Estimation of the quality of energy sources and uses

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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 ($\triangle H$) 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 ($\triangle H$) 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 problem[3] 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:

[1] A 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.

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$$m_1 \sum_{i=1}^{i=j} (Y_1)_i + m_2 \sum_{i=1}^{i=j} (Y_2)_i + \ldots m_n \sum_{i=1}^{i=j} (Y_n)_i \qquad (1)$$

$$= n_1 \sum_{i=1}^{i=j} (X_1)_i + n_2 \sum_{i=1}^{i=j} (X_2)_i + \ldots n_n \sum_{i=1}^{i=j} (X_n)_i$$

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 ($Y_1 \ldots . Y_n$) and the primary energy inputs ($X_1 \ldots .. X_n$) are known. The quality coefficients of the effective energy outputs ($m_1 \ldots .. m_n$), and the quality coefficients of the primary energy inputs ($n_1 \ldots .. n_n$) 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:

$$\sum_{i=1}^{i=j} -(X_1)_i = n_2 \sum_{i=1}^{i=j} (X_2)_i + \ldots .. n_n \sum_{i=1}^{i=j} (X_n)_i + \qquad (2)$$

$$m_1 \sum_{i=1}^{i=j} -(Y_1)_i + m_2 \sum_{i=1}^{i=j} -(Y_2)_i +$$

$$\ldots .. m_n \sum_{i=1}^{i=j} -(Y_n)_i$$

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 ($m_1 \ldots .. m_n$, $n_1 \ldots .. n_n$). 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]

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[2] G. Leach, 'Net energy analysis – is it any use?', *Energy Policy*, Vol 3, No 4, 1975, pp 332–334.

[3] The 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.

[4] International Federation of Institutes for Advanced Study, *Energy Analysis Workshop on Methodology and Conventions*, IFIAS, Stockholm, 1974.

[5] For 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 texts[6] and are outputed 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 ($X_1 \ldots X_n$, $Y_1 \ldots Y_n$) should form the basis of this 'experimentation'. The original classifications may not necessarily be the 'best' way of classifying the inputs ($X_1 \ldots X_n$) and outputs ($Y_1 \ldots Y_n$) 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.

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[6] For 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* ($X_1....X_n$) and all *outputs* ($Y_1....Y_n$) have *intrinsic quality coefficients.*

This hypothesis will hold true in any system or economy where the outputs are proportional[7] 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 dissaggregate 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 notional[9] 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

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[7] Multiple linear regression assumes linear proportionalities. For non-linear proportionalities non-linear multiple regression should be used.

[8] Time 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.

[9] A regression model based on actual energy use in the New Zealand economy has also been successfully constructed.

[10] Historical 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.

[11] 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.

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

[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.

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) $\text{Coal} \xrightarrow{\text{gasification}} \text{Methanol} \xrightarrow{\text{Mobil process}} \text{Gasoline}$

(2) $\text{Coal} \xrightarrow{\text{gasification}} \text{Methanol}$

(3) $\text{Coal} \xrightarrow{\text{hydrogenation}} \text{Crude oil} \rightarrow \text{Gasoline, diesel}$

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

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[12] The 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.

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]

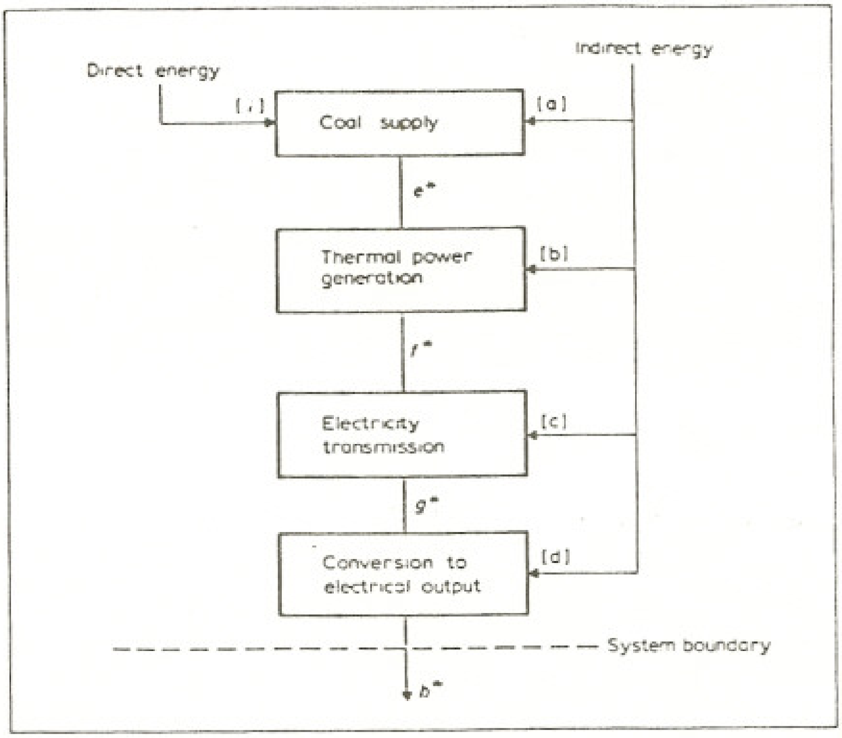
From these data the GER of each pathway was estimated, and normal-

[15] 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. It is also expected that in some instances considering multiple outputs could lead to the problem of correlation between variables.

[16] New Zealand Ministry of Energy, Energy data files, Wellington, New Zealand, 1978–81.

[17] New 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).

[18] A.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.



* 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.

$$\mathrm{GER} = \left(\frac{\frac{\frac{[a]}{e^*}}{f^*}}{g^*}\right) + \left(\frac{\frac{\frac{[i]}{e^*}}{f^*}}{g^*}\right) + \left(\frac{\frac{[b]}{f^*}}{g^*}\right) + \left(\frac{[c]}{g^*}\right) + \left([d]\right)$$

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_1 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:

$n_2 = 1$, *F* ratio = 13.43, gas equivalents
$n_3 = 1$, *F* ratio = 10.75, oil equivalents
$n_4 = 1$, *F* ratio = 8.00, coal equivalents

Table 2. Data set: gross energy requirements of energy supply–use pathways in an energy efficient New Zealand economy.

	Primary energy inputs (MJ)[a]					Effective energy outputs (MJ)[a,b]						
Pathway	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

[a] Expressed in enthalpy (ΔH) terms; 1 kWh = 3.6 MJ.
[b] Normalized 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 → 1.46 hydroelectricity equivalents
1MJ of high grade transport output → 3.71 hydroelectricity equivalents
1MJ of medium grade transport output → 3.06 hydroelectricity equivalents
1MJ of industrial heat → 0.59 hydroelectricity equivalents
1MJ of water heating → 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

[a] Expressed in terms of hydroelectricity equivalents per MJ of input or output.
[b] By 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 ratios[20] 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.

[19] For example, it could mean that if this amount was to come entirely from wood, the following amount of energy would be required:

$$1\text{MJ of output} = \frac{3.71 \text{ hydroelectricity equivalent}}{0.51 \text{ hydroelectricity equivalent MJ}^{-1}} = 24.73 \text{ MJ}$$

[20] $\text{Net energy ratio} = \frac{\text{GER of systems output}}{\text{GER of systems input}}$

[21] W.B. Earl, 'Methanol from wood in New Zealand', in *Alcohol Fuels*, Institution of Engineers, University of Sydney, Sydney, Australia, 1978, pp 517–521.

[22] M. Slesser and C. Lewis, *Biological Energy Resources*, Spon, London, 1979, Table 5.5.

[23] P.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 resources[25] 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]

Preliminary consideration of the technique's use in energy analysis

By using the technique described in this paper, an intrinsic[28] 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

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[24] IFIAS, 1974, *op cit*, Ref 3. It is recommended that for 'developed or industrialized economies' the energy associated with labour should not be considered.

[25] M. 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.

[26] These 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).

[27] J.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.

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.

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[29] These 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).

[30] In 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.