Ecological Economics, 6 (1992) 139–162
Elsevier Science Publishers B.V., Amsterdam

Energy quality and energy surplus in the extraction of fossil fuels in the U.S.

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(Accepted 4 February 1992)

ABSTRACT

Cleveland, C.J., 1992. Energy quality and energy surplus in the extraction of fossil fuels in the U.S. *Ecol. Econ.*, 6: 139–162.

The goal of net energy analysis is to assess the amount of useful energy delivered by an energy system, net of the energy costs of delivery. The standard technique of aggregating energy inputs and outputs by their thermal equivalents diminishes the ability of energy analysis to achieve that goal because different types of energy have different abilities to do work per heat equivalent. This paper describes physical and economic methods of calculating energy quality, and incorporates economic estimates of quality in the analysis of the energy return on investment (EROI) for the extraction of coal and petroleum resources in the U.S. from 1954 to 1987. EROI is the ratio of energy delivered to energy used in the delivery process. The quality-adjusted EROI is used to answer the following questions: (1) are coal and petroleum resources becoming more scarce in the U.S.?, (2) is society's capability of doing useful economic work changing?, and (3) is society's allocation of energy between the extraction of coal and petroleum optimal? The results indicate that petroleum and coal became more scarce in the 1970s, although the degree of scarcity depends on the type of quality factor used. The quality-adjusted EROI shed light on the coal-petroleum paradox: when energy inputs and outputs are measured in thermal equivalents, coal extraction has a much larger EROI than petroleum. The adjustment for energy quality reduces substantially the difference between the two fuels. The results also suggest that when corrections are made for energy quality, society's allocation of energy between coal and petroleum extraction meets the efficiency criteria described by neoclassical and biophysical economists.

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INTRODUCTION

The substantial fluctuation in energy prices during the past two decades and their effect on the economy sparked the analysis of the performance of energy systems that extract energy from the environment and convert it to useful forms. One technique for evaluating energy systems is net energy analysis, which compares the quantity of energy delivered to society by an energy system with the direct and indirect energy used in the delivery process. Energy return on investment (EROI) is the ratio of energy delivered to energy costs (Cleveland et al., 1984). Biophysical economists argue that net energy analysis has several advantages over standard economic analysis (Gilliland, 1975; Hall et al., 1992). First, net energy analysis assesses the change in the physical scarcity of energy resources, and therefore is immune to the effects of market imperfections that distort monetary data. Second, because goods and services are produced from the conversion of energy into useful work, net energy is a measure of the potential to do useful work in economic systems. Third, EROI can be used to rank alternative energy supply technologies according to their potential abilities to do useful work in the economy. Most neoclassical economists reject methods of economic analysis that are not based on human preferences, arguing that net energy analysis does not generate useful information beyond that produced in a thorough economic analysis. The longstanding debate between the two groups is a matter of public record [1].

One limitation of net energy analysis to deliver the insights it promises is the standard approach towards the issue of energy quality. In most net energy analyses, inputs and outputs of different types of energy are aggregated by their thermal equivalents (Btu, joules, etc.). The thermal equivalent approach ignores the important fact that all Btu's are not equal — a Btu of electricity generates more economic output than a Btu of petroleum, and a Btu of petroleum generates more economic output than a Btu of coal (Adams and Miovic, 1968; Cleveland et al., 1984). Widely accepted in principle by many energy analysts, the concept of energy quality has proven difficult to operationalize. Bullard suggested the development of "weighting systems" that account for the differences in quality among fuels (Bullard, 1976), but most research to date uses the standard thermal equivalent approach (Slesser, 1978; Herendeen et al., 1979; Cleveland et al., 1984)

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[1] In 1974 and 1975, the journal *Energy Policy* published a series of papers examining energy analysis. Many of these papers were collected in a volume (Thomas, 1977). For other exchanges on the subject, see Gilliland (1975); Huettner (1976); Costanza (1981); Daly (1981); Berndt (1983); Hall et al. (1992); Herendeen (1988).

The aggregation of energy flows of different quality by their thermal equivalents blunts several apparent advantages of energy analysis. The EROI of two energy systems whose energy inputs and outputs differ in quality cannot be used to distinguish which system maximizes the potential to do useful work in the economy. For example, two energy systems can have the same EROI but different potentials to do useful economic work if one system produces a high quality energy (electricity) using lower quality energy inputs (coal), and the other produces a low quality energy output using high quality inputs (e.g., electricity used to produce coal). Similarly, the change in the EROI over time for an energy system may be an ambiguous indicator of the change in useful energy delivery if the mix of energy inputs to the system changes. For example, crude oil was extracted in the late 19th century with relatively low quality energies such as draft animals and wood-powered steam engines. Oil is now extracted with energy convertors powered by refined oils, natural gas, and electricity. Such changes in energy quality must be accounted for in an assessment of the potential to do useful work by the net energy delivered by oil extraction.

The purpose of this analysis is to incorporate estimates of energy quality in an analysis of the EROI of the extraction of coal and petroleum in the U.S. from 1954 to 1987. The results will answer the following questions:

- Are coal and petroleum resources becoming more scarce in the U.S.?
- Is society's capability of doing useful economic work changing?
- Is society's allocation of energy between the extraction of coal and petroleum optimal?

The outline of the paper is as follows. The second section defines the standard thermal equivalent EROI and a quality-corrected EROI. The third and fourth sections describe and compare production and end-use methods of measuring energy quality. The fifth section describes the data used to calculate the EROI for the extraction of coal and petroleum. The sixth section presents the results of the empirical analysis, and the seventh discusses the results in the context of the questions raised about the scarcity of fossil fuels and the allocation of society's energy between the extraction of coal and petroleum.

ACCOUNTING FOR ENERGY QUALITY IN NET ENERGY ANALYSIS

A net energy analysis requires the aggregation of many types of fuel and electricity that are measured in diverse physical units (e.g., barrels of oil, kilowatt-hours of electricity, etc.). Physical units of fuel and electricity are usually summed by their thermal equivalents. To illustrate this approach, define n distinct types of fuels at time t as E_{1t}, E_{2t}, $\ldots$, E_{nt}, where E

represents the thermal equivalent of each fuel. The simple thermal equivalent approach defines aggregate energy at time t (E_t) as:

$$E_t = E_{1t} + E_{2t} + \ldots + E_{nt} \tag{1}$$

The advantage of the thermal equivalent approach is that it uses a simple and well-defined accounting system based on the conservation of energy. The thermal equivalent approach underlies most methods of energy aggregation in economics and ecology, such as trophic dynamics (Odum, 1957), national energy accounting (Department of Energy, 1991), energy input–output modeling in economies (Bullard et al., 1978) and ecosystems (Hannon, 1973), and most net energy analyses (Chambers et al., 1979).

Given these basic assumptions, the thermal equivalent EROI is defined as:

$$\mathrm{EROI}_t = \frac{\sum_{i=1}^{n} E^{\mathrm{o}}_{i,t}}{\sum_{i=1}^{n} E^{\mathrm{c}}_{i,t}} \tag{2}$$

where E^{o} and E^{c} are the energy output and input of energy type n at time t, measured in thermal equivalents. As discussed in greater detail below, the quantity E^{c} is the sum of direct and indirect energy inputs to the energy system. Equation (2) is the technique used in the vast majority of net energy analyses.

Modification of the standard method of energy aggregation to account for energy quality requires a system that weights the thermal equivalent of each type of energy type by its relative economic usefulness. Such an approach defines a new aggregate energy, E^*, as the weighted sum of individual fuel types:

$$E_t^* = \lambda_{1t} E_{1t} + \lambda_{2t} E_{2t} + \ldots + \lambda_{nt} E_{nt} \tag{3}$$

where the λ's are the quality factors for individual fuels. The quality-corrected energy return on investment (EROI*) is then defined as:

$$\mathrm{EROI}_t^* = \frac{\sum_{i=1}^{n} \lambda_{i,t} E^{\mathrm{o}}_{i,t}}{\sum_{i=1}^{n} \lambda_{i,t} E^{\mathrm{c}}_{i,t}} \tag{4}$$

where $\lambda_{i,t}$ is the quality factor for fuel type i at time t, and E^{o} and E^{c} are the thermal equivalents of energy costs and energy outputs as defined in equation (2). The EROI in equation (4) is the appropriate method to compare the EROI for different energy delivery systems. The next and more difficult step is the choice of technique for calculating the quality factors for each type of energy. There are two basic techniques to assess energy quality: production side approaches and end-use approaches. I discuss each of these perspectives in turn.

PRODUCTION SIDE APPROACHES TO ENERGY QUALITY

The production side approach measures energy quality by the cost of producing a fuel or by the cost of converting it from one form to another. The most notable of these techniques is emergy (with an "m") analysis as developed by Odum and his colleagues (Odum and Odum, 1983; Odum et al., 1987; Odum, 1988; Huang and Odum, 1991). Emergy analysis is a pure cost-of production approach that measures the quality of a particular type of energy by its transformity. Transformity is the amount of one type of energy required to produce a heat equivalent of another type of energy. To account for the difference in quality of thermal equivalents among different energies, all energy costs are measured in solar emjoules (SEJ), the quantity of solar energy used to produce another type of energy. Fuels with higher transformities require larger amounts of sunlight for their production, and therefore are more economically useful (Odum, 1988) (Table 1).

Odum's method of calculating transformities assesses the efficiency of the sequence of energy conversions that produces a thermal equivalent of fuel. That sequence has two components: environmental energy conversions and industrial energy conversions. The basis for these calculations is the production of electricity in a wood-fired power plant (Odum and Odum, 1983). The principal environmental energy conversion is the solar energy required to produce a heat equivalent of wood in the standing stock of the forest: 3.23×10^4 SEJ of sunlight are required to produce one joule of standing wood. The sunlight embodied in the wood undergoes a series of energy conversions in the economy (harvest, transport, combustion, etc.) that generate a joule of electricity. The generation of each heat unit of electricity requires 1.59×10^5 SEJ. The transformities for coal, oil, and natural gas are based on a series of calculations that assesses the efficiency of converting coal to electricity, crude oil to refined fuel, and the efficiency of coal relative to natural gas as a boiler fuel.

There are several conceptual and computational problems with emergy analysis that make transformities incomplete indicators of energy quality in their present state of development. The calculation and application of transformities are time, location, and technology specific, yet Odum and his colleagues mix the temporal, spatial, and technical scales of their analysis in ways that are poorly defined. First, Odum presents the transformities as constants, but based on the method used to calculate them (Odum and

TABLE 1

Quality factors for various energy types

Energy type	Transformity [a] (SEJ/joule)	Market price [b] (cents/10^6 Btu)
Coal		
Bituminous	3.98×10^4	
• mine-mouth		105
• delivered cost [c]		
Anthracite		
• mine-mouth		189
Oil		
• wellhead	5.3×10^4	265
• No. 2 fuel oil		614
• gasoline	6.6×10^4	718
Natural gas		
• wellhead	4.8×10^4	150
• delivered cost [c]		285
Electricity		
• leaving power plant	1.59×10^5	
• delivered cost [c]		1398

[a] Source: Odum and Odum (1983). Units are solar emjoules per joule.
[b] Source: Department of Energy (1991). Values are 1987 prices.
[c] Coal, price paid by electric utilities; natural gas and electricity, price paid by industrial users.

Odum, 1983), the transformities are clearly dynamic because they are based on the first law efficiency of technologies such as power plants, coal liquefaction, and oil refineries. The efficiency of those technologies has changed dramatically over time. Second, the emergy calculations also contain an ad hoc mixture of spatial scales. The basis for the calculation of the transformities is the thermal efficiency of a wood-fired power plant in Brazil, but the efficiency of power plants vary throughout the world (Smil, 1991) as do all the other energy conversion technologies used in the emergy calculations. Similarly, energy/output data from the New Zealand economy are mixed with the Brazil power plant data to calculate the transformities, which are then applied to many other economies throughout the world (Odum and Odum, 1983; Odum et al., 1987; Odum and Arding, 1990; Huang and Odum, 1991). Third, the values of the transformities are highly sensitive to technological assumptions made by Odum and Odum (1983). They calculate the relative quality of oil, gas, and coal based in part on the fact that the first law thermal efficiency of converting natural gas in boilers is 20% more efficient than the conversion of coal. However, the relative thermal efficiency of fuels varies with the task they perform (Adams and

Miovic, 1968). The transformities would change, and hence the estimate of relative fuel qualities, if a different task were used for comparing the thermal efficiency of fuel conversion.

The transformities in Table 1 are based on a set of assumptions and techniques that need substantially greater explanation and development. It is unclear how sensitive the values of the transformities are to alternative but plausible temporal, spatial, and technological assumptions. For that reason, the techniques are not sufficiently developed to stand the test of self-consistency, completeness, or coherence, and transformities cannot be used to measure energy quality.

END-USE APPROACHES TO ENERGY QUALITY

There are several different methods of measuring energy quality at the point of end use. Physical approaches such as exergy analysis use the thermodynamics of energy conversion to assess quality. Economic approaches use relative price and marginal product to measure quality, and thereby assume that a combination of physical characteristics of energy, engineering characteristics of human technology, and human preferences combine to determine a fuel's quality.

Exergy

Exergy analysis is based on the second law of thermodynamics, which describes the change in the quality of energy that accompanies its conversion from one form to another. Exergy therefore accounts for physical quality differences among different forms of energy. Exergy is the maximum amount of physical work that can be extracted from a given flow of energy. Exergy is calculated by multiplying the heat equivalent of a fuel or heat source by the appropriate Carnot factor $[1\text{-}(T_a/T_0)]$, where T_a and T_0 are the ambient temperature and output temperature of the process, respectively, measured on the Kelvin scale. Note that energy quality in exergy analysis is defined in concise thermodynamic terms: the potential to do *mechanical* work. Mechanical drive and electricity are rated the highest in the exergy hierarchy of energy quality because of the theoretical capacity of those sources to be transformed into useful work with 100% efficiency. The exergy approach accounts for the important reduction in quality (ability to do work) that accompanies the conversion of energy from one form to another, and is typically applied to individual processes or technologies (Cleveland and Herendeen, 1989; Schilizzi, 1987).

The economic perspective: relative prices and marginal product

Economists have a markedly different perspective of energy quality than that reflected in other end-use approaches and the one used in Odum's emergy analysis. From an economic perspective, the evaluation of energy quality using thermal equivalents, exergy, emergy, and other cost-of-production techniques fall on the same sword: they ignore the role of economic forces that determine the usefulness of a fuel. Economists criticize the physical perspective of energy quality because thermal equivalents and the emergy content of different fuels are not sufficient to explain why a thermal equivalent of oil is more useful in many tasks than is a heat equivalent of coal (Mitchell, 1974; Webb and Pearce, 1975). Oil and coal have a different combination of attributes that determine their usefulness: heat content, weight, cleanliness, cost of conversion, safety, amenability to storage, volatility, etc. Economists argue that the heat equivalent of each fuel, the method used by most energy analysts to aggregate fuels, does not reflect those characteristics. The emergy explanation is equally untenable from an economic perspective. There is no defensible theoretical basis and no empirical support for the argument that all the differences in the attribute combinations of oil and coal are due solely to the amount of solar energy required to produce a heat equivalent of each. Thus, economists use alternative methods to assess energy quality.

The relative price approach

From an economic perspective, the value of a heat equivalent of fuel is determined by its marginal product — the marginal increase in the quantity of a good or service produced by the use of one additional heat unit of fuel. The marginal product of a fuel is determined not only by its heat equivalent, but also by all of its other attributes, just as the marginal product of labor and capital is determined by a combination of qualitatively different attributes unique to each unit of labor and capital. According to neoclassical theory, the price per heat equivalent of fuel in a competitive equilibrium is equal to its marginal product, and therefore its economic usefulness. In theory then, the market price of a fuel reflects the myriad factors that determine the economic usefulness of a fuel from the perspective of the end-user.

Not surprisingly, the price per heat equivalent of fuel varies substantially among fuel types (Table 1). The different prices demonstrate that end-users are concerned with attributes other than heat content. As Berndt (1978) states:

> Because of [the] variation in attributes among energy types, the various fuels and electricity are less than perfectly substitutable — either in production or consumption. For example, from the point of view of the end-user, a Btu of coal is not perfectly substitutable with a Btu of electricity; since the electricity is cleaner, lighter, and of higher quality, most end-users are willing to pay a premium price per Btu of electricity. However, coal and electricity are substitutable to a limited extent, since if the premium price for electricity were too high, a substantial number of industrial users might switch to coal. Alternatively, if only heat content mattered and if all energy types were then perfectly substitutable, the market would tend to price all energy types at the same price per Btu (p. 242).

The economic perspective of energy quality suggests another method to measure energy quality: use the price of fuels to weight their heat equivalents. The simplest approach economists use is to define the weighting factor (λ's) in equation (3) as:

$$\lambda_{it} = \frac{P_{it}}{P_{1t}} \tag{5}$$

where P_{it} is the price per Btu of the ith type of fuel. In this case the price of each fuel is measured relative to the price of fuel type 1. Note that the customary practice of aggregating fuels by their heat equivalent [equation (1)] is a special case of equation (3) when the price per Btu is the same for all fuels, and when all types of fuel are perfectly substitutable (Berndt, 1978). A weighting procedure similar to equation (5) was used in an analysis of energy use in the United Kingdom from 1964 to 1974 and showed that it gave a more accurate assessment of energy use than the thermal equivalent approach (Turvey and Nobay, 1965).

From an economic perspective, equation (5) is a superior measure of energy quality compared with the thermal equivalent method defined in equation (1). However, it embodies the restrictive assumption that fuels are perfect substitutes for each other. As a result, economists have devised more sophisticated methods such as the Divisia index (Diewert, 1976) that allows for more realistic possibilities of substitution between fuels. The Divisia index uses time-varying prices and fuel expenditure shares to aggregate different types of fuel, and has the desirable property of permitting variable substitution possibilities among fuel types without imposing any a prior restrictions on the substitution parameters. Berndt (1978) discusses the application of the Divisia index in aggregate energy accounting.

The marginal product of energy approach

Another economic perspective defines energy quality by the quantity of output generated per thermal equivalent of different fuels. Adams and Miovic (1968) estimated a pooled annual cross-sectional regression model of industrial output as a function of fuel use in seven European economies from 1950 to 1962. Their results showed that petroleum was 1.6 to 2.7 times more efficient than coal in producing industrial output. Electricity was 2.7 to 14.3 times more efficient than coal. Adams and Miovic calculated a revised aggregate energy use index using those quality factors to weight the heat equivalents of individual fuels. They found that the adjusted energy use series showed a closer correlation with aggregate economic output than the unadjusted series. Cleveland et al. (1984) manipulated the results of a regression model of the energy/GDP ratio in the U.S. and found that the quality factors of petroleum and electricity relative to coal were 1.9 and 18.3, respectively.

Kaufmann (1991) extended the marginal product approach to estimate the difference in the quantity of economic output generated by a heat equivalent of different fuels, and to show how the estimate of energy quality for a fuel changes as the fuel captures a larger or smaller share of total fuel use. Building on a model developed by Cleveland et al. (1984) and Gever et al. (1986), Kaufmann calculated the marginal product of oil, natural gas, and electricity relative to coal in a regression model of the amount of energy used to produce a unit of real GDP in France, Germany, and the U.S. (Fig. 1).

Kaufmann's results show that (1) the quality factor of a fuel, as measured by its marginal product, diminishes as its share of total fuel use increases in each economy, and (2) relative marginal product adjusts to relative fuel prices over time. The first result indicates that differences in the amount of useful work obtained per heat unit follow the law of diminishing returns. For example, electricity is a premium energy source for many tasks. The first uses of electricity are directed at tasks such as lighting and powering computers that are best able to utilize its unique physical, technical, and economic attributes. The quality factor is high for electricity in those applications. As the market share of electricity expands, it is used increasingly for tasks that are less able to utilize those attributes. Electricity is used eventually to produce heat, at which point it loses much of its advantage over the direct combustion of oil, gas, and coal. As electricity, or any other fuel, is used increasingly for tasks that are less able to utilize its unique attributes, its marginal product declines.

There are limitations and uncertainties in the economic approach to energy quality. Foremost is the assumption that price is an accurate measure of marginal product. According to economic theory, market price will unambiguously reflect marginal product only when markets are perfectly competitive. Markets are not perfect. The price differences in Table 1 are caused in part by market imperfections such as government regulation of energy markets and by market concentration (e.g., the OPEC

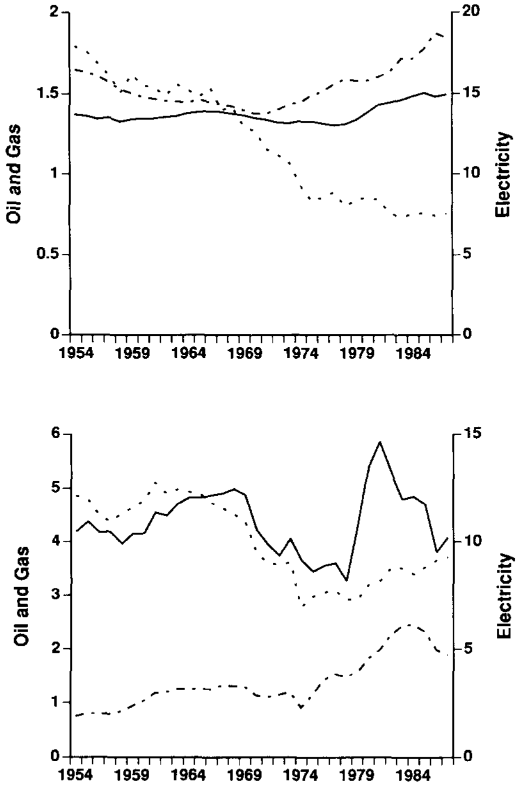

Fig. 1. Two economic perspectives of energy quality. Top chart: Changes over time in the quality factor for oil (solid line), natural gas (dashed and dotted line), and electricity (dashed line) relative to coal in the U.S. as calculated by Kaufmann (1991). Quality is measured by each fuel's marginal product, which is calculated from Kaufmann's regression model of energy use and economic output in the U.S. See text for details. Bottom chart: Changes over time in the price of oil (solid line), natural gas (dashed and dotted line), and electricity (dashed line) relative to the price of coal in the U.S. Price data are from the Department of Energy (1991).

cartel). The complexity of world energy markets makes it difficult to know the degree of deviation from the theoretical ideal. Critics of economic analysis argue that imperfections are pervasive and that prices are not reliable indicators of energy quality (Gilliland, 1975). Economists argue that deviations from the free market are not fatal (Mitchell, 1974; Berndt, 1978). That argument is consistent with Kaufmann's (1991) empirical finding that the marginal product of energy tracks the price of energy after a period of adjustment. Kaufmann argues that the market allows end-users to adjust their use of energy to equate the relative marginal product and relative prices within the constraints imposed by government regulation.

Physical versus economic perspectives of energy quality: who is right?

Is the economic usefulness of a fuel something that is *put into* the fuel as suggested by cost-of-production approaches such as emergy analysis, or is it *derived from* the use of the fuel by end-users who make choices about fuel use based on some valuation procedure? Neither approach may be necessary and sufficient to explain energy quality. Embodied sunlight alone does not determine the economic usefulness of a thermal equivalent of a fuel. It would also be dangerous to rely on market price alone to reflect quality because the markets for fuels are less than perfect and because markets do not even exist for many biogeochemical cycles that produce coal, petroleum, and all other natural resources and ecosystem services.

A starting point is the recognition that the physical and technical aspects of energy quality must be considered in the broader arena of the market where end-users select the fuels that are best suited for the particular task at hand. I explore that question in an analysis of the performance of the coal and petroleum industries in the U.S. in which I use net energy analysis modified with economic measures of energy quality. The method I develop is not a grand synthesis of the two approaches, but instead is a tentative step forward in the search for bridges between the economic and biophysical perspective.

DATA PREPARATION

Three different EROI are calculated for the extraction of coal and petroleum. The first is the standard thermal equivalent EROI that is defined in equation (1). The second and third are quality-corrected EROI that are defined in equation (4), where the weights (λ's) are relative energy prices and the marginal products of energy as calculated by Kaufmann (1991) (Fig. 1). This section describes the data sources and techniques used to calculate those indices in the U.S. from 1954 to 1987.

System boundaries

The EROI for petroleum and coal is calculated at the extraction stage of the resource transformation process. Only industrial energies are evaluated: the fossil fuel and electricity used directly and indirectly to extract coal and petroleum. The costs include only those energies used to locate and extract petroleum and coal and prepare them for shipment from the wellhead or minemouth. Transportation and refining costs are excluded from this analysis. Cleveland (1988) gives a detailed description of the system boundaries used in this analysis.

Crude oil, natural gas, and natural gas liquids are extracted by Standard Industrial Code sector 13, "Oil and gas extraction", which includes several subsectors. The oil and gas extraction industry includes firms that explore for oil and gas, drill oil and gas wells, operate and maintain oil field properties that produce oil and gas, and all other activities in the preparation of oil and gas up to the point of shipment from the producing property. Sector 13 also includes firms engaged in producing liquid hydrocarbons (natural gas liquids) from oil and gas field gases. Output in the petroleum industry is the sum of the marketed production of crude oil and natural gas.

Anthracite, bituminous, and lignite coal is extracted by Standard Industrial Code sectors 11 and 12, "Anthracite mining" and "Bituminous coal and lignite mining". These industries include firms engaged in the production of coal from underground and surface mines, the operation of coal preparation plants, the provision of coal mining services, and all other activities in the preparation of coal for shipment to consumers. Output in the coal industry is the sum of marketed production of bituminous and anthracite coal.

Sector 13 includes exploration, development, and extraction activities, some of which are not directly responsible for the production of E°, the numerator of the EROI. Geophysical surveys and exploratory drilling identify new deposits of oil and gas, but do not lift oil and gas from the ground. In previous work I calculated the EROI for exploration separate from production and also distinguished the extraction of oil from gas (Cleveland, 1988). That procedure required assumptions about the allocation of costs between oil and gas, the allocation of certain activities within sector 13 between exploration and production, and time lags between exploration and production. In this analysis I calculate the EROI for sector 13 in order to compare the petroleum and coal industries using equivalent system boundaries.

Direct energy costs

The direct energy cost of extracting coal or petroleum is the fuel and electricity used in coal mines and oil fields. The data are from the *Census of Mineral Industries* (Bureau of Census, 1987) which reports the quantities of fuel and electricity used in the petroleum and coal sectors for the years 1954, 1958, 1963, 1967, 1972, 1977, 1982, and 1987. The fuels used are coal, crude oil, natural gas, and refined liquid fuels such as gasoline, residual and distillate fuel. The electricity data reported by the Census include purchased electricity and electricity generated by captive fuel use. I exclude self-generated electricity because including it would double count the fuels used to generate it. I have modified the Census data to correct for reporting errors and omissions based on fuel use data from other sources and from conversations with the Census staff (Cleveland, 1988).

Fuel use in years not covered by a Census is estimated with a technique used to construct the *National Energy Accounts*. For Census years, energy intensities for each fuel are defined as the quantity of fuel used per constant dollar of GNP originating in sector 12 or 13. The data on GDP are published annually in the *National Income and Product Accounts of the United States*. Linear interpolation between Census years is used to estimate the energy intensities for non-Census years. Fuel use in non-Census years is estimated by multiplying the estimated energy intensity times real GNP.

Indirect energy costs

Indirect energy is the energy used in the economy to produce material inputs and to produce and maintain the capital used to extract petroleum and coal. The indirect energy cost of materials and capital is calculated with data on the dollar cost of those inputs to the petroleum and coal extraction processes.[2] The dollar value of material inputs is from the *Census of Mineral Industries*. Materials include the purchase of chemicals, wood products, steel mill shapes and forms, and other supplies "used up" each year in the coal and petroleum industries. The dollar value of capital inputs is from the *National Income and Product Accounts of the United States*. Capital use is approximated by the dollar value of capital consumption by the coal and petroleum industries. Capital consumption is not an ideal measure of capital input because it reflects financial variables in addition to actual physical depreciation. However, capital consumption is the only aggregate measure of capital input available for both the petroleum and coal industries, and despite its shortcomings, it serves as an approximate indicator of the trend in capital use over time.

The indirect energy cost of capital and materials is defined as the dollar cost of capital and materials times the energy intensity of capital and materials (Btu/\$). The energy intensity of capital and materials is measured by the quantity of energy used to produce a dollar's worth of output

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[2] In previous work I used hybrid energy analysis to calculate the EROI for oil and gas production (Cleveland, 1988). That procedure requires very detailed information on the dollar cost of oil or coal production. Detailed cost information is available for the U.S. petroleum industry, but not for the coal industry. In order to calculate the EROI of petroleum and coal on a common basis, I use a more aggregated technique to calculate indirect energy cost.

in the industrial sector of the U.S. economy. [3] That quantity is the ratio of fossil fuel and electricity use to real GNP produced by industry (Department of Energy, 1991; Bureau of Economic Analysis, various years). The energy/GNP ratio is an aggregate measure of the energy cost of producing a dollar's worth of industrial output.

Accounting for energy quality

Two sets of quality factors are used to weight thermal units in the quality-corrected EROI. The first is the relative price of energy (Fig. 1). The benchmark fuel price is the price of bituminous coal paid by electric utilities, the primary end-users of coal (Table 1). The numerators of the EROI for coal and petroleum are the sum of individual fuels produced, weighted by their minemouth and wellhead prices relative to coal. The prices used to weight the fuel use in the denominator of the EROI are as follows: electricity, price of electricity paid by industrial users; coal, CIF price of coal to utilities; natural gas, price of gas paid by industrial users; refined oil products, price of No. 2 diesel fuel. The second set of quality factors are from Kaufmann's (1991) analysis of the marginal products of fuel use in the U.S. economy (Fig. 1).

RESULTS

Coal extraction

The effect of energy quality is most striking in the EROI for the extraction of coal (Fig. 2). The thermal equivalent EROI is three to five times greater than the quality-corrected EROI. The difference in magnitude is due to the fact that the extraction of coal, a relatively low quality fuel, uses large quantities of higher quality fuels such as diesel fuel and electricity. Thus, the energy surplus delivered by the extraction of coal is much smaller when viewed in energy quality terms.

The trend in the EROI for coal extraction is also affected by the adjustment for energy quality. These effects are illustrated by comparing changes in the two quality-corrected EROI with changes in the thermal equivalent EROI. The thermal equivalent EROI shows three distinct periods of change: it increases from 1954 to 1967, declines from 1968 to 1978, and then increases from 1979 to 1987. Compared with the thermal equivalent EROI, the quality-corrected EROI remains relatively stable

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[3] As defined by the Department of Energy (1991), the industrial sector includes agriculture, forestry, fisheries, mining, construction, and all manufacturing industries.

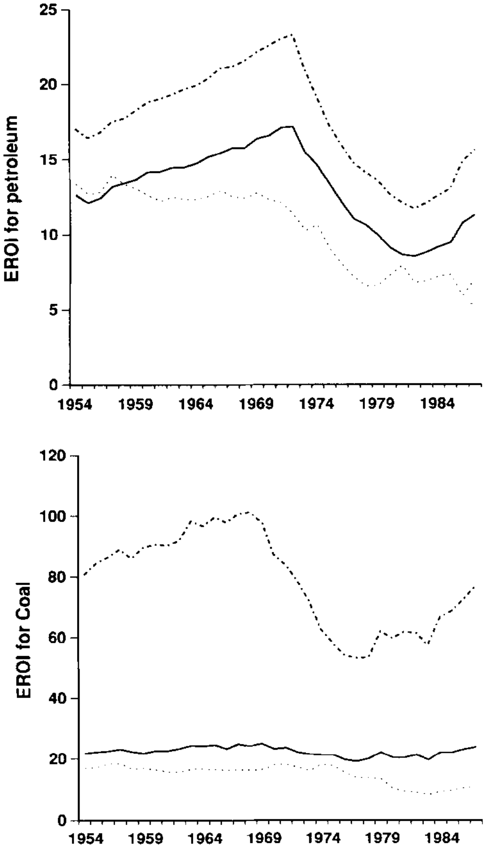

Fig. 2. The energy return on investment (EROI) for petroleum (top chart) and coal (bottom chart) extraction in the U.S. from 1954 to 1987. Energy inputs and outputs are measured in thermal equivalents (dashed and dotted line), marginal products weights (solid line), and relative price weights (dashed line).

from 1954 to 1967. That difference is caused by the rapid substitution of oil, natural gas, and electricity for coal as an energy input, and by the changes in the relative quality factors of those fuels.[4]

Energy quality affects the timing and extent of the decline in the quality-corrected EROI compared with the 50% decline from 1968 to 1978

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[4] In the price-weighted EROI, the increasing use of natural gas and the increase in its price relative to coal is countered by a decline in the price of electricity relative to coal and a relatively constant price of oil relative to coal. In the marginal product-weighted EROI, the quality factors for natural gas and electricity decline and that for oil increases slightly from 1954 to 1967. The net result is a slight increase in the marginal product-weighted EROI (21:1 to 24:1) in that period.

in the thermal equivalent EROI. The marginal product-weighted EROI only declines about 20% in part because the quality factors for oil and electricity decline in that period. The price-weighted EROI declines 50% from 1974 to 1983. One reason for that difference is that energy use in thermal equivalents is relatively constant from 1977 to 1987, but price-adjusted energy use increases sharply because the price of electricity and oil, the dominant energies used in the extraction of coal, increase relative to coal. The increase in the quality factor of oil is particularly important because by the 1970s it accounts for almost 50% of total energy use in coal extraction. As a result of these changes, the price-weighted EROI drops steadily from 1974 to 1983.

Energy quality also affects the timing and extent of the increase in the quality-corrected EROI compared with the large increase from 1978 to 1987 in the thermal equivalent EROI. The percentage increases in the quality-corrected EROI are much smaller than that for the thermal equivalent EROI. Part of that difference is due to changes in the quality factors for energy inputs. Energy use in thermal equivalents declined slightly from 1978 to 1987, but in the adjusted EROI that decline is offset partially by the increase in the quality factors for oil and electricity.

Petroleum extraction

The effects of the adjustment for fuel quality in the EROI for petroleum are not as dramatic as they are for the extraction of coal for two reasons (Fig. 2). First, the quality of energy inputs and outputs in petroleum extraction is closely matched relative to coal extraction. The extraction of oil and natural gas uses large amounts of fuels made from oil and gas, and to a lesser degree electricity. Second, the fuel mix of energy inputs has always been dominated by oil products and especially natural gas. As a result of the closer match of quality in energy inputs and outputs, the thermal equivalent EROI for petroleum extraction is moderately larger than the quality-corrected EROI.

One interesting result is that the price-weighted EROI declines from 1954 and 1973 while the thermal equivalent and marginal product-weighted EROI both increase significantly. The cause of that difference is the different estimates of the quality factor for natural gas, the principal energy input. Kaufmann's estimate of the quality factor for gas declines from 1954 to 1973 while the price-weighted quality factor increases. Those differences cause the EROI adjusted with each set of quality factors to move in opposite directions. The seemingly contradictory signals about the quality of natural gas are probably due to the lag required by end-users to adjust their use in response to price changes. The relative price approach to energy quality assumes that marginal product adjusts instantaneously to a change in the relative price of fuels. Kaufmann (1991) shows that there is a substantial lag between the time when the price of a fuel changes relative to other fuels and the time when the marginal product of that fuel actually adjusts to the change in price. Thus, the difference between the two adjusted EROI series from 1954 to 1973 is due in part to a lag in the marginal product of natural gas to the change in its relative price.

All three measures of EROI decline precipitously in the 1970s corresponding to the decline in the domestic production of oil and gas. That decline reversed to some degree in the case of the thermal equivalent and marginal product-weighted EROI, but not in the case of the price-weighted EROI. Energy use declines in the 1980s in all three models, but there are important differences in energy outputs. In the 1980s the wellhead price of oil and natural gas declined sharply relative to coal, causing a large decline in energy output in the price-weighted model. The drop in the relative price of oil was especially important because there was a shift in the mix of energy output towards crude oil after 1974.

Petroleum and coal compared

The thermal equivalent EROI for coal is 3.5 to 5 times greater than the thermal equivalent EROI for petroleum from 1954 to 1987 (Fig. 3). The adjustment for energy quality suggests a much smaller difference in the energy surplus delivered by the two extraction processes. The price-

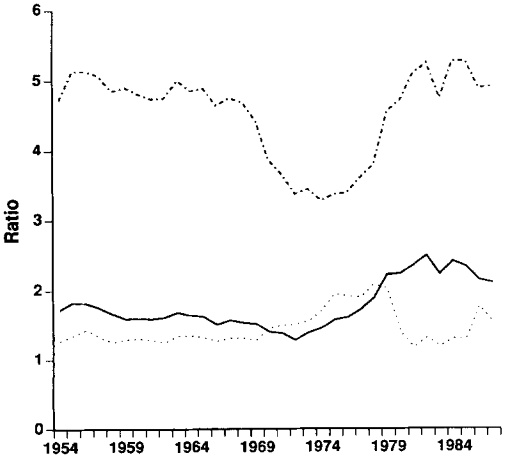

Fig. 3. The EROI for coal extraction relative to the EROI for petroleum extraction. Energy inputs and outputs are measured in thermal equivalents (dashed and dotted line), marginal products weight (solid line), and relative price weights (dashed line).

weighted EROI for coal is 1.2 to 1.4 times that for petroleum, except for a period in the 1970s when the EROI for the two fuels diverge. That divergence may be due to the large fluctuation in the relative price of fuels caused by the oil price shocks of the 1970s and early 1980s. Note that in the mid-1980s the ratio of the price-weighted EROI returns to the level of the pre-embargo period. The ratio of the marginal product-weighted EROI also changes in the 1970s, but by 1987 it had not returned to its pre-embargo level to the same degree as the price-weighted EROI. One interpretation of that difference is that the price-weighted EROI assumes a rapid adjustment of fuel use to changes in relative fuel prices, while the marginal product approach assumes a longer period of adjustment. If that is true, additional data through the 1990s will show a further decline in the ratio of the marginal product-weighted EROI.

DISCUSSION

The scarcity of U.S. fossil fuel resources

All of the EROI indices indicate that petroleum resources became significantly more scarce in the 1970s. The thermal equivalent EROI declines from about 24:1 in 1970 to about 12:1 in the early 1980s. The quality-corrected EROI exhibit similar relative declines. Those results are a clear indication that the amount of surplus energy delivered to the economy by petroleum has diminished significantly. The decline in the EROI for petroleum extraction is consistent with research that documents that the cost-increasing effects of resource depletion outweigh the cost-reducing effects of technological improvements in that industry (Cleveland, 1991a,b). The improvement in the EROI for petroleum extraction in the mid-1980s is consistent with the sharp reduction in the rate of exploratory and extractive effort in the petroleum and coal industries that reduced costs (Cleveland, 1991b). However, the precise effect on the EROI due to long run forces, such as depletion, and short run forces, such as the rate of effort, needs more explicit econometric analysis before a definitive conclusion can be made about recent trends.

The EROI indices for coal extraction give a mixed picture of scarcity. The thermal equivalent and the price-weighted EROI were significantly lower in 1987 than they were at their peak in the late 1960s. Despite a 20% decline in the 1970s, the marginal product-weighted EROI for coal shows no long-term decline. The decline in all three indices in the 1970s is consistent with the decline in the quality of the coal resource base as reflected by smaller seam thickness in underground mines and greater overburden-to-seam-thickness in surface mines (Dale, 1984; Gelb, 1984).

The decline in the EROI for coal is also caused by the increase in energy use caused by regulations that have internalized some of the environmental and human health costs associated with the extraction of coal.

A note on the interpretation of the quality-corrected EROI as indicators of scarcity. The thermal equivalent EROI defines a precise ultimate limit to the economic usefulness of a fuel: the energy break-even point. An EROI less than 1 : 1 implies that the process is a net sink rather than a net source of energy for the rest of the economy, if the resource is used for its heat of combustion. The quality-corrected EROI have a different interpretation in this context. In theory, the thermal equivalent EROI for petroleum could decline below 1 : 1, but the quality-corrected EROI could be above 1 : 1, and it could even be increasing. Society may choose in the future to use large quantities of low quality fuel such as coal to extract oil. If oil is used only for tasks that it is best suited for (e.g., as gasoline in transportation), its marginal product will be high, and that high quality could boost the quality-corrected EROI relative to the thermal equivalent EROI.

The coal–petroleum paradox

The adjustment for energy quality provides insight into a paradox that standard net energy analysis cannot explicitly account for. The extraction of coal delivers a larger energy surplus than petroleum when energy is measured in thermal equivalents, yet the use of petroleum dominates the use of coal in the U.S. despite the abundant supply of domestic coal resources. The result of this analysis suggest that much of the apparent advantage of coal relative to petroleum evaporates when the quality of energy inputs to and outputs from the two energy delivery systems are accounted for. Foremost is the fact that the extraction of coal uses large amounts of oil, natural gas, and electricity.

The optimal investment of energy: economic and biophysical perspectives

The difference between the unadjusted and adjusted EROI for petroleum and coal suggests an interesting connection between the maximizing behavior described by neoclassical economists and the importance of energy surplus described by biophysical economists. [5] Biophysical economists argue that economies with access to fuels with higher EROI have a competitive advantage over those with access to fuels with lower EROI because

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[5] I am indebted to Robert Kaufmann for his help in the development and clarification of this argument.

more economic work can be done with fuels that deliver a large net surplus of energy (Cottrell, 1955; Cleveland et al., 1984). The biophysical argument suggests that societies confronted with multiple fuel choices will adopt a mix that maximizes the net surplus, and hence maximize the potential to do work. But the ability to do work depends not only on the EROI, but also on the quality of fuel. The difference in the thermal equivalent EROI for coal and petroleum presents the U.S. economy with a choice for maximizing the potential to do useful work by investing energy to extract fuels from the environment; it can use small amounts of high quality fuel to extract large amounts of low quality coal, or it can use greater amounts of high quality fuel to extract smaller amounts of high quality petroleum.

The neoclassical perspective of this situation is that the U.S. economy should allocate the energy used to extract coal and petroleum in a way that maximizes the amount of work that can be derived from the energy invested. To maximize the return, the marginal product of the energy investment alternatives should be equal. That is, if the extra amount of work done by a heat unit of petroleum is significantly greater than the amount of work that can be done by the energy used to extract that heat unit, the U.S. economy could increase the amount of work it can do by diverting some of the energy used to extract coal towards the extraction of petroleum.

Satisfaction of the optimizing criterion described by neoclassical economists seems consistent with the biophysical argument that selective pressures lead the U.S. to maximize the net surplus from fossil fuel extraction. The EROI for petroleum and coal are similar when corrections are made for fuel quality (Fig. 3). This suggests that the U.S. is maximizing the amount of useful work it can obtain from the energy used to extract fossil fuels from the environment. The difference in the two quality-corrected ratios is due to the assumption each makes about the speed with which society adjusts the allocation of energy between petroleum and coal extraction. The price–weighted EROI assumes a rapid adjustment to changes in physical scarcity and energy prices, while the marginal product EROI assumes a much slower adjustment.

The EROI are not identical for the two fuels even after the correction for quality, indicating that the results of this analysis alone cannot confirm this argument. At a minimum, improved estimates of fuel quality factors and distinction between the EROI for oil and gas are required to develop a more rigorous test of the surplus-maximizing argument. Also, EROI represents the average, not marginal, return on energy invested to recover energy from the environment.

CONCLUSION

Cottrell (1955, 1972) was one of the first to emphasize the importance of changes in the EROI for society's primary energy delivery systems:

> It will only be when we get another response from nature, in the form of greatly diminished return in the form of surplus energy, that we can expect the present (industrial) revolution markedly to slow down... There is knowledge that leads to the conclusion that the time this will take place is not so far away as we would think (Cottrell, 1972, p. 142).

Cottrell recognized that changes in the net energy surplus change the ability of the economy to transform natural resources into goods and services. But the ability to do useful work in the economy cannot be assessed fully when all forms of energy are measured in thermal units. This analysis has suggested one method of incorporating estimates of the difference in quality among fuels in a standard net energy analysis.

Is the combination of net energy analysis and relative prices an unholy wedding? Net energy purists might argue that the introduction of prices in net energy analysis is a step backwards to the economic analysis they were trying to move away from. Economists might argue that net energy analysis in any form does not appreciably increase our understanding of energy use beyond a thorough economic analysis. But a pure physical analysis of energy surplus does not account for economic forces that determine the economic usefulness of a fuel in conjunction with the fuel's physical attributes. Equally simplistic is the assumption that a pure economic analysis that relies exclusively on price will embody all the factors that determine a fuel's utility. In and of itself, the rejection of the pure physical and economic approaches does not validate the method I use to modify net energy analysis to account for fuel quality. Yet the approach demonstrates that it is possible to combine aspects of the two approaches in a way that illuminates the important concepts of energy surplus and energy quality. The results should stimulate further discussion of issues that are central to the understanding of the importance of energy in economic systems.

ACKNOWLEDGEMENTS

Robert Kaufmann, David Stern, Irisita-Azary Lee, Charles Hall, Robert Herendeen, Carl Folke, and an anonymous reviewer provided valuable comments on earlier drafts of this manuscript.

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