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What is energy efficiency?

Concepts, indicators and methodological issues

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This paper critically reviews the range of energy efficiency indicators that can be used, particularly at the policy level. Traditional thermodynamic indicators of energy efficiency were found to be of limited use, as they give insufficient attention to required end use services. The specific limitations and appropriate uses of physical-thermodynamic, economic-thermodynamic and pure economic indicators of energy efficiency are also considered. The paper concludes with a discussion of the persistent methodological problems and issues which are encountered when attempting to operationalize all of the energy efficiency indicators. These include the role of value judgements in the construction of energy efficiency indicators, the energy quality problem, the boundary problem, the joint production problem and the question of isolating the underlying technical energy efficiency trend from the aggregate indicator. Copyright © 1996 Elsevier Science Ltd.

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Energy efficiency now has an important place in the public policy agenda of most developed countries. The importance of energy efficiency as a policy objective is linked to commercial, industrial competitiveness and energy security benefits, as well as increasingly to environmental benefits such as reducing CO_2 emissions. Despite the continuing policy interest and the very many reports and books written on the topic of 'energy efficiency', little attention has been given to precisely defining the term.[1] The purpose of this paper is therefore to open up this debate, by critically reviewing the range of possible energy efficiency definitions and how they can be operationalized by the use of indicators. The methodological problems and issues which are then encountered when attempting to operationalize such definitions will also be discussed.

Energy efficiency is a generic term, and there is no one unequivocal quantitative measure of 'energy efficiency'. Instead, one must rely on a series of indicators to quantify changes in energy efficiency. In general, energy efficiency refers to using less energy to produce the same amount of services or useful output. For example, in the industrial sector, energy efficiency can be measured by the amount of energy required to produce a tonne of product. Hence, energy efficiency is often broadly defined by the simple ratio:[2]

$$\frac{\text{Useful output of a process}}{\text{Energy input into a process}}$$

The issue then becomes how to precisely define the useful output and the energy input, which in turn gives rise to a number of important methodological considerations which are often ignored in the literature.

A number of indicators can be used to monitor changes in energy efficiency. These fall into four main groups:

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[1] For example, in New Zealand, three recent reports on energy efficiency have been released by the Ministry of Commerce (Harris *et al*, 1992) the Electricity Corporation of New Zealand (ECNZ, 1993) and the New Zealand Planning Council (Terry, 1991). None of these reports, however, has explicitly defined the term energy efficiency.

[2] The 'useful output' of the process need not necessarily be an energy output. It could be a tonne of product or some other physically defined output, or it could be the output enumerated in terms of market prices. Energy efficiency indicators sometimes involve ratios that reverse the numerator and the denominator. For example, the energy:GDP ratio, commonly used as an indicator of 'energy efficiency' (eg Wilson *et al*, 1994), is constructed in this way. It could be argued, by reversing the numerator and the denominator, that an 'energy intensity' ratio is now being constructed. However, as such ratios implicitly contain information about the energy efficiency of a process, they are therefore covered in this review of energy efficiency indicators.

1. Thermodynamic: these are energy efficiency indicators that rely entirely on measurements derived from the science of thermodynamics. Some of these indicators are simple ratios and some are more sophisticated measures that relate actual energy usage to an 'ideal' process.
2. Physical-thermodynamic: these are hybrid indicators where the energy input is still measured in thermodynamic units, but the output is measured in physical units. These physical units attempt to measure the service delivery of the process – eg in terms of tonnes of product or passenger miles.
3. Economic-thermodynamic: these are also hybrid indicators where the service delivery (output) of the process is measured in terms of market prices. The energy input, as with the thermodynamic and physical-thermodynamic indicators, is measured in terms of conventional thermodynamic units.
4. Economic: these indicators measure changes in energy efficiency purely in terms of market values ($). That is, both the energy input and service delivery (output) are enumerated in monetary terms.

Thermodynamic indicators

In one sense, thermodynamic indicators of energy efficiency seem to be the most natural or obvious way to measure energy efficiency, as thermodynamics nowadays is often defined as the science of energy and energy processes. Surprisingly, though, thermodynamic measures of energy efficiency are not as satisfactory measures of energy efficiency as they might at first appear. There are good methodological and operational reasons for not wholeheartedly accepting the use of thermodynamic measures of energy efficiency which are discussed later on in this paper.

However, one attraction of using thermodynamic quantities for measuring energy efficiency is that they are calculated in terms of 'state functions' of the process. This means that they provide unique and objective measures for a given process in the context of a particular environment (prescribed by temperature, pressure, concentration, chemical formula, nuclear species, magnetization etc). Thus for any change in physical conditions that results from some dynamic process, the associated change in the values of the state functions can be uniquely measured or imputed. Similarly, for a specified change in physical conditions, the minimum energy requirement can be unequivocally calculated.

First-law energy efficiency

First-law efficiency is also referred to as thermal efficiency or enthalpic efficiency. This is because it measures efficiency in terms of the heat content of the inputs and outputs of the process, and 'heat content' is measured in terms of enthalpic change values (ΔH).

The enthalpic efficiency ratio for any process is therefore the ΔH value of the useful output of the process, divided by the ΔH value of the inputs of the process:

$$E_{\Delta H} = \frac{\Delta H_{\text{out}}}{\Delta H_{\text{in}}}$$

where

$E_{\Delta H}$ = enthalpic efficiency
ΔH_{out} = sum of the useful energy outputs of a process (ΔH)
ΔH_{in} = sum of all of the energy inputs into a process (ΔH)

It is important to realize that the enthalpic efficiency indicator only measures the 'useful' output – for example, an incandescent light bulb has an enthalpic efficiency of about 6%. In this process, only 6% of the input of electricity (ΔH) is converted to light energy, with the other 94% being lost to the environment as 'waste' heat. If the 'waste' output of any process is added to the 'useful' output of any process, the total output then equals the total inputs, when the energy is measured in enthalpic terms. In essence, this is another way of stating the first law of thermodynamics – ie that in any conversion process, energy cannot be created or destroyed. For this reason, enthalpic efficiency is often called first-law efficiency.

The use of enthalpic (ΔH) measurements of energy does not take account of the quality of energy. No distinction is made between high quality energy sources which are more useful and productive, and low quality energy sources which are less useful and productive. For example, one unit of electricity (high quality energy) is implicitly assumed to have the same usefulness as solar energy (low quality energy). Despite this well-known deficiency of enthalpy (ΔH) measures with respect to energy quality, many analysts, such as Sioshansi (1986) and Schurr (1984) still use these measures in macro-level energy efficiency studies. Such studies are misleading as they treat different energy inputs as being homogeneous in quality terms. They are only strictly homogeneous in terms of heat equivalents, but not in terms of any sensible system-wide quality measure that takes account of other energy end uses apart from heat.[3]

Second-law energy efficiency (using work potentials to adjust for energy quality)

A significant problem with first-law energy efficiencies is that they do not take account of the energy quality of the inputs and the useful outputs. Therefore, if either the inputs or useful outputs of the two processes are of different qualities you cannot meaningfully compare their relative energy efficiencies. You are comparing 'apples' with 'oranges'.

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[3] Patterson (1983, 1993a) has proposed the quality equivalent methodology to measure energy quality in complex economic systems where there are many desired end uses of energy apart from just heat.

A number of thermodynamic quality numeraires[4] can be used to convert the input denominator (ΔH_{in})[5] in the thermal efficiency ratio to common quality units, in an attempt to overcome this problem of energy quality. These quality numeraires are based on second-law considerations. First, it has been suggested by the International Federation of Institutes for Advanced Study (1974) among others, that Gibbs free energy change (ΔG) be used to measure the relative energy quality of inputs. When a process is carried out at constant temperature and pressure, the decrease in Gibbs free energy represents the maximum work that can be done by a process. This decrease in Gibbs free energy (ΔG) is defined by:

$$\Delta G = \Delta H - T\Delta S$$

where:

ΔG = change in Gibbs free energy
ΔH = change in enthalpy
T = temperature
ΔS = change in entropy

Other work potentials that could be used to commensurate the energy quality of the inputs include exergy and available work. The difference between available work and Gibbs free energy is that in the former, pressure and temperature refer to the surroundings, whereas in 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 work potential being defined by Ahern (1980) 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 most commonly used is sea-level atmospheric conditions, which is considered to be the sink for terrestrial energy systems.

While both available work and exergy might seem to be more appropriate than Gibbs free energy change (ΔG), in that they explicitly refer to environmental conditions encountered in economic production processes, they still present a number of fundamental problems. First of all, 'work' is not the only useful desired energy output in the economy, with modern economies having a significant end use demand for heat. Second, it is unclear what type of work should be used as the quality numeraire, and this is important as not all forms of work (chemical, electrical, mechanical etc) are the same or necessarily commensurable with each other. If mechanical work is selected as the quality numeraire, as is often suggested, there is no sound theoretical basis for this selection, as again mechanical work is only one of the many desired energy outputs in modern economies. Ultimately, therefore, it is argued that the call for commensurating energy inputs (ΔH_{in}) in terms of some work potential still does not provide a rigorous solution to the energy quality problem which is encountered in using first law energy efficiency indicators.

Second-law energy efficiency (ideal limits)

Another approach is to define energy efficiency relative to the 'ideal' minimum energy required to undertake a task. In mathematical terms, this 'ideal' efficiency can be defined by the following ratio:

$$\rho = E_{\Delta H(\text{actual})}/E_{\Delta H(\text{ideal})}$$

where

ρ = second-law efficiency of a process in performing a specified task
$E_{\Delta H(\text{actual})}$ = actual enthalpic efficiency of a process in performing a specified task
$E_{\Delta H(\text{ideal})}$ = ideal enthalpic efficiency to perform a task reversibly by a perfect device

This ratio can therefore be used to measure how close a real world energy conversion process is to the ideal efficiency, where the most efficient process possible has an efficiency of $\rho = 1$. Often the Kelvin formuia, for the conversion of heat to work, is used in these calculations:

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

where

M = mechanical work done by a conversion process (J)
ΔH = heat input into the conversion process (J)
t_1 = temperature of the heat input into the conversion process (K)
t_2 = 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 ideal level of conversion efficiency, between other sources

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[4] It has also been suggested in the thermodynamic literature (eg Groscurth *et al*, 1989; Horsley, 1993) that temperature is an appropriate quality numeraire. The rationale for using temperature as a quality numeraire seems to relate to the Kelvin formula which sets the upper limit for a Carnot engine's conversion of heat to mechanical work. According to this formula, temperature differences between the heat source (t_1) and sink (t_2) define the maximum efficiency of converting heat to mechanical work. In essence, therefore, using temperature in this way is tantamount to using maximum mechanical work as the quality numeraire. Hence, the following discussion in so far as it relates to using mechanical work potentials as quality numeraires also applies to using temperature as a quality numeraire.

[5] The literature and hence this discussion focuses on the commensuration of energy inputs (ΔH inputs) in terms of their energy quality. However, the energy quality problem also occurs when you try to compare two processes with different outputs. The outputs also need to be commensurated in terms of their energy quality, to enable the valid comparison of the relative energy efficiencies of the two processes.

and end uses of energy besides the standard conversion of heat to mechanical work (Offen, 1978). For example, by using the Kelvin formula, the maximum enthalpic efficiency of converting heat to electricity can be calculated at $E_{\Delta H(\text{ideal})} = 71.2\%$ ($t_1 = 1000$ K, $t_2 = 288$ K), and this can be compared with an actual enthalpic efficiency of New Zealand power stations of about 30%. Hence, the second-law efficiency (ρ) in this instance is 30%/71.2% = 42%.

Second-law efficiency (ρ) measures can be applied to a wide range of processes including chemical (Gyftopoulos *et al*, 1974; Sussman, 1977), transport (Berry and Fels, 1973), heat transfer (Bejan, 1980; Kay and Scholenhls, 1980), refrigeration, air conditioning and electric drive. A practical but not theoretical problem with establishing the ideal minimum energy requirements of processes is that for some processes it is not exactly clear if such calculations can be carried out in an unambiguous fashion yielding a unique result (Jaynes, 1989). Frequently, the strategy is to adapt the Kelvin formula to processes that do not have mechanical energy as their output (eg to the process of electricity generation as explained above) or to processes that cannot be strictly considered to be heat engines. In other circumstances various other methods can be used to define the minimum energy requirements of a task. For example, Slesser (1982) cites the use of Betz's theory to determine the maximum efficiency of a wind turbine.

While second-law efficiencies based on defining the ideal limits of processes are useful in pointing to the theoretical energy savings that can be achieved by engineering and technical improvements, they are restricted in their applicability to real world systems. The first limitation of the method is that it fundamentally assumes perfect reversibility, which is equivalent to assuming infinitely slow processes. Obviously real world processes are required to occur in finite time periods – a chemical engineer requires a chemical reaction to take place within a specified time period if it is to be of any economic value; and all engines in actual operating conditions, must consider human impatience, which in turn introduces a whole series of unavoidable losses such as friction losses.

Andresen *et al* (1977) and Wu (1988) have, however, developed optimization methods to overcome this assumption of perfect reversibility (infinitely slow processes) which is used in the calculation of 'ideal' energy efficiencies. This method, termed 'finite time thermodynamics', contains a minimum set of constraints that engines can accept. It can be argued that by moving away from infinite time classical thermodynamics Andresen *et al* (1977) have explicitly accepted that so-called subjective factors such as 'human impatience' are of importance in calculating energy efficiency. The usefulness of their method, however, is that it makes explicit the trade off between time constraints and energy use.

The second limitation of the 'ideal limit' method of energy efficiency definition is that it is not capable of taking account of indirect energy inputs. Van Gool (1980) makes this point by citing a number of examples including, for instance, the case of increasing the length of a heat exchanger to recover a higher fraction of available heat. Usually, but not always, there is an optimum point between increasing capital equipment to 'save' process energy, and the energy 'lost' in the indirect energy embodied in the extra capital equipment. The 'ideal limit' method is incapable of considering such factors. Essentially, by including indirect energy inputs, the 'energy quality problem' is once again encountered, as almost inevitably there will be a multiplicity of different types of energy inputs that need to be somehow equivalenced.

Physical-thermodynamic indicators[6]

One criticism of traditional thermodynamic indicators of energy efficiency is that they do not adequately encapsulate the end use service required by consumers in the output measurement. That is, the numerator in the thermodynamic efficiency ratios measure either heat content (in the first-law efficiency), or some work potential (in second-law efficiencies). Consumers, of course, do not value the end use service on the basis of its heat content or work potential. Therefore, energy analysts have developed efficiency ratios that measure the output in physical units rather than in thermodynamic terms. These physical units are specifically designed to reflect the end use service that consumers require. For example, the desired output of freight transport is the carriage of a given mass of freight over a given distance – this output can therefore be measured by tonne kilometres. Hence, an appropriate energy efficiency measure for freight transport could be:

$$\frac{\text{Output (tonne kilometres)}}{\text{Energy input } (\Delta H)}$$

One advantage of using these physical measures is that they can be objectively measured, just as thermodynamic measures can, but they also have the added advantage that they directly reflect what consumers are actually requiring in terms of an end use service. Because they are physical measures, these can readily be compared in longitudinal (time series) analyses. That is, difficulties are not encountered in time series studies, as happens in the use of economic indicators of energy efficiencies, due to changes in market values. A tonne kilometre or a tonne of product is always a tonne kilometre or a tonne of product, whereas the market value ($) of a tonne kilometre or tonne of product can change quite markedly over long time periods.

If hybrid physical-thermodynamic measures of energy efficiency are to be used, it is appropriate that they be developed on a sectoral basis, as different sectors tend to have different industry based standards for specifying their outputs. In the residential and commercial sectors, the most frequently

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[6] Purely physical indicators of energy efficiency can also be developed eg litres of fuel oil/tonne of butter. These purely physical indicators are quite limited for comparative purposes, as they can only validly be used for records which have the same units for the denominator and numerator.

used measure is energy input/square metre, although this does present several problems when it is used to measure the aggregate energy efficiency performance of buildings. Accordingly the energy input/square metre indicator is sometimes adjusted to take account of degree days (as a significant proportion of energy use in buildings involves space heating/ cooling) and to take account of hot water usage. The Joint Economic Committee of the US Congress (1981) suggested that cubic metres are a better measure than square metres, although such data are difficult to obtain from official statistics. The fundamental problem with either the energy input/m^2 or energy input/m^3 indicator, is that they are predicated on the idea that the main services delivered to buildings are HVAC and lighting, and that these are directly proportional to square or cubic metres. Building structures, particularly residential buildings, are the focus for the delivery for many other energy services eg water heating, cooking and mandatory electrical services. Hence, for the residential sector it may be appropriate to also develop indicators for measuring the efficiency of delivery of cooking and water heating services eg:

(1) energy input/cooking heat delivered, to a specified temperature;
(2) energy input/water heating delivered, to a specified temperature.

Different types of physical-thermodynamic indicators can be developed for the transport sector. The output measurements need to reflect the objective of the specific type of transport activity. For freight transport, an appropriate indicator is therefore energy input/tonne kilometres, as the function of freight transport is to move a freight mass (measured by tonnes) over a given distance (measured by kilometres). For passenger transport, energy input/passenger kilometres or energy input/vehicle kilometres may be appropriate indicators of energy efficiency. It has been suggested by Collins (1992) that energy input/vehicle kilometres is an inappropriate indicator, as the objective of passenger transport is to move people across distances, not to move vehicles which may be near empty across distances. It can also be argued that for many transport operations, the objective is not tonne kilometres or passenger kilometres, but rather tonne kilometres or passenger kilometres per unit time. This is because speed and the necessity to minimize transport time is the essence of much freight and passenger movement. Therefore, it could be argued that transport energy efficiency indicators should be adjusted to take account of this speed objective which is applicable to many transport operations.

Due to the relative heterogeneity of both the industrial and agricultural sectors, in terms of the very different products produced by various industries, any attempt to devise an aggregative physical output measurement is futile. For most industries the product can be measured in terms of its mass – eg tonnes of butter, tonnes of bricks, tonnes of wheat, tonnes of aluminium. Hence appropriate indicators may be:

(1) energy input/tonne of butter;
(2) energy input/tonne of bricks;
(3) energy input/tonne of wheat;
(4) energy input/tonne of aluminium.

For other industries, volumetric output measurements may be appropriate – eg litres of milk, cubic metres of wood or timber, litres of oil. In each case the standard industry measure needs to be applied, and care must be taken in precisely defining the output – eg some industries use oven dry tonnes to measure output rather than tonnes that are inclusive of water content.

The measurement of energy efficiency in terms of physical-thermodynamic indicators is not as straightforward as it first appears because of the so-called joint production or partitioning problem. This refers to the difficulty in allocating one energy input to several outputs in an industry. For example, a given amount of energy input (ΔH) is required to produce essentially two products from a sheep farm: wool (tonnes) and meat (tonnes). The problem arises when the energy input (ΔH) has to be allocated to the different outputs (tonnes) in order to generate the desired indicators.

Economic-thermodynamic indicators

These indicators are hybrid indicators, with the energy input being measured in thermodynamic units and the output being measured in terms of market prices ($). That is, instead of the output being measured in physical units as for physical-thermodynamic indicators, the output is measured in terms of the market value ($) of this output. These indicators can be applied to various levels of aggregation of economic activity – product, sectoral or national levels.

Energy:GDP and sectoral energy:output ratios

These energy efficiency measurements of energy input divided by the output ($), can be applied at both the national and sectoral levels. The energy:GDP ratio is the most commonly used aggregate measure of a nation's 'energy efficiency', although there has been widespread criticism of the use of this indicator for this purpose. The main problem with energy:GDP, as pointed out by Wilson *et al* (1994), is that it does not measure the underlying technical energy efficiency. Other factors such as changes in the sectoral mix in the economy (Jenne and Cattell, 1983), energy for labour substitution (Renshaw, 1981), and changes in the energy input mix (Liu *et al*, 1992) can influence movements in the energy:GDP ratio, and these factors have nothing to do with technical energy efficiency. Recently methods have been developed by Patterson (1993b) and others, to specifically exclude these extraneous factors from the energy:GDP ratio, in order to isolate the underlying technical energy efficiency.

Methodological problems can also emerge in the measurement of GDP between countries. Usually GDP measurements are commensurated using the exchange rate method, which does not necessarily take account of the purchasing power of different currencies. For this reason, it is often argued in the literature that the purchasing power parity method of equivalencing GDP should be used to obtain valid cross-national comparisons in the energy:GDP ratio (Reister, 1987).

Energy input:output ($) ratios are also widely used at the sectoral level and they have exactly the same methodological problems as the energy:GDP ratio has at the national level. Such sectoral level ratios can be calculated by using official statistics, or derived from undertaking algebraic manipulations of input–output tables (Bullard and Herendeen, 1975). These sectoral ratios can be either direct energy or total energy ratios. Direct energy ratios only take account of the energy directly used by a sector. Total energy ratios also take account of the energy indirectly used by a sector – ie the energy embodied in the supply of other materials and services required by a sector. For example, a farm will use a certain amount of direct energy to operate its machinery and farm equipment (eg diesel to run a tractor), but it will also require other inputs (eg fertilizers, pesticides) which in turn require energy for their manufacture – the energy required to produce these other inputs is called indirect energy.

Energy productivity ratio

This is the reciprocal of the energy:GDP ratio – ie it is the GDP (Y) divided by a nation's energy consumption (E). The more goods and services (Y) an economy produces per unit of energy (E), the more productive or efficient it is said to be with respect to energy. The energy productivity indicator is analogous to the well established labour and capital productivity ratios used in economics, and can also be applied at the sectoral level.

A detailed rationale for monitoring energy productivity changes in the US economy is outlined in a publication by the Joint Economic Committee of the Congress of the United States (1981). The energy productivity ratio is seen as a mechanism for focusing attention on the productive use of energy as a complementary measure to the orthodox capital and labour productivity ratios used in economic analysis.

The use of the energy productivity ratio in conjunction with labour and capital productivity ratios can provide useful insights into whether energy inputs act as complements or substitutes to these other factor inputs. For example, Patterson (1989) found by using such ratios for New Zealand (1960–85) that energy and labour inputs acted as mild substitutes to each other, and energy and capital inputs were mild complements to each other.

The uncritical use of the energy productivity ratio like that of the energy:GDP ratio, can lead to misleading conclusions. For example, the energy productivity ratio may decrease solely because energy is substituting for labour, rather than any underlying deterioration in the technical energy efficiency. To overcome this analytical problem, the analyst can calculate the marginal energy productivity ratio by using standard econometric modelling techniques. This ratio measures the marginal effect on output ($) by increasing the energy input (ΔH) by one unit.[7]

Economic indicators

The output measurement in the economic-thermodynamic indicators of energy efficiency is measured in terms of economic value ($). The energy input is still, however, measured in thermodynamic terms for these hybrid indicators. It could be argued, as some economists do, that both the input and output measurements should be enumerated in terms of economic value ($). It is argued, for example, by the Joint Economic Committee of the Congress of the United States (1981), that the energy dollars:GDP ratio is a 'more accurate reflection of the economic productivity of energy, provided that energy prices reflect energy supply and demand forces' (ie more 'accurate' in comparison to the energy input:GDP ratio).

It is argued by Turvey and Norbay (1965) and Berndt (1978) that the use of energy prices, instead of thermodynamic units to measure the energy input, provides a solution to the energy quality problem – ie the problem of validly adding up energy inputs of different qualities. This analytical problem is discussed in the next section of this paper in relationship to the fundamental problem it creates in using energy efficiency indicators. In brief, Turvey and Norbay (1965) and Berndt (1978) suggest the use of 'ideal prices' for measuring the energy inputs. These 'ideal price' weights reflect either the marginal rates of transformation in production, or marginal rates of substitution in consumption of different energy forms. The use of 'ideal prices' to measure energy inputs does, however, appear to be problematical on an operational level due to difficulties in calculating these 'ideal prices' in any measurable, consistent and assumption free manner. There is also evidence that such 'ideal prices' are unstable over time, unlike thermodynamic measures of energy which remain constant.

Beyond the theoretical and operational problems with using prices for measuring energy inputs in efficiency indicators, it could be argued on axiomatic grounds that a pure economic indicator of energy efficiency is not truly an energy efficiency indicator. Rather, it is an economic efficiency indicator because it is fully enumerated in economic value ($) terms, and therefore it should be immediately dismissed as a candidate measure of energy efficiency.

The most widely advocated pure economic indicator of energy efficiency which has been proposed in the literature is:

national energy input ($)/national output ($ GDP)

This indicator, which is the direct analogue of the energy input:GDP ratio, was proposed by the Joint Economic

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[7] The term 'marginal energy productivity ratio' is exactly equivalent to the term 'marginal product of energy' used in economics. That is, the extra output obtained by employing one extra unit of energy. The concept of marginal product can also be applied to other factors of production such as capital or labour.

Committee of the Congress of the United States (1981), although the Committee was fairly cautious about its widespread use due to the unpalatable assumptions which underpin its use. Other pure economic indicators of energy efficiency could be developed at both the national and sectoral levels, by simply converting the energy input measurements to monetary units by using appropriate energy prices. These other indicators would be analogous to their physical-thermodynamic indicator counterparts. Although this is possible, to the author's knowledge, these types of indicators have not to date been developed for monitoring energy efficiency.

Another possibility suggested by the Joint Committee (1981) is to construct an 'energy consumer cost savings' measure. This is seen to have the advantage of directly informing the public as to how much money has been saved from improvements in energy efficiency. It is argued that such an indicator will express the energy efficiency measure in terms that everyone can understand – money gained from energy efficiency. These economic indicators could be developed at the national level and/or for particular sectors in the economy.

Methodological issues in operationalizing energy efficiency indicators

There are a number of persistent methodological problems and issues associated with the operationalization of the energy efficiency indicators outlined in the previous sections of this paper. Most of these methodological problems are common to the full range of energy efficiency indicators, and some are just common to a particular type of energy efficiency indicator. Policy analysts and other practitioners have tended to ignore and/or not fully appreciate the implications of these methodological problems when attempting to use such energy efficiency indicators.

Valuation and value judgements

The implication in some of the literature is that the thermodynamic measures of energy efficiency are somehow objective and free of value judgements. This is true in one sense, as given the *a priori* definition of energy efficiency according to a particular thermodynamic formula, two independent observers will obtain the same answer when calculating an efficiency index.[8] This, of course, assumes that they are both competent at undertaking the calculations and the problem is unambiguously defined. Furthermore, the thermodynamic efficiency will remain constant over historical time and not be subject to changes – eg an enthalpic efficiency of 20% in 1960 will still be 20% in 1996. This is in contrast to energy efficiency measures that incorporate economic units ($) which change as people's preferences and tastes change, and hence market prices ($) change.

Nevertheless, it is false to assert that thermodynamic measures of energy efficiency are free of human values and perceptions. The most common way to define thermodynamic energy efficiency in general terms, is:

$$\frac{\text{Useful energy output}}{\text{Energy input}}$$

Of key importance in considering this ratio, is what constitutes a useful energy output. The definition of useful implicitly requires some assignment of human values in order to define what is considered to be a useful output. So-called unuseful or waste energy (eg waste heat) does not enter into the calculation of thermodynamic energy efficiency. Hence, in all thermodynamic energy efficiency definitions there is an implicit value judgement. Boulding (1981) succinctly summarizes this issue in his criticism of thermodynamic measures of energy efficiency in social contexts:

> In applying physical concepts like energy to social and economic systems, certain pitfalls have to be avoided, some of which are very easy to fall into. In the first place, it is very important to recognise that all significant efficiency concepts which are based on purely physical inputs and outputs may not be significant in human terms, or at least the significance has to be evaluated. The more output per unit of input the more efficient we suppose it to be. The significance of the efficiency concept, however, depends on the significance of the outputs and inputs in terms of human valuations.

Once it is accepted that valuations and value judgements are an integral part of any definition of energy efficiency, the next question that can be asked is what is the appropriate way to assign value to energy inputs and outputs of a particular process? It is increasingly being recognized that the value of an energy input should be measured in terms of how much end use service it can deliver (eg ECNZ, 1992). None of the thermodynamic indicators of energy efficiency measures output in terms of an adequate index of end use service delivery. Instead they measure the value or quality of an energy source in terms of an arbitrarily chosen numeraire – heat content (ΔH), a work potential (ΔG), or an ideal limit which is defined by the restrictive assumption of infinitely slow processes. Obviously, neither heat content (ΔH) nor work is the only required end use of energy in the economy; so therefore, a methodology needs to be developed to take account of all end uses of energy in the economy eg light, sound, mechanical drive, heating, chemical reduction, refrigeration, pumping and so forth.

Energy quality problem

The energy quality problem is encountered when attempts are made to measure energy efficiency in complex economic systems. That is, in systems or processes where there are many sources and end uses of energy of differing qualities. Before any energy efficiency calculations can be made, these energy forms need to be commensurated or adjusted in terms of energy quality.

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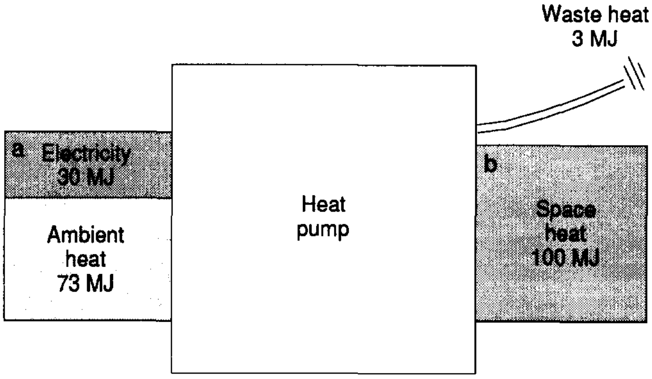
[8] Babbie (1975) refers to this phenomenon of the observers arriving at the same conclusion if the ground rules are agreed upon, as 'intersubjectivity' rather than objectivity. This is because choice of the ground rules themselves involves subjective judgements.

This problem always emerges when using enthalpic measurements (ΔH), which is the most common way of measuring energy. Enthalpic measurements (ΔH) only measure the heat content of energy forms, and do not necessarily make any distinction between low quality energy sources (such as coal) and higher quality energy sources (such as electricity). From this basis it has consequently been argued that energy, when measured in enthalpic terms (ΔH), cannot be added up because it has different qualities. This problem has variously been called the apples and oranges or aggregation problem (Leach, 1975; Roberts, 1979). The energy quality problem is therefore a fundamental problem in constructing conceptually sound energy efficiency indicators. It is a focus of concern in the construction and use of all energy efficiency indicators, whether they be at the macro-level or micro-level.

At the macro-level, for example, the energy quality problem arises in the calculation of the energy:GDP ratio, when the energy input aggregate is being calculated. In this case there are many primary energy inputs into the economy of differing qualities. Care needs to be taken in aggregating these primary energy inputs and ensuring that adjustments are made for varying qualities. Quite often analysts ignore this matter, and consequently spurious results are achieved, particularly when major shifts in the mix of primary energy inputs into the economy are being analysed. If, for instance, the change in the New Zealand energy:GDP ratio is calculated in enthalpic terms, it increased only 15.45% from 1960 to 1987; but if the energy:GDP ratio is calculated taking account of energy quality, it increased by 20.26% (Patterson, 1993b). The 4.81% difference between the two figures is quite significant and this discrepancy would not be acceptable when calculating other macro-level aggregates such as the Consumer Price Index.

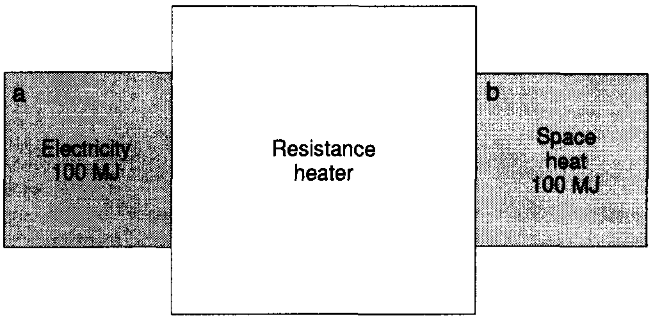
The energy quality problem is perhaps more acute and problematical at the micro-level, where the analyst is attempting to compare the energy efficiency of several processes with energy inputs of different qualities and possibly with energy outputs also of different qualities. For example, take the relatively simple case of comparing the energy efficiencies of three space heating technologies (refer to Figure 1):[9]

(1) electricity $\xrightarrow{\text{heat pump}}$ space heat;
(2) electricity $\xrightarrow{\text{resistance heater}}$ space heat;
(3) natural gas $\xrightarrow{\text{enclosed burner}}$ space heat.



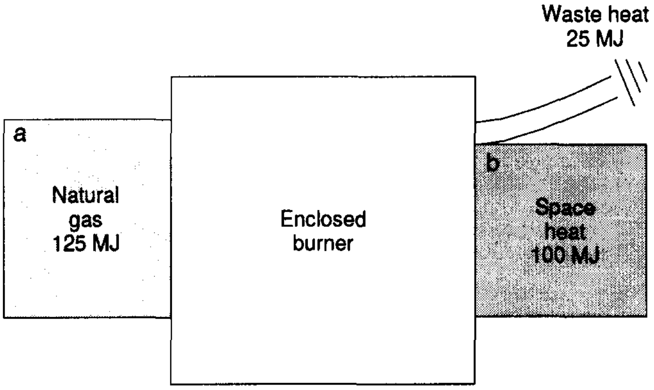
Enthalpic efficiency = 333% (b/a) first

Quality adjusted efficiency = 267% first



Enthalpic efficiency = 100% (b/a) second

Quality adjusted efficiency = 80% third



Enthalpic efficiency = 80% (b/a) third

Quality adjusted efficiency = 107% second

Figure 1 Ranking of three processes using enthalpic efficiency and quality adjusted measures[a]

[a] The following quality coefficients were used in these calculations: space heat = 0.80, electricity = 1.00 and natural gas = 0.60. The quality adjusted efficiencies of each process are therefore: process 1 = (0.80 × 100)/(1.00 × 30) = 267%; process 2 = (0.80 × 100)/(1.00 × 100) = 80%; process 3 = (0.80 × 100)/(0.60 × 125) = 107%.

In comparing the enthalpic efficiencies of processes 1 and 2, we can validly deduce that process 1 is more efficient than process 2. That is, in using electricity to produce space heat, the heat pump technology with an enthalpic efficiency of 333% is more efficient than the resistance heater tech-

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[9] This example is a 'simple case' as it involves only one type of output (space heat). The energy quality problem becomes a more complex proposition, when you are comparing processes that have different types of outputs (eg space heat, light, motive power). In this situation it is even more difficult to compare the relative energy efficiency of all of the processes with each other.

nology at 100%. This comparison can be validly made because we are comparing like with like – both processes have the same input (electricity) and have the same output (space heat). In fact, it does not really matter if the units of electricity or space heat are measured in enthalpic units (ΔH), or any other measurements, as long as the same units are consistently used in measuring both processes. For example, the electricity units could be measured in terms of kilowatt hours and exactly the same relative efficiencies would result in comparing processes 1 and 2.

The energy quality problem, however, emerges when one attempts to compare the relative efficiency of process 3 with processes 1 and 2. This is because process 3 has natural gas as an input, not electricity as do processes 1 and 2. This means the analyst is confronted with the problem of comparing two energy inputs of different qualities (electricity versus natural gas), and the conventional enthalpic measures do not take account of these quality differences. Consequently, the enthalpic efficiency indicator provides an invalid measure of the comparative energy efficiency of these processes. Once energy quality factors have been taken into account, the relative order of the energy efficiencies of these technologies changes. Instead of natural gas → space heat being the least efficient process as measured by the enthalpic indicator, it is now the second most efficient process once energy quality is taken into account.

A recent paper by Patterson (1993a) reviews the different approaches for dealing with the energy quality problem, including thermodynamic measures and their modern derivatives, OECD thermal equivalents and fossil fuel equivalents. Each of these approaches were critically examined and 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. In Patterson's (1993a) paper, the quality equivalent methodology was also presented as a candidate method for resolving the energy quality problem in this type of situation.

Boundary problem

Boundary assumptions are implicit in the use of any of the energy efficiency indicators. On the output side, as was previously pointed out, only useful energy is included in the calculations. On the input side, however, the situation becomes even more problematical, as often quite arbitrary and poorly justified boundaries are drawn. First, when calculating energy efficiency indicators, only certain energy inputs are considered, and others are considered to be outside the study's boundary. Non-commercial energy inputs are often excluded – ie energy inputs that are not acquired through the market exchange process. For example, in New Zealand, wood energy inputs are often not included in energy statistics, and hence not included in indicators which use such statistics. This is because a significant amount of wood is obtained free of charge from wood processing industries, scavenged from demolition sites, collected from beaches and so forth.

Solar energy is another energy input often excluded from energy efficiency indicators because it is considered to be free. This is, of course, a misconception as there is often a considerable capital investment and hence financial cost in capturing solar energy – eg in the use of solar water heaters. In addition to minor uses such as solar water heating, solar energy is also a major input into pastoral, horticultural and forestry industries. It is converted via photosynthesis to chemical energy, but this energy is excluded from official statistics, and therefore energy efficiency indicators, because it is considered to be a free source of energy.

Another dimension of the boundary problem highlighted by the IFIAS (1974) is how far back to trace primary energy inputs. For example, for energy products such as refined oil, do we take account of the energy losses in the refining of the oil? If we do take account of these losses in this example, then the energy input measurement (ΔH) of an energy efficiency indicator will increase. This will in turn lead to a decrease in the measured energy efficiency of any process that uses refined oil. If such factors are not taken into account by the energy efficiency methodology being employed, spurious results could emerge if there is a major shift towards or away from the use of such refined oil products. Another more philosophical example of how far back to trace energy inputs, is whether to track primary energy inputs back to flows of solar energy inputs. For example, do we take account of the solar inputs that drive the hydrological cycle to produce hydroelectricity? Some analysts such as Costanza (1980), a leading ecological economist, suggest we should take account of solar energy inputs in this way. It should be noted that these issues of 'how far back to trace energy inputs' are, for the most part, resolved by using the quality equivalent methodology.[10]

Joint production problem

The partitioning or joint production problem refers to the difficulty of allocating one energy input to several (or multiple) outputs of a process or system. This problem is particularly encountered in the calculation of physical-thermodynamic energy efficiency indicators – eg when calculating the energy input (ΔH)/output(kg) indicator for an industry that produces multiple outputs. For instance, a given amount of energy (MJ) is required to produce essentially two 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 IFIAS (1974) recommended four possible conventions for resolving the partitioning problem:

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[10] It is beyond the technical scope of this paper to fully justify this statement. It can, however, be formally justified by using the mathematics of the quality equivalent methodology. This justification hinges on the fact most primary energy inputs are non-basic energy inputs as defined by Sraffa (1960) and these inputs play no role in determining the quality coefficients of other energy forms in the reference energy economy. Therefore, they need not be included in the reference energy economy for determining the quality coefficients; and consequently, the system's boundaries need not encapsulate these inputs.

(1) Assign all energy requirements to the output of interest.
(2) Assign energy requirements in proportion to financial value or payments.
(3) Assign energy requirements in proportion to some physical parameter characterizing the system (eg weight, volume, energy content).
(4) Assign energy requirements in proportion to marginal energy savings which could be made if the good or service was 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 problem where the inputs or outputs are produced in quantities not proportional to each other. For example, Cleland *et al* (1981) used regression analysis to allocate energy inputs to multiple products from food factories. Regression analysis has also been used successfully by others (Jacobs, 1981; Rao *et al*, 1981) in addressing the partitioning problem. However, when the inputs or outputs are proportional, or near proportional, to each other (eg in the case of meat and wool production from a sheep farm), the problem is said to be confounded and cannot be solved by regression analysis. This type of regression analysis can usually only be applied at the individual factory level using day-by-day longitudinal data. There usually is not sufficient data available from official statistics, either longitudinal or cross-sectional, to undertake such analyses at the sectoral level.

Technical or gross energy efficiency?

Most of the indicators of energy efficiency outlined in this paper measure gross energy efficiency of a process, system or economic sector. As recently pointed out by Wilson *et al* (1994) in this journal, this can lead to difficulties and misunderstandings in interpreting these indicators. For example, indicators of gross energy efficiency, such as the energy:GDP ratio, include a number of other structural factors that can significantly affect the numerical magnitude of the indicator; but they have nothing to do with the underlying technical energy efficiency of the economy. Policy analysts and commentators are often more concerned with the technical improvements in energy efficiency, rather than extraneous structural factors such as sectoral mix changes, energy input mix changes and energy-for-labour substitution processes, all of which affect the aggregate measure of energy efficiency. Liu *et al* (1992) and Patterson (1993b) among others have recently devised methods for isolating this underlying technical energy efficiency.

For example, a study by Patterson and Wadsworth (1993) found that New Zealand's energy:GDP ratio increased by 37.82% over the 1979–90 period, mainly due to effects other than technical energy efficiency change (refer to Figure 2). By far the most influential effects were due to the restructuring of the economy towards more energy intensive sectors (26.72% increase). In comparison, the deterioration in technical efficiency (technical change residual) only contributed to a 6.9% upward movement in the New Zealand energy:GDP ratio. Therefore, in the New Zealand case, the gross energy:GDP ratio is highly misleading as an indicator of technical improvements of energy use, even though some commentators and politicians use it for this purpose. Studies of other countries (eg by Wilson *et al*, 1994; Schipper *et al*, 1990) have isolated the technical energy efficiency of the energy:GDP ratio and unlike the New Zealand situation they have found a consistent improvement in the underlying technical energy efficiency over the 1970s to 1990s. Nevertheless, in these countries structural effects have still significantly contributed to changes in the energy:GDP ratio, eg for the USA (Schipper *et al*, 1990), UK (Bending *et al*, 1987) and Australia (Wilson *et al*, 1994).

The same phenomenon occurs with energy efficiency indicators at both the sectoral and product levels. For example, the energy intensity (MJ/kg) of a factory output may increase because of greater mechanization (and hence energy use) rather than any deterioration in the technical efficiency of machinery in utilizing energy. Similarly, a sectoral energy:output (MJ/US$) ratio may also increase due to a movement towards more energy intensive products in that sector.

Both the technical and gross energy efficiency indicators are equally valid, but they are designed to analyse different types of issue. For example, if the policy analyst is exploring the broader issues of societal levels of energy use as they relate to resource depletion and sustainability issues, a gross energy efficiency indicator (eg energy:GDP) may be more appropriate and should not immediately be dismissed. However, if one is analysing the efficacy of targeted energy conservation programmes where the focus is quite obviously on improving technical levels of energy use, then a technical energy efficiency indicator is more appropriate.

Conclusions

Energy efficiency is now a central focus of many national energy policies and at the forefront of the debate on energy sustainability issues; but surprisingly little serious attention has been given to defining and measuring the concept. If energy efficiency policy objectives are going to be properly set in place and progress towards them monitored, theoretically sound operational definitions of energy efficiency need to be developed. This paper has however shown that there are number of critical methodological problems that stand in the way of the establishment of such operational indicators of energy efficiency. More attention needs to be given by policy analysts and others to addressing and overcoming these methodological problems.

Thermodynamic indicators of energy efficiency, unless they are adjusted for energy quality, are very limited at the macro-level because they do not allow for the ready comparison of energy efficiency across processes which have different energy inputs and outputs. Physical-thermodynamic indicators, whereby the output is measured in physical units which reflect the desired end use service of the

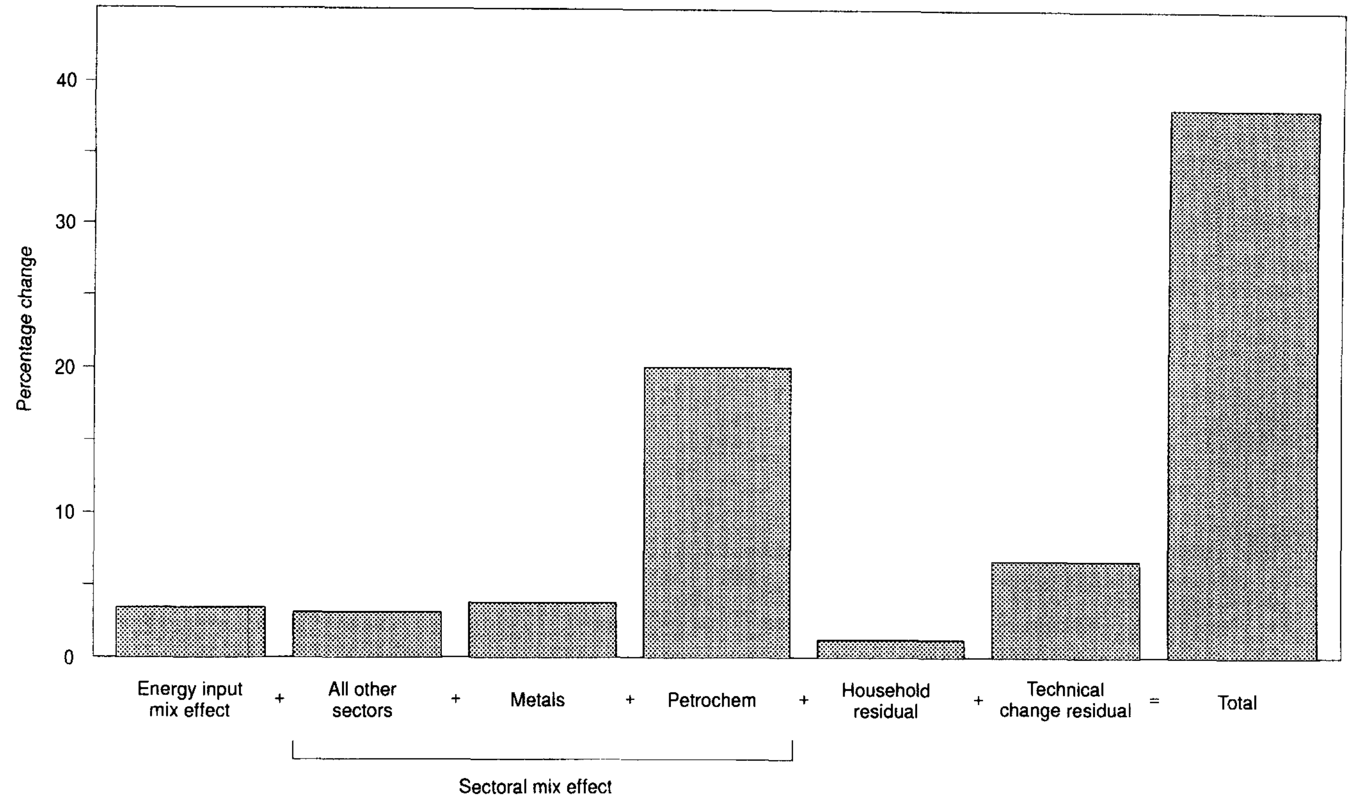

Figure 2 Components of change in New Zealand's energy:GDP ratio, 1979–90

process, are often more useful. However, these indicators only allow for the comparison of the efficiency of processes which require the same end use service and hence physical-thermodynamic indicators are restrictive as general measures of energy efficiency. Economic-thermodynamic indicators, such the energy:GDP ratio, are more useful for macro-level policy analysis, but often encounter problems with separating the structural effects from the underlying technical energy efficiency trends.

The energy quality problem is a fundamental problem across all energy efficiency indicators, when trying to compare processes with different quality inputs and outputs. In particular, the potency of thermodynamic indicators as macro-level indicators really depends upon the successful resolution of this problem; and until this is achieved, thermodynamic indicators will remain only useful at the process level of analysis. The quality equivalent methodology developed by Patterson (1983, 1991, 1993a) is advocated as an appropriate way of commensurating energy inputs and outputs in terms of their quality. This methodology has been specifically designed to measure energy quality in complex economic systems which usually are the context for macro-level policy studies. Other methodological problems are less critical to measuring energy efficiency, but nevertheless need to be carefully considered by policy analysts before attempting to measure energy efficiency at the macro-level.

Acknowledgements

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Appendix

Brief explanation of the quality equivalent methodology

The purpose of the quality equivalent methodology[11] is to define an energy unit which allows energy inputs and outputs to be compared on a common basis. This energy unit is called a quality equivalent and is defined by solving a system of simultaneous linear equations. These equations, which are termed a reference system, quantify the flow of energy in national energy systems eg the 1995 UK energy system. As such, there is a description of the flow of energy from primary energy sources to delivered energy and eventually to end uses of energy.

Reference system equations

The flow of energy in any complex system, such as a national energy system, can be quantified by a system of simultaneous linear equations represented by:

$$X\beta + e = 0$$

where

X = matrix ($m \times n$) of m processes describing the conversion of energy between n types of energy. The energy flows are measured in ΔH terms, with inputs entered as negative entries and outputs as positive entries

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[11] Fuller explanations of the quality equivalent methodology are contained in Patterson (1993a) and also in an earlier publication in *Energy Policy* by Patterson (1983).

$\boldsymbol{\beta}$ = column vector ($n \times 1$) of quality coefficients of each energy type. The quality coefficients are measured in terms of $E/\Delta H$units, and are determined by solving the simultaneous equations

e = residual vector ($m \times 1$). The residual expressed in quality equivalents (E) for each process. For a process with an efficiency equalling the system's average $e = 0$, for a process efficiency less than the system's average $e > 0$ and for a process efficiency greater than the system's average $e < 0$.

This system of simultaneous equations needs to be solved so as to determine the quality coefficients for each of the energy types – ie to obtain a solution vector $\boldsymbol{\beta}$. This presents a number of problems. First, the system of equations is nearly always overdetermined, as there are more conversion processes (m) than energy types (n). Therefore, deterministic solution methods, such as those used in Leontief-style input output analysis, are not suitable solution methods. Second, the system of equations are homogeneous, as the right hand side of the equations is a vector of zero entries. For this reason, the trivial solution of $\boldsymbol{\beta} = 0$ is always a possible solution but not meaningful. The key to solving the equation is to avoid the trivial solution by setting one of the quality coefficients to unity and transferring the resultant vector to the other side of the system of equations.[12] The solved quality coefficients $\boldsymbol{\beta}$ are expressed in terms of multiples of the variable which has been transferred to the right-hand side. These multiples are called quality equivalents. Any one of the specific coefficients in the reference system can be used as the quality equivalent unit. For a properly specified system of equations, it does not matter which coefficient is set to unity as the relativities between the quality coefficients remain constant.

Quality equivalent unit and quality coefficients[13]

The concept of the quality equivalent unit is pivotal in the QEM. The quality equivalent unit is the 'measuring rod', which allows energy forms to be compared on a common basis in terms of their energy quality. Energy inputs and outputs have been traditionally measured in terms of their heat content (ΔH) which takes no account of energy quality. To convert energy inputs and outputs measured in heat units (ΔH) to quality equivalent units (E), they need to be multiplied by the quality coefficients ($E/\Delta H$) obtained from solving the above specified system of equations.

In general, the quality coefficients (E/ΔH) provide a measurement of the quality of energy inputs and outputs. The specific meaning that can be attached to the numerical value of each quality coefficient, depends on the type of energy input/output. For primary energy inputs, the quality coefficient ($E_{\mathrm{out}}/\Delta H_{\mathrm{in}}$) is the relative efficiency at which a primary energy input (ΔH_{in}) is converted to energy end-uses (E_{out}) in the reference system. The higher the energy quality of a primary energy input, the more end use energy it will produce. For example, a primary energy input such as natural gas is usually more efficient or productive at producing end uses of energy, than lower quality energy inputs such as coal. That is, one unit of natural gas (ΔH_{in}) will produce more end use energy (E_{out}), than one unit of coal (ΔH_{in}). Therefore, natural gas will have a higher quality coefficient ($E_{\mathrm{out}}/\Delta H_{\mathrm{in}}$) than that for coal.

For an end use of energy (which does not feedback into the system), its quality coefficient ($E_{\mathrm{in}}/\Delta H_{\mathrm{out}}$) is the total embodied energy required to produce that end use. For example, a typical high quality end use, such as light energy, requires a greater input of direct and indirect energy (ΔH_{in}) to produce one useful output of energy ($\mathrm{E}_{\mathrm{out}}$).

The QEM, provides for an integration of the concepts of quality of inputs and quality of outputs within one framework. In fact, it is argued that it is impossible to rigorously measure the quality of either an input or output, without reference to each other. Again, analogies can be drawn with economic thinking with respect to how equilibrium prices enable supply-side (cost) and demand-side (utility) ideas to be reconciled.

A simple numerical example

Consider the notional reference system of energy conversions portrayed by Figure 3. Algebraic equations can be used to describe the conversion of inputs (ΔH) to outputs (ΔH) of energy for each process in the reference system. In the following equations, the inputs are arranged on the left-hand side and the output on the right-hand side, with feedbacks of energy required by each process denoted by underlining.

(1) $b_1 14.50 + b_7\underline{0.10} + b_8\underline{0.20} + e_1 = b_4 13.50$
(2) $b_6 6.00 + b_8\underline{0.02} + e_2 = b_4 2.00$
(3) $b_5 2.00 + b_7\underline{0.80} + b_8\underline{0.01} + e_3 = b_4 0.50$
(4) $b_2 16.00 + b_8\underline{0.01} + e_4 = b_6 14.00$
(5) $b_3 125.00 + b_7\underline{0.20} + e_5 = b_5 100.00$
(6) $b_4 6.00 + b_8\underline{0.04} + e_6 = b_7 6.00$
(7) $b_6 4.00 + b_8\underline{0.03} + e_7 = b_7 3.00$
(8) $b_5 8.00 + b_8\underline{0.10} + e_8 = b_7 4.80$
(9) $b_6 4.00 + b_7\underline{0.04} + e_9 = b_8 0.60$
(10) $b_5 80.00 + b_7\underline{0.04} + e_{10} = b_8 8.00$
(11) $b_4 10.00 + b_8\underline{0.04} + e_{11} = b_9 1.00$

This system of simultaneous equations can be solved and expressed in terms of multiples of any of the energy forms (in this particular case delivered electricity equivalents).

(1) $b_1 = 0.8823$ (hydroelectricity)
(2) $b_2 = 0.3755$ (wellstream gas)
(3) $b_3 = 0.2509$ (crude oil)
(4) $b_4 = 1.0000$ (delivered electricity)
(5) $b_5 = 0.3152$ (oil products)
(6) $b_6 = 0.4314$ (delivered gas)
(7) $b_7 = 0.7813$ (heat)
(8) $b_8 = 3.1403$ (transport)
(9) $b_9 = 10.1256$ (lighting)

End-use matching and process efficiencies

It becomes evident from solving the equations that not all processes are equally efficient, as demonstrated by the existence of non-zero residuals ($e \neq$ o). The relative efficiency (Φ) of each process can be calculated by dividing the outputs (E_{out}) by the inputs (E_{in}) of each process (see Table 1):

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[12] The most straightforward solution method although not the most reliable, is to solve the equations by using least squares regression. In this method proposed by Patterson (1983), each coefficient is in turn set to unity to generate different regression models. Out of all of these regressions, the model with the highest R^2 is selected for final use. Other more reliable solution methods have been developed by Patterson (1991).

[13] These concepts have direct analogues in economic thinking: quality equivalent (E) = monetary value ($); quality coefficient ($E$/unit of energy) = relative price ($/unit of commodity).

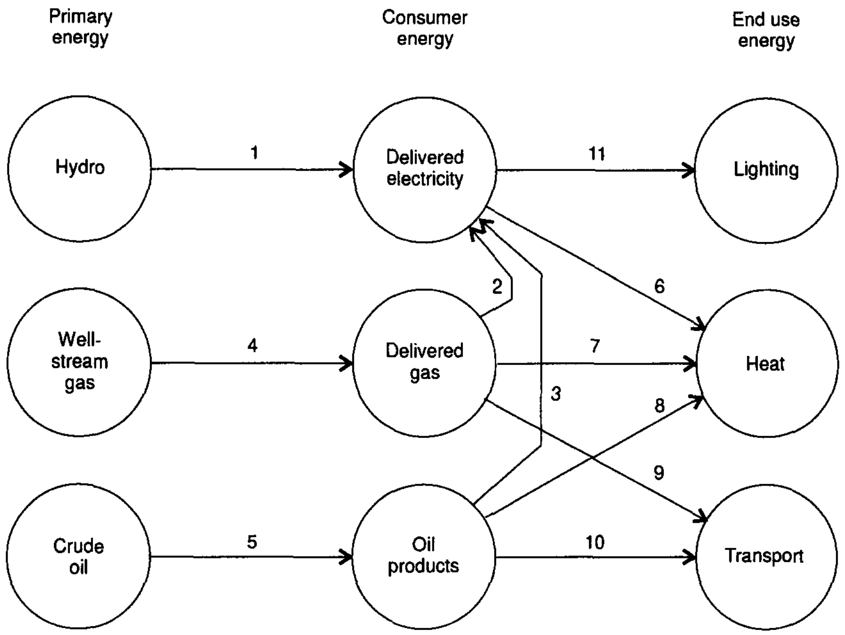

Figure 3 Reference system energy conversion processes[a]

[a] Only direct energy conversion processes are depicted. All conversion processes also require feedbacks of end use energy for their operation.

Table 1 Process efficiencies and residuals for the simple numerical example

Process input		Process output	Relative efficiency	Residual
Hydroelectricity	→	Delivered electricity	$\Phi_1 = 1.0000$	$e_1 = 0$
Delivered Gas	→	Delivered electricity	$\Phi_2 = 0.7544$	$e_2 = 0.6512$
Oil products	→	Delivered electricity	$\Phi_3 = 0.3885$	$e_3 = 0.7869$
Wellstream gas	→	Delivered gas	$\Phi_4 = 1.0000$	$e_4 = 0$
Crude oil	→	Oil products	$\Phi_5 = 1.0000$	$e_5 = 0$
Delivered electricity	→	Heat	$\Phi_6 = 0.7652$	$e_6 = 1.4381$
Delivered gas	→	Heat	$\Phi_7 = 1.2879$	$e_7 = -0.5239$
Oil products	→	Heat	$\Phi_8 = 1.3224$	$e_8 = -0.9142$
Delivered gas	→	Transport	$\Phi_9 = 1.0725$	$e_9 = -0.1273$
Oil products	→	Transport	$\Phi_{10} = 0.9950$	$e_{10} = 0.1273$
Delivered electricity	→	Lighting	$\Phi_{11} = 1.0000$	$e_{11} = 0$

Processes that have relative efficiencies of 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. By using these relative efficiencies, it is possible to rigorously match end uses and sources of energy, in accordance with the type of ideas promoted by Lovins (1977). For example, the most efficient way of providing heat is by using oil products ($\Phi_8 = 1.3224$); whereas, the least efficient way of providing heat is by using electricity ($\Phi_6 = 0.7652$).