Approaches to energy quality in energy analysis

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Abstract: The concept of energy quality has been a persistent problem area, since energy analysis emerged as a separate discipline in the early 1970s. Various methods for measuring energy quality have been proposed, including: thermodynamic measures and their modern derivatives, OECD thermal equivalents and fossil fuel equivalents. Each of these methods are critically examined, and are found to be inappropriate for measuring energy quality in complex economic systems where a whole variety of processes, sources and end-uses are concurrently used. The quality equivalent methodology is introduced in the final section of the paper as a candidate method for measuring energy quality in complex economic systems, as well as providing a method for operationalising the Lovins-type end-use matching framework.

Key words: end-use matching, energy analysis, energy efficiency, energy quality.

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1 INTRODUCTION

The discipline of energy analysis involves the quantification and analysis of energy flows in complex economic systems, in contrast to the narrower focus of thermodynamics on isolated processes. For this reason a number of unique methdological problems have emerged in energy analysis, with one of the most important being the so-called 'energy quality problem'. This is the problem of taking account of the different qualities of the entire array of energy inputs and outputs involved in the energy conversion processes in economic systems. For example, it is evident that a conventionally measured joule of solar energy is not equal to a joule of electricity, as solar energy cannot usually be converted to the same proportion of useful output as electricity. Some means is required for measuring the relative quality of these energy forms, before any calculations can be performed on a common basis, e.g. in the calculation of net energy ratios of competing energy supply projects.

The purpose of this paper is to review critically the different approaches to dealing with energy quality that have emerged since energy analysis' beginnings in the early 1970s. These approaches include the traditional thermodynamic measures of energy quality and their modern derivatives, OECD thermal equivalents and fossil fuel equivalents. The usefulness, limitations and appropriateness of these energy quality numeraires are evaluated in terms of energy analysis' theoretical setting in the study of energy flows in economic systems. The quality equivalent methodology is then introduced and explained, both as a candidate method for resolving the energy quality problem and as a means of operationalising the end-use matching concept.

2 CONCEPTS OF ENERGY QUALITY

The term 'energy quality' is used in very many different ways in the technical literature. These range from physical/thermodynamic definitions, to ecological definitions to ones with more of a social-economic character to them. In broad terms, however, energy quality is most often measured in terms of some physical parameter and is seen to be an appropriate indicator of the worth or usefulness of an energy source.

Originally concepts of energy quality were drawn from the science of thermodynamics, utilising principles from the Second Law. In this respect 'energy quality' is frequently measured by various work potentials such as available work, exergy or Gibbs free energy change (ΔG) [1,2]. Similarly 'energy quality' is often said to be defined in terms of the temperature of the energy source, as according to the Kelvin formula this determines the amount of work that can be produced relative to environmental temperatures [3,4].

Another quite different approach in energy analysis, is to define energy quality in terms of what Peet and Baines [5] call 'ecosystem quality differences'. These energy quality measures attempt to account for the energy requirements for the interconversion between one energy form and another, in an ecological or economic system. In contrast to thermodynamic measures they are defined relative to the system of interest, rather than some pre-specified thermodynamic standard of measurement. This systems based approach to energy quality is the methodology advocated by Odum [6] and this author[7].

Some writers have broadened the definitional basis of energy quality even further to explicitly reflect those desirable attributes of an energy source. For example, Cronin [8] equates low quality energy with the following attributes: dispersed, low concentration, non-available, disorder and entropy; and high quality energy with the opposite attributes. Although the listing of such descriptives may have a superficial conceptual attractiveness, they don't lead to any measurable operational definition of energy quality and therefore are of no use in the context of quantitative Energy Analysis.

3 THE ENERGY QUALITY PROBLEM

One of the main thrusts of criticism of energy analysis since its emergence in the early 1970s has centred around the 'energy quality problem' [9,10,11]. It is argued that without the ability to validly compare energy of different types on a common basis, Energy Analysis cannot perform its proposed evaluative role, and therefore it will remain only of limited use in guiding policy decisions with respect to energy efficiency and other related matters.

Different forms of energy have different qualities or grades, which are not taken into account by enthalpic (ΔH) measurements. Enthalpic measurements (ΔH) 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 enthalpic terms (ΔH), cannot be 'added up' because it has different grades. This particular problem has variously been called the 'oranges and lemons' or aggregation problem of energy analysis [11]. Finally, it has been argued that because energy measured in enthalpic (ΔH) terms is not additive, energy analysis is without a numeraire, and therefore has no basis for its proposed evaluative role.

The energy quality problem is peculiar to energy analysis and does not present itself in thermodynamics. This is because thermodynamics is only concerned with energy transformation in simple systems, whereas energy analysis is concerned with energy tranformations in complex systems (multiple inputs, multiple outputs and interdependent processes). Any attempt to determine the efficient or optimal use of energy in complex systems, necessarily encounters the energy quality problem, as the analyst is confronted with comparing unlike (unequal quality) inputs and outputs. Whereas, in simple thermodynamic systems this problem does not arise as only straightforward energy conversions from one input to one output are being dealt with [12].

Outside the field of energy analysis, the 'energy quality problem' is in fact encountered whenever energy types of different qualities need to be compared or commensurated against each other. These include:

1 *National energy statistics:* When different types of energy are required to be added up when calculating the total 'energy' consumption of a country; or in determining the proportion of 'energy' supplied by different sources [13,14].
2 *End-use matching of energy sources:* This concept was proposed by Lovins [15,16], as a means of appropriately matching sources and end-uses of energy. Without a common unit of energy, however, there is no numeraire or criteria, to operationalise this theoretical construct.
3 *Economic analysis:* Aggregative measures of energy are often required in modern economic analysis, e.g. in incorporating an energy variable into production functions, in devising an energy productivity ratio (analogous to a labour or a capital productivity ratio), or in using energy:GDP ratios to trace the 'energy efficiency' performance of national economies.
4 *Net energy analysis:* Whether energy production systems actually 'produce' net energy is of critical concern when contemplating the worth of future energy supply systems (e.g. biomass or nuclear). This, however, requires that different energy inputs and outputs can be validly commensurated with each other.

4 REVIEW OF CONVENTIONAL QUALITY-NUMERAIRES IN ENERGY ANALYSIS

To resolve the energy quality problem, energy analysts have attempted to establish a number of appropriate numeraires for converting the conventional enthalpy based statistics to a common unit. The IFIAS workshop on energy analysis [17] in Stockholm explicitly addressed this question. It recommended that all energy data should be based on thermodynamic quantities of enthalpy (H), Gibbs free energy (G), and entropy (S).

The attraction of these thermodynamic quantities are that they are state functions, which means they give unique and objective measures for each prescribed set of conditions (prescribed by temperature, pressure, concentration, chemical formula, nuclear species, magnetisation, etc.). Thus for any actual change in physical conditions that results from some dynamic process, the associated change in the values of the state functions can be measured or imputed. Similarly, for a specified change in physical conditions, the minimum energy requirement can be calculated.

Other non-thermodynamic measurements of energy have been devised with respect to addressing the energy quality problem. Namely, the use of OECD thermal equivalents which are now quite commonly used in the compilation of national energy statistics – and fossil fuel equivalents devised by Odum and Odum [18]. Fossil fuel equivalents attempt to take account of the energy requirements for interconversion between one energy form and another. The use of the latter two equivalents is recognised as introducing a number of 'subjectivities' into the process of measuring energy quality. Hence there is a tendency in the literature to prefer the use of thermodynamic quantities for equivalencing energy types of different qualities because they are perceived to be more 'objective'.

Enthalpy

Most energy analyses and official statistics use enthalpy measurements of energy, although it is frequently acknowledged that the use of enthalpy measurements ignores the energy quality problem. It is often contended that enthalpy figures are good enough for the sake of obtaining 'ballpark' estimates, and further refinements are unnecessary given the indicative long term nature of many energy analyses.

Enthalpic change (ΔH) measurements are essentially a quantification of the heat content of an energy form. Heat content (ΔH) defined in this way is often used to measure energy, as in one sense it represents the maximum *quantity* of energy available for conversion to any other form of energy (i.e. all forms of energy as measured in enthalpic potential terms are 100 per cent convertible to heat (ΔH), but not 100 per cent convertible to other forms of energy such as mechanical work). However, the use of enthalpic (ΔH) measurements of energy does not take account of the *quality* of energy. No distinction is made between low quality (low efficiency) energy sources such as solar energy and higher quality (higher efficiency) energy sources such as natural gas. For example, in this instance a much greater proportion of natural gas can be converted to a useful output such as mechanical energy than solar energy.

Despite the well known deficiency of enthalpy (ΔH) measures with respect to measuring energy quality [18, 19,20]; many compilers of national energy statistics still incorrectly use such measurements. This not only gives a misleading picture of national energy supply-use patterns, but frequently leads to false analyses of macro-level statistics. For example, macro-level energy productivity studies such as that undertaken by Berndt [19] are misleading as they treat different energy inputs as homogeneous in quality terms. They are only strictly homogeneous in terms of heat equivalents, but not in terms of any sensible system-wide measure that takes account of a whole multiplicity of energy end-uses in addition to heat.

Gibbs free energy

This thermodynamic measure of energy quality is based on the second law of thermodynamics, and on the idea that energy quality can be gauged by the ability of an energy form to produce mechanical work. Although the change in Gibbs free energy (ΔG) measurement of energy takes account of energy quality in a very narrow thermodynamic sense; it cannot be applied to real-world systems which have multiple energy outputs. To do so, would wrongfully assume that the only ultimate useful (or effective) energy output is work. This clearly is not the case in modern economic systems where many other effective energy outputs such as light, sound, heat and various other outputs are required as well as work.

Practical problems also emerge in the calculation of the Gibbs free energy (ΔG) measurement, although they present no theoretical barrier to the putative role of ΔG as a measurement of energy quality. When the reactants and products are diverse, as in the making of ferro-concrete from aggregate, steel and cement; the data simply is not available for all materials involved. Where the system is extremely complex, as in the growth of plants or in human nutrition, not enough is known to estimate the entropic contribution to free energy to better than one order of magnitude, even when we can measure the enthalpic (ΔH) contribution fairly accurately.

Exergy and available work

The measurement of exergy and available work are closely related to Gibbs free energy and accordingly can also be said to be based on second law considerations, albeit a rather narrow interpretation of that law. The difference between available work and Gibbs free energy is that in the former, pressure and temperature refer to the surroundings; whereas in the case of Gibbs free energy, they refer to the reference state. Hence, it is argued by proponents of available work that this is a more realistic measurement of work, as it takes account of the physical conditions that exist in reality.

Exergy is a very similar measurement of energy, being defined by Ahern [20] as 'the work that is available in a gas, fluid or mass as a result of its non-equilibrium condition relative to some reference condition'. The reference condition usually used is sea-level atmospheric conditions, which is considered to be the sink for terrestrial energy systems.

Whilst both available work and exergy seem more appropriate measurements than Gibbs free energy change (ΔG), in that they explicitly refer to environmental conditions encountered in the economic production processes dealt with in energy analysis; they still have the same fundamental weakness of not taking account of other end-uses apart from work. However, by explicitly allowing for a 'reference condition', we are therefore seeing the movement away from 'objective' thermodynamic measurements of energy, as the energy analyst is confronted with real-world economic systems which are the context for their studies.

Temperature

The idea of using the temperature of heat sources and the temperature required to produce a desired output, has been suggested in the literature [2] as an appropriate criterion for measuring energy quality. This criterion seemingly underlies Lovins [15,16] end-use matching concept [21]. The rationale behind this idea of using temperature as the quality-numeraire seems to lie in Kelvin's formula for setting the upper limit of a Carnot engine's conversion of heat to work:

$$M = \Delta H[(t_1 - t_2)/t_1]$$

where: M is the mechanical work done by the conversion process (J); ΔH is the heat input into the conversion process (J); t_1 is the temperature of the heat input into the conversion process (K); t_2 is the temperature of the heat output from the conversion process (K).

Temperature differences between the heat source (t_1) and the heat sink (t_2), therefore limit the efficiency by which heat can be converted to mechanical work. Similar temperature defined potentialities can be shown to quantify the level of conversion efficiency between other sources and end-uses of energy and hence the attractiveness of using temperature as a numeraire for measuring the relative quality of different energy sources.

Despite the apparent simplicity and attractiveness of using temperature differences in process optimisation [4], the use of temperature does have a number of shortcomings in terms of being an appropriate measure of energy quality in energy analysis. Specifically these shortcomings include:

- Neither the Lovins [15,16] nor Linnhoff [4] temperature-based techniques, are capable of taking account of indirect energy inputs into processes. As van Gool [22] points out, the inclusion of indirect energy inputs inevitably gives rise to the 'energy quality' problem because indirect energy inputs invariably are of different types and hence qualities.
- Implicitly, in the Linnhoff, Lovins and related temperature minimisation type methods, are the assumptions of the Kelvin formula, especially if these methods are being applied to heat-to-work conversion processes. These include the unrealistic assumption that such processes operate in a perfectly reversible fashion (or equivalently stated they can be said to operate at an infinitely slow rate). Methods [23] have been proposed to overcome this shortcoming and these could be used to effectively modify the Linnhoff method in this respect.
- Although the upper limits of many processes can be defined according to temperature differentials between heat source and sink, there is at least some doubt that such differentials can be sensibly applied to all energy conversion processes of socio-economic interest [24].

OECD thermal equivalents

OECD thermal equivalents represent an attempt, albeit a very partial one, to move away from thermodynamic measures of energy quality [25]. The OECD thermal equivalents measure the relative efficiency of converting primary energy resources (coal, gas, hydro, oil, geothermal) to electricity.

They have two crucial shortcomings in terms of being satisfactory quality numeraires in energy analysis studies. Firstly, they only encompass one part of the energy conversion system that operates in modern economies – that is, those processes that convert primary energy resources to electricity. Obviously, in modern energy economies there are many more energy conversion processes operating, and there are many other required outputs apart from electricity. A comprehensive system-wide quality numeraire should take account of all of these processes and ultimately reflect the ability of primary energy inputs to be converted to the whole range of desired end-uses (heat, lighting, chemical reduction, mechanical drive and so forth). Secondly, OECD thermal equivalents do not take account of the indirect energy inputs required to convert primary energy inputs into electricity, e.g. the energy embodied in the construction of a hydro-electricity dam. If these indirect energy inputs were introduced into the calculation the 'energy quality problem' would immediately reappear as invariably such indirect inputs are of many different types and qualities.

Fossil fuel equivalents

Odum [6] made the first attempt to establish a methodology for measuring energy quality in complex economic systems; whereas the approaches described so far are only applicable to simple energy transformation to one output. Essentially, Odum attempts to measure the quality of an energy form by its embodied energy content, i.e. the amount of direct and indirect energy required to produce it. Higher quality energy (as measured by embodied energy content) is also considered to have greater amplifier effects, i.e. it can be fedback into the system to increase the flow of energy into the system.

Odum constructs a hypothetical energy hierarchy to measure the energy conversion efficiency from an energy form of 'low quality' through to energy forms of 'higher quality'. These conversion ratios are standardised by equating one of the energy forms to unity, and hence all other energy forms in the chain are expressed in terms of 'equivalents' of that energy form. The term fossil fuel equivalent (FFE) is often used by Odum [18] as he usually expresses the equivalents in terms of a notional fossil fuel. Accordingly Odum and Odum [7] have derived the following hierarchy for the United States economy:

Sunlight	0.0005 FFE
Wood	0.05 FFE
Fossil Fuel	1.00 FFE (by definition)
Energy in Elevated Water	3.00 FFE
Electricity	4.00 FFE

There are however some technical problems in operationalising Odum's approach, which have lead to its non-acceptance outside the eco-energetics school of energy analysis:

1 There is an implicit assumption, that simple straight

chains of transformation exist in reality, or at the very least that such chains have relevance to the analysis of real-world systems. The justification for this assmption is not provided by Odum in his various publications [6,18]. For example, the hierarchical chain implicit in the above data is: Sunlight → Wood → Fossil Fuel → Energy in Elevated Water → Electricity. Obviously, in complex economic systems such straight chains do not exist; rather economic systems are complex networks of energy transformation with feedback loops, which are not accounted for in the empirical side of Odum's approach [26].

2 There is an *a priori* assumption, that certain energy forms are of higher quality than others. Odum's approach provides no rigorous means of determining these energy rankings, in terms of a set of pre-specified criteria.

Another possible criticism of Odum's approach to energy quality measurement is that it fails to consider explicitly the eventual end-uses of energy, such as heating, mechanical drive, chemical reduction, lighting and so forth. Odum's flow diagrams usually stop at the delivered energy level and provide little characterisation of the end-use purpose for which his energy is used.

Summary

The thermodynamic measures of energy quality have been found to be deficient numeraires in the context of energy analysis studies. This is because fundamentally they ultimately place value only on one form of energy—either heat or some work measurement. Similarly, the OECD thermal equivalent only places value on electricity. This practice of placing value on one chosen energy form is purely arbitrary and without justification in terms of energy analysis' focus on quantifying energy flows in complex economic systems. In such systems, there is a simultaneous requirement for many end-uses of energy; such as heat, mechanical energy, refrigeration, pumping, space cooling, chemical reduction, lighting, sound propagation and so forth. In this context, it is simply inappropriate to measure the quality of an energy form by its ability to be converted to any one energy output, when obviously very many different types of energy are required.

In energy analysis there is a requirement for a systems-based approach to energy quality, given the complex interlinked conversion processes that are used in economic systems to convert primary energy forms to end uses of energy. This has been attempted by Odum [6], but unfortunately despite his stated concern with feedbacks and interlinkages of energy supply pathways, his operational methodology falls short in this crucial respect. Odum's [6] energy quality measurements are not only based on straight chains rather than complex webs, but he presents no scientifically reproducible way of uniquely determining the quality coefficients of the energy forms in these chains.

5 QUALITY EQUIVALENT METHODOLOGY

The quality equivalent methodology (QEM) was developed in an explicit attempt to resolve the energy quality problem, and to overcome some of the specific difficulties encountered in using those quality-numeraires reviewed in the previous section. Like Odum's method the QEM approach is based on a *systems perspective* of energy quality, although the exact means of commensurating the various energy forms in terms of their energy quality is distinctly different. Instead of depending on constructing hypothetical straight chains of energy transformation, the QEM depends on setting up and solving a system of simultaneous linear equations that exactly describe the energy flows and feedbacks in the economy.

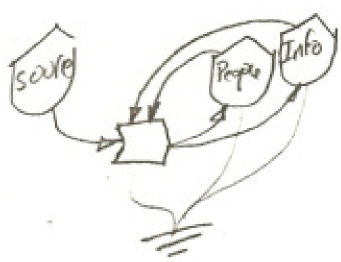
The QEM introduces a number of new concepts which are critical to the measurement and conceptualisation of the idea of energy quality in complex economic systems. These concepts are explained in this section, followed by the presentation of a simple numerical example of the application of the QEM. The QEM is outlined in greater mathematical and technical depth elsewhere [27].

Reference system: a system of simultaneous equations

In practice, the reference system is usually an actual national energy system (e.g. the 1991 United Kingdom energy system), or some postulated future national energy system (e.g. the 2020 United Kingdom energy system). It consists of a number of energy conversion processes, each represented in the QEM by an algebraic equation relating energy inputs to energy outputs. Collectively, in the QEM, these equations are treated as a system of simultaneous linear equations that can be solved by using matrix algebra techniques. The function of this reference system is to establish a reference point, for quantifying the quality of the various inputs and outputs, in terms of a common numeraire (the quality equivalent unit). Consequently this enables the relative efficiency of the constituent processes to be determined.

Conventionally the flows of energy in the reference system are described at three different levels: (i) primary energy inputs, (ii) consumer energy forms, and (iii) effective energy forms (refer to Figure 1). The primary energy inputs are the inputs into the reference system economy from external sources (from the natural resource base or from imports); the consumer energy (or delivered energy) is the various energy forms as they are delivered to the premises of end-use; and effective energy refers to the useful energy output which results from end-use processes in a given economy or reference system. Effective energy outputs only include that proportion of energy actually useful to consumers, e.g. in cooking it includes the energy absorbed into the cooking load, but not the waste heat lost to the surrounding environment.

The effective energy outputs not only serve as end-uses by directly providing consumers with services such as



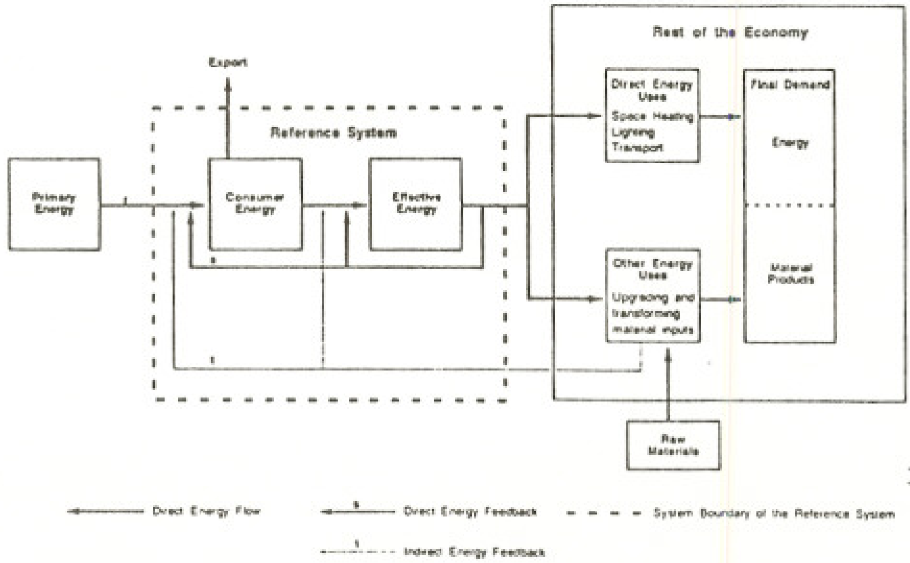


Figure 1 *Energy flows in the reference system.*

heating, lighting and personal transport; but they are also 'fedback' into the energy system. Effective energy outputs can be fedback either directly or indirectly via some material input required in the operation of an energy conversion process. An example of a *direct energy feedback* is the use of mechanical drive energy in coal mining, in driving the drag lines. Using the same example, the *indirect energy feedback* includes the energy embodied in the manufacture of the drag line equipment.

Quality equivalent unit

The quality equivalent unit (E) is central to operationalising the QEM. It is the common unit which all energy inputs (ΔH) and outputs (ΔH) can be converted to. It provides the 'measuring rod' by which all the inputs and outputs can be validly compared with each other. The quality equivalent unit is defined by solving the system of simultaneous linear equations that represent the energy flows in the reference system. In the economic literature, such 'measuring rods' or 'unit of accounts' are called numeraires; being the general value equivalent whereby all commodities are commensurated with each other.

Quality coefficients

These are determined by solving the system of simultaneous linear equations that constitute the reference system. They are expressed in terms of quality equivalent units per unit of energy (expressed in enthalpic terms), i.e. $E/\Delta H$. All inputs (ΔH) and outputs (ΔH) can be converted to quality equivalent units (E) by multiplying them by the appropriate quality coefficient ($E/\Delta H$) for that energy form.

Dualistic concept of energy quality

The quality of each energy form in the reference system is measured by its quality coefficient ($E/\Delta H$). The actual concept of quality in the QEM is dualistic, requiring the concomitant measurement of energy quality both in terms of the 'productivity of primary inputs' and the 'gross energy requirements of effective energy outputs'. It is impossible to measure energy quality rigorously solely in terms of only one of these components.

For a primary energy input its quality ($E_{out}/\Delta H_{in}$) is measured by the relative efficiency at which it is converted to effective energy outputs and other system outputs [29]. In a sense it measures the *productivity* of a particular energy input. A high quality primary input such as hydro-electricity can be converted to a higher proportion of a given mix of effective energy outputs than other inputs such as coal, and therefore is said to be more productive (efficient) than those other energy inputs.

The quality of an effective energy output ($E_{in}/\Delta H_{out}$) is the exact converse of that for a primary energy input. It is defined as the *gross energy requirements* (direct plus indirect energy inputs) needed to produce an effective energy output. A typical high quality effective energy output is therefore road transport, as it requires a considerable amount of energy inputs to produce one useful unit of output.

The situation is more complex and subtle when it comes to consumer energy forms. Without explaining the technical details, the quality of consumer energy forms can incorporate elements of their 'productivity' and their 'gross energy requirements' [refer to Figure 2] [30].

A simple numerical example

A simple example can be used to demonstrate the application of the QEM, in resolving the energy quality problem and for measuring the quality of energy forms in complex economic systems. This example involves 9 energy forms (3 primary inputs, 3 consumer energy forms and 3 effective energy outputs) and 11 energy conversion processes. To

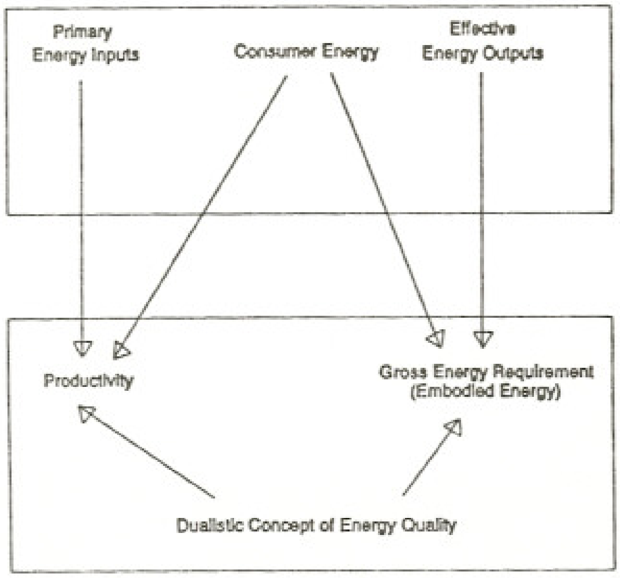


Figure 2 *The dualistic concept of energy quality in the QEM.*

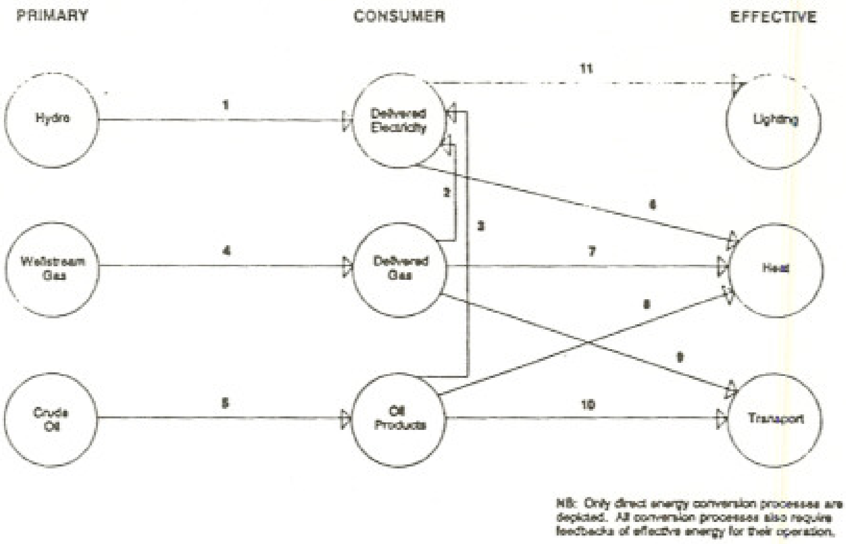


Figure 3 *Energy conversion processes in the reference system example.*

obtain meaningful results, for most economies the reference system would need to contain in the order of 20–30 energy forms and about 40–50 processes.

The following energy conversion processes describe the energy flows in the national reference system, with the enthalpic efficiency of the main direct energy flows indicated in the square parenthesis (refer to Figure 3):

1	Hydro-electricity → delivered electricity	[100%]
2	Delivered gas → delivered electricity	[33%]
3	Oil products → delivered electricity	[25%]
4	Wellstream gas → delivered gas	[87.5%]
5	Crude oil → oil products	[80%]
6	Delivered electricity → heat	[100%]
7	Delivered gas → heat	[75%]
8	Oil products → heat	[60%]
9	Delivered gas → transport	[15%]
10	Oil products → transport	[10%]
11	Delivered electricity → lighting	[10%]

Algebraic equations can be used to describe the direct and indirect energy inputs (ΔH) and the outputs (ΔH) of each of these conversion processes. In the following equations, the inputs are arranged on the left-hand side and the output on the right-hand side, with the direct and indirect *feedback* inputs indicated by dashed underlining (-----):

1 $\quad a_1 13.50 + c_1 \underline{0.10} + c_2 \underline{0.20} + e_1 = b_1 13.50$

2 $\quad b_3 6.00 + c_2 \underline{0.02} + e_2 = b_1 2.00$

3 $\quad b_2 2.00 + c_1 \underline{0.80} + c_2 \underline{0.01} + e_3 = b_1 0.50$

4	$a_2 16.00 + c_2 \underline{0.01} + e_4 = b_3 14.00$
5	$a_3 125.00 + c_1 \underline{0.20} + e_5 = b_2 100.00$
6	$b_1 6.00 + c_2 \underline{0.04} + e_6 = c_1 6.00$
7	$b_3 4.00 + c_2 \underline{0.03} + e_7 = c_1 3.00$
8	$b_2 8.00 + c_2 \underline{0.10} + e_8 = c_1 4.80$
9	$b_3 4.00 + c_1 \underline{0.04} + e_9 = c_2 0.60$
10	$b_2 80.00 + c_1 \underline{0.04} + e_{10} = c_2 8.00$
11	$b_1 10.00 + c_2 \underline{0.04} + e_{11} = c_3 1.00$

In these equations the quality coefficients for the various energy forms are represented by:

a_1 = hydro-electricity;
a_2 = wellstream gas;
a_3 = crude oil;
b_1 = delivered electricity;
b_2 = oil products;
b_3 = delivered gas;
c_1 = heat;
c_2 = transport;
c_3 = lighting.

The symbols $e_1 \ldots e_{11}$ represent the residuals of each conversion process – if all processes were equally efficient all these residuals would equal zero.

The system of simultaneous linear equations can be solved and be expressed in terms of multiples of any of the energy forms (in this case in terms of delivered electricity equivalents):

a_1 = 0.9477 (hydro-electricity)
a_2 = 0.3755 (wellstream gas)
a_3 = 0.2509 (crude oil)
b_1 = 1.0000 (delivered electricity)
b_2 = 0.3152 (oil products)
b_3 = 0.4314 (delivered gas)
c_1 = 0.7813 (heat)
c_2 = 3.1403 (transport)
c_3 = 10.1256 (lighting)

This transitive scale of energy quality shows that hydro-electricity (0.9477 $E/\Delta H$) is the most productive primary energy input followed by wellstream gas (0.3755 $E/\Delta H$) and then by crude oil (0.2509 $E/\Delta H$) [31]. On the end-use side, lighting (10.1256 $E/\Delta H$) is the highest quality effective energy output having the highest gross energy requirements, followed by transport (3.1403 $E/\Delta H$) and then by heat (0.7813 $E/\Delta H$).

All processes are not equally efficient

One of the significant implications of solving these equations, is that it becomes evident that not all processes are equally efficient at converting inputs to outputs. The relative efficiency (Φ) for each process can be calculated, by dividing the outputs (E_{out}) by the inputs (E_{in}) of each conversion process:

		Relative efficiencies	*Residuals*
1	Hydroelectricity → delivered electricity	$\Phi_1 = 1.0000$	$e_1 = 0$
2	Delivered gas → delivered electricity	$\Phi_2 = 0.7544$	$e_2 = -0.6512$
3	Oil products → delivered electricity	$\Phi_3 = 0.3885$	$e_3 = -0.7869$
4	Wellstream gas → delivered gas	$\Phi_4 = 1.0000$	$e_4 = 0$
5	Crude oil → oil products	$\Phi_5 = 1.0000$	$e_5 = 0$
6	Delivered electricity → heat	$\Phi_6 = 0.7652$	$e_6 = -1.4381$
7	Delivered gas → heat	$\Phi_7 = 1.2879$	$e_7 = 0.5239$
8	Oil products → heat	$\Phi_8 = 1.3224$	$e_8 = 0.9142$
9	Delivered gas → transport	$\Phi_9 = 1.0725$	$e_9 = 0.1273$
10	Oil products → transport	$\Phi_{10} = 0.9950$	$e_{10} = -0.1273$
11	Delivered electricity → lighting	$\Phi_{11} = 1.0000$	$e_{11} = 0$

Processes that have relative efficiencies greater than one ($\Phi > 1$) are more efficient than the system's average, and those that have relative efficiencies less than one ($\Phi < 1$) are less efficient than the system's average.

Using these relative efficiencies, end-uses and energy sources can be 'matched', in accordance with the type of theoretical idea proposed by Lovins. For example, the most efficient means of providing heat is by using oil products ($\Phi_8 = 1.3224$) and the most efficient means of providing transport is by using delivered gas ($\Phi_9 = 1.0725$). Conversely the data highlights that electricity is never the most efficient way of providing heat, as is reflected in the relative efficiency for converting delivered electricity to heat ($\Phi_6 = 0.7652$). Instead of converting oil products or gas to electricity and then electricity to heat, it is more efficient to use oil products or gas directly in producing heat.

It can also be noted from this illustrative example that the relative efficiency of some of the processes equal one (the system's average). This is for the simple reason that each of these processes are the only processes, either producing a direct output or using a direct input – that is, they have no other competitive processes, so therefore not surprisingly their relative efficiencies must equal one.

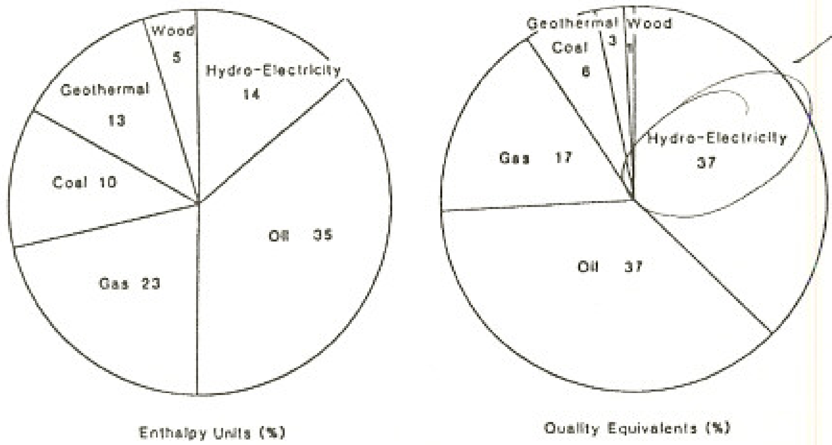


Figure 4 *Primary energy inputs into the 1984 New Zealand economy.*

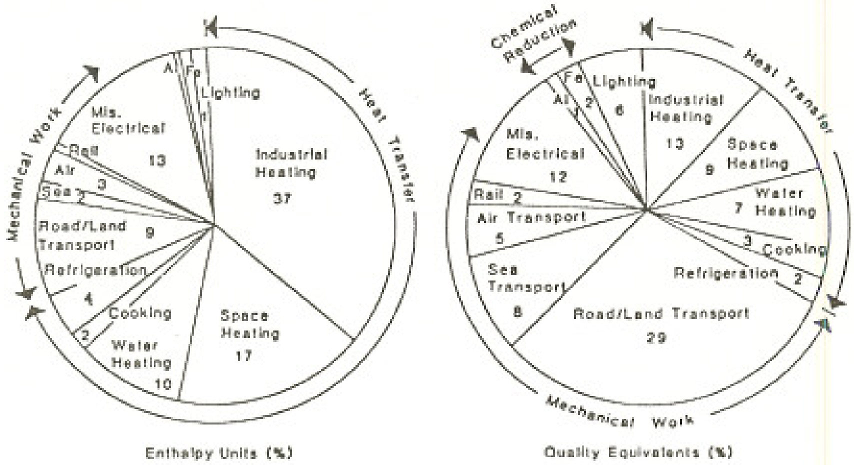


Figure 5 *End-uses of energy in the 1984 New Zealand economy.*

Different picture of energy use in the economy

The conventional way to present data on energy use in the economy is to use enthalpic statistics, although occasionally partial adjustments are made for energy quality by using OECD thermal equivalents. A more comprehensive adjustment however, can be made by using the quality coefficients ($E/\Delta H$) derived from the QEM.

Such an adjustment for energy quality, usually gives rise to a very different picture of energy flows in the economy (refer to Figures 4 and 5). For the 1984 New Zealand economy this is most markedly the case for the primary energy inputs. For example, in enthalpic terms, hydro-electricity is only 14 per cent of the total input compared with 37 per cent when it is expressed in quality equivalent terms. The enthalpic-based statistics do not take account of the fact that hydro-electricity is a relatively efficient (high quality) input and they thereby 'under-estimate' its contribution in producing desired end-uses of energy in the economy. Conversely, the enthalpic based statistics 'over-estimate' the contribution of low quality energy inputs such as coal, geothermal and wood inputs.

Similarly, in terms of the effective energy outputs, the enthalpic based statistics give rise to a different representation of the end-use of energy. The enthalpic statistics usually ignore the fact that a considerable amount of energy is required to produce the higher quality mechanical work outputs, and consequently they 'under-estimate' their total value. For example, for the 1984 New Zealand economy, the enthalpic based statistics indicate that 18 per cent of the end-uses are for various forms of mechanical work whereas the quality equivalent statistics indicates a contribution of 50 per cent.

6 CONCLUSION

If energy analysis is to fulfil its evaluative role then the energy quality problem must be satisfactorily resolved [32]. It is critical that any resolution of this methodological problem must be capable of taking account of the complex nature of energy flows and feedbacks in modern economies. So called 'objective' thermodynamic measures fall short in this critical respect, as they ultimately place value on one arbitrary chosen standard (usually some work potential). This has no more theoretical validity than the use of the discarded gold standard had in economics. Quite simply, energy is valued for many other end-use purposes apart from mechanical work. Instead, a systems-based approach is required to take account of both the complexity of energy flows in economic systems and the whole multiplicity of required end-uses. In this paper the quality equivalent methodology is presented as a candidate method for meeting the need for such an approach.

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21 It is not entirely certain if Lovins [15] equates temperature with energy quality, despite devoting all of chapter 4 of his book to the subject of energy quality. However, this is the clear implication of the way the data is presented and interpreted in this chapter.

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26 The irony is that Odum in his various books lays great emphasis on complexity of energy flows in economic and ecological systems with his flow diagrams and analyses highlighting complex webs rather than linear chains of energy flow. When it comes to enumerating energy quality this distinction seems to be curiously lost as exemplified by the following passage from Odum [6, p. 15] 'Real systems form webs rather than chains, but the energy changes are similar'. Why the energy changes are presupposed to be 'similar' is not explained.

27 Full mathematical and technical details are outlined in a published journal article [7] and this author's PhD Thesis [28]. A full exposition of the methodology is about to be published in a forthcoming monograph.

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29 In some cases, consumer energy outputs are also system outputs, e.g. when refined oil is exported to another country.

30 A formula can be used for calculating the exact contributions of the 'productivity' and 'gross energy requirements' factors, in determining the quality of consumer energy forms. However, this formula requires an understanding of the distinction between 'basic' and 'non-basic' energy forms which is beyond the technical scope of this paper.

31 Odum's [6] straight chain energy quality factors cannot ever be transitive except by a rare chance event, because the equivalencing process only involves equating one energy input into one energy output, instead of simultaneously equivalencing energy inputs and outputs of many processes across the entire system. No general transitivity can be guaranteed using Odum's [6] piecemeal approach, as there are numerous possible permutations for generating his "energy hierarchies" and no one unique way.

32 The resolution of the energy quality problem is also critically important, when aggregative measures of energy are required to be used in economic analyses.