, electrical output equivalents
 $m_2 = 1$, F ratio = 40.60, high grade transport equivalents
 $m_3 = 1$, F ratio = 18.87, medium grade transport equivalents
 $m_4 = 1$, F ratio = 1.14, industrial heat equivalents
 $m_5 = 1$, F ratio = 1.43, space heating equivalents
 $m_6 = 1$, F ratio = 1.47, water heating equivalents
 $m_7 = 1$, F ratio = 12.58, cooking equivalents

Using the procedures outlined in the methodology section, these basic models can be improved, and the criteria outlined in the same section should be used to finally determine which basic model should be adopted. At this stage, it appears that those models where $m_4 = 1$, $m_5 = 1$ and $m_6 = 1$ are unsatisfactory, as they are not significant at the $p = 0.10$ level.

Comment on results

The most important implication of these results is that different primary energy resources can be ranked in terms of their energy qualities. Not surprisingly, hydroelectricity was found to have the highest quality coefficient, followed by natural gas and oil, then coal and finally by wood (see Table 3). These quality coefficients enable conventional enthalpy-based statistics and data to be converted into quality equivalent terms. Such quality-based statistics and data should be of greater use in energy planning and policy formulation, as they reflect the energy qualities of different primary energy resources.

Further explanation of the quality equivalent concept

This concept is fundamental in terms of the use and understanding of this technique. Most importantly, it provides an independent means of converting inputs and outputs to common energy units. For example, all outputs can be converted to hydroelectricity equivalents (using data from the above example):

- 1MJ of electrical output $\rightarrow$ 1.46 hydroelectricity equivalents
 1MJ of high grade transport output $\rightarrow$ 3.71 hydroelectricity equivalents
 1MJ of medium grade transport output $\rightarrow$ 3.06 hydroelectricity equivalents
 1MJ of industrial heat $\rightarrow$ 0.59 hydroelectricity equivalents
 1MJ of water heating $\rightarrow$ 0.66 hydroelectricity equivalents

Table 3. Results – estimate of quality coefficients for primary energy inputs and effective energy outputs.

Coefficient	Estimate of coefficient ^a	Standard deviation ^a	t ratio	Quality ranking
n_1 Hydroelectricity	1.00 ^b	—	—	High quality input
n_2 Natural gas	0.43	0.06	6.99	Medium quality input
n_3 Oil	0.40	0.06	6.27	Medium quality input
n_4 Coal	0.21	0.04	4.73	Low-medium quality input
n_5 Wood	0.15	0.03	4.46	Low quality input
m_1 Electrical output	1.46	0.25	5.82	Medium quality output
m_2 High grade transport	3.71	0.32	11.26	High quality output
m_3 Medium grade transport	3.06	0.42	7.31	High quality output
m_4 Industrial heat	0.59	0.20	3.01	Low quality output
m_5 Water heating	0.66	0.20	3.30	Low quality output
m_6 Space heating	0.66	0.20	3.30	Low quality output
m_7 Cooking	1.97	0.27	7.21	Medium quality output

^aExpressed in terms of hydroelectricity equivalents per MJ of input or output.

^bBy definition.

1MJ of space heating → 0.66 hydroelectricity equivalents
1MJ of cooking output → 1.97 hydroelectricity equivalents

It is important to realize that this does not *necessarily* mean that 3.71 MJ of primary hydroelectricity is required to produce 1MJ of high grade transport output. However, it does mean that any *equivalent package* of primary energy equal to 3.71 hydroelectricity equivalents is required, to produce 1 MJ of high grade transport output.¹⁹ Similarly, all inputs can be converted to hydroelectricity equivalents (using data from the above example):

1MJ of hydroelectricity → 1.00 hydroelectricity equivalents
1MJ of natural gas → 0.43 hydroelectricity equivalents
1MJ of oil → 0.40 hydroelectricity equivalents
1MJ of coal → 0.21 hydroelectricity equivalents
1MJ of wood → 0.15 hydroelectricity equivalents

It is important to realize that the amount of primary energy required to produce a hydroelectricity equivalent, is independent of the eventual end use (or effective output class). In this way the quality equivalent concept allows *intrinsic quality coefficients* (independent quality coefficients) to be assigned to each primary energy input and each effective energy output. This is a fundamental element of the nature of this regression modelling technique.

Discussion and review

Uses of data derived from the technique

The data derived from the use of this technique are particularly useful in the evaluation of alternative energy supply options. In EA, net energy ratios²⁰ are frequently used to assess the amount of net energy which an energy producing system would supply.

However, these net energy ratios are quite often misleading because the inputs and outputs of the industry or system are of differing qualities. For example, with many biomass energy production systems the energy inputs are high quality energy resources (particularly electricity) and the outputs are only of medium quality. This was found to be the case with wood gasification and catalysis to methanol,²¹ and the production of biogas from wastes.²² Therefore, particularly in countries such as New Zealand where most consumer-level electricity cannot be converted back to fossil fuel energy units, this leads to inflated net energy ratios when conventional enthalpy units (ΔH) are used in the calculation. In fact, by converting all inputs and outputs to common quality equivalents it can be seen that some systems actually produce no net energy, and are therefore not viable as energy producing systems.

The opposite is the case in the estimation of net energy ratios of nuclear power stations where the main output is a high quality energy resource (electricity) and the main inputs are medium quality energy resources (fossil fuels).²³ That is, in this case, if the net energy ratio is expressed in conventional enthalpy units (ΔH), it is deflated. This is because no weight is given to the fact that a high quality energy resource (electricity) is produced from lower quality energy resources (fossil fuels). In such cases as this, the use of quality coefficients to convert all inputs and outputs to quality equivalent terms should add more weight to the net energy concept in technology evaluation and assessment.

¹⁹For example, it could mean that if this amount was to come entirely from wood, the following amount of energy would be required:

1MJ of output
= $\frac{3.71 \text{ hydroelectricity equivalent}}{0.51 \text{ hydroelectricity equivalent MJ}^{-1}}$
= 24.73 MJ

²⁰Net energy ratio = $\frac{\text{GER of systems output}}{\text{GER of systems input}}$

²¹W.B. Earl, 'Methanol from wood in New Zealand', in *Alcohol Fuels*, Institution of Engineers, University of Sydney, Sydney, Australia, 1978, pp 517–521.

²²M. Slesser and C. Lewis, *Biological Energy Resources*, Spon, London, 1979, Table 5.5.

²³P.F. Chapman, 'Energy analysis of nuclear power stations', *Energy Policy*, Vol 3, No 4, 1975, pp 285–298.

In a similar way, converting forms of energy to common quality equivalents should assist energy planning and policy formulation at the macro level. Difficulties often arise in determining the most energy efficient method or strategy for providing a given service, because the technologies and infrastructures involved require different mixes of primary energy of different qualities. By converting all forms of energy to common quality equivalents, optimization techniques such as linear or non-linear programming can be used to determine the most energy efficient strategies or policies. Information gained from such procedures should be useful to organizations and agencies concerned with investigating energy efficient or low energy futures, as the terms 'energy efficient' and 'low energy' tend to have somewhat nebulous meanings, unless all forms of energy can be expressed in common quality terms.

Possible extensions of the technique relevant to energy analysis

One of the major limitations and points of criticism of conventional EA is that it does not take account of all energy resources (particularly solar) and labour inputs.²⁴ The approach has tended to take account of high quality non-renewable resources²⁵ and neglect lower quality renewable energy resources. This approach is to some extent justifiable in modern economies where such inputs are no longer significant in terms of sustaining their high levels of economic growth. However, these inputs can be critical, particularly in less developed economies and in less energy intensive systems.²⁶ In such circumstances it could be considered appropriate to include labour and those renewable energy resources which are usually excluded from the analysis. This can easily be done by including these inputs as extra x variables in the regression model.

Coefficients for labour inputs could be expressed in terms of man-years per effective energy output. In effect, these would be an expression of the energy equivalents of labour, such as those which are implicit in data presented by Steinhart and Steinhart.²⁷

²⁴IFIAS, 1974, *op cit*, Ref 3. It is recommended that for 'developed or industrialized economies' the energy associated with labour should not be considered.

²⁵M. Slesser, *Energy in the Economy*, Macmillan, London, 1978. Slesser defines GER as 'the sum of all energy resources expressed in enthalpy terms that had to be sequestered from the earth's non-renewable resources of energy in order to deliver a good or service to the point of interest'. This definition therefore excludes renewable energy resources such as solar energy and hydroelectricity.

²⁶These inputs can also be critical in developed economies. For example, New Zealand's economic growth depends to a large extent on renewable energy resources (hydroelectricity and solar energy via agricultural production systems).

²⁷J.S. Steinhart, and C.E. Steinhart, 'Energy use in the US food system', *Science*, No 184, pp 307-316, (see Figure 3).

²⁸'Intrinsic' to the system being considered. Refer to the definitions in the Appendix.

Preliminary consideration of the technique's use in energy analysis

By using the technique described in this paper, an intrinsic²⁸ value can be placed on all forms of energy which are expressed in enthalpy (ΔH) terms. Value is defined in terms of the relative efficiency at which a given energy source is converted to *any* useful output. Therefore, by using these energetic values, EA can be used as an evaluative rather than descriptive technique. This is particularly the case if the rationale of the most efficient use of current technology, which was used in the application described in this paper, is used in applying this technique. This is because such a rationale reflects the long-run efficient use of an energy source to a greater degree.

It should be noted that this extended form of EA also has its weaknesses and limitations, like any evaluation technique, including conventional economics. As mentioned above, *value* is defined in terms of the intrinsic efficiency with which an energy source is converted to a useful output. Defining 'useful' has its problems as it is essentially a values statement which has no meaning outside a given human values system. Furthermore, there is often an indistinct boundary between what can be considered a valuable or a wasteful form of energy. For example, is waste

heat emanating from household cooking appliances really 'wasted'? It could be considered to be a useful form of space heating. However, by using a series of working definitions, this definitional problem can at least be in part overcome.

Like monetary values in economics, these energetic values do not necessarily take account of environmental or social values.²⁹ However, by allowing for such things as 'clean technologies' such values can often be implied in these energetic values. Another limitation of energetic valuations is that they are particular to the structural mix of technology which is assumed. However, this is not unlike economics, where monetary costs depend on, amongst other things, the structural mix of technologies which underpin a given production system.

Probably the most important limitation which this extended form of EA has in common with conventional economics, is that energetic values, like the monetary values, do not take account of the comparative long-term value of stock and flow of energy resources. Neither economics nor EA can reconcile, in terms of some intergenerational welfare function, the possible requirements of future generations and the requirements of the present generation for stock energy resources, which for all intents and purposes are finite and depletable.

The author does not consider the use of energy as a unit of value to be an arbitrary gimmick. Energy is considered to be a primary resource which 'drives' all natural and economic systems. Furthermore, it is the only physical resource,³⁰ according to the Second Law of Thermodynamics, which is absolutely depletable. Material resources can always, at least theoretically if not in practice, be manufactured, recycled or re-used out of used or virgin materials by using energy. Therefore, because of its fundamental nature in all systems, energy is often an appropriate unit of value to use, particularly when considering the long-term use and sustainability of physical systems.

Therefore, by using these common energetic values (quality equivalents) in EA, its evaluative scope and potential should be improved. However, it should be noted that, by definition, energy based valuation techniques do not necessarily say anything about monetary values. Nor do energy based evaluation techniques necessarily say anything about the efficient or optimal allocation of financial resources, and should therefore not be directly used for guiding such decisions.

Conclusions

The most important finding of this study has been that different primary energy resources can be ranked in terms of their energy quality, using the regression technique outlined in the article. Preliminary applications of this technique for the New Zealand situation, indicate that hydro-electricity is the highest quality energy resource, followed by natural gas and oil, then coal and finally by wood. By using quality coefficients for these energy resources, conventional enthalpy based statistics and data can be converted to quality equivalent terms. This has particular relevance in improving the evaluative scope and potential of energy analysis, but should also provide valuable information for energy planning and policy formulation purposes. The technique is versatile and flexible, as it can be used to estimate quality coefficients of any energy resource for any economy or for any system.

²⁹These economic 'externalities' are sometimes 'internalized' into economic analyses. Refer to A.K. Dasgupta and D.W. Pearce, *Cost-Benefit Analysis: Theory and Practice*, Macmillan, London, 1972, (particularly Chapter 5).

³⁰In a fundamental sense, time could be considered to be a physical resource that is always consumed, and cannot be created or supplied from existing resources.

Appendix

Definitions

Primary energy inputs. Any given economy is considered to have a number of primary energy inputs, that is, energy inputs into the economy from exogenous sources, such as from a natural resource base or from imports. All secondary or intermediary energies can be converted back to primary energy inputs. The primary energy inputs in this study are expressed in terms of their enthalpic values (ΔH), as is normal practice.

Effective energy outputs. Any given economy is also considered to have a number of effective energy outputs. These outputs refer to effective or useful energies resulting from end-use processes in the economy. For example, in cooking this refers to energy absorbed by the cooking load, and it does not refer to the waste heat which is lost to the surrounding

environment. In any specific analysis it is important that these effective energy outputs be clearly defined. In this study the effective energy outputs are also expressed in terms of their enthalpic values (ΔH).

Quality of primary energy inputs. This is defined as the relative efficiency at which a given primary energy input is converted to effective energy outputs. In this study it is expressed in terms of common quality units per unit of enthalpy (ΔH) of primary energy input.

Quality of effective energy outputs. This is defined as the gross energy requirements (direct and indirect) of an effective energy output, expressed in quality terms. In this study it is expressed in terms of common quality units per unit of enthalpy (ΔH) of

effective energy output.

Intrinsic quality. This is the quality of a primary input or effective energy output which is intrinsic to a given economy with its given structural mix of technologies. These qualities are independent of each other, and only depend on the given mix of technological structures and their operational efficiencies, which are specific to a given economy. By using the technique described in this paper, these intrinsic qualities can be mathematically determined by analysing a given set of energy supply-use pathways of that given economy.

Quality equivalents (or common energy units). These are common energy units to which all primary energy inputs (ΔH) and effective energy outputs (ΔH) can be converted.