Net Energy From the Extraction of Oil and Gas in the United States

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Abstract

Depletion and technological change exert opposing forces on the cost of delivering energy to society. One technique for evaluating the costs of energy systems is net energy analysis, which compares the quantity of energy delivered to society by an energy system to the energy used directly and indirectly in the delivery process, a quantity called the energy return on investment (EROI). Such an investigation involves aggregating different energy flows. A variety of methods have been proposed, but none has received universal acceptance. This paper shows that the method of aggregation has crucial effects on the results of the analysis. It is argued that that economic approaches such as the index or marginal product method are superior because they account for differences in quality among fuels. The thermal equivalent and quality-corrected EROI for petroleum extraction in the U.S. show the same general pattern: a rise to a maximum in the early 1970s, a sharp decline throughout the 1970s, a recovery in the 1980s, and then another modest decline in the 1990s. However, the quality-corrected EROI is consistently much lower than the thermal equivalent EROI, and it declines faster and to a greater extent than the thermal-equivalent EROI. The results indicate that quality corrections have important effects on the results of energy analyses. The overall decline in the EROI for petroleum extraction in the U.S. suggests that depletion has raised the energy costs of extraction. This is general consistent with the overall pattern of oil extraction, i.e., both extraction and the EROI for extraction show a decline since the early 1970s.

Introduction

There is continuing debate about the state of depletion of domestic oil and gas resources, and about the appropriate method to make such an assessment. Cottrell (1955) and Odum (1971) were the first to identify the socioeconomic importance of net energy. Energy return on investment (EROI) is the ratio of energy delivered to energy costs (Cleveland et al., 1984). There has been a long debate about the relative strengths and weaknesses of net energy analysis. One restriction on the ability of net energy analysis to deliver the insights it promises is its treatment of energy quality. In most net energy analyses, inputs and outputs of different types of energy are aggregated by their thermal equivalents. Following Cleveland (1992) and Cleveland et al. (2000), this case study illustrates how accounting for energy quality affects the calculation of the EROI for oil and gas extraction in the U.S. from 19545 to 1997.

Energy Aggregation and Energy Quality

An energy system such as petroleum (oil and natural gas) extraction uses several different energy types of energy to extract three different types of energy : crude oil, natural gas, and natural gas liquids. Figure 1 demonstrates this for petroleum extraction in the U.S. in 1997. When measured in thermal units, oil account for 38 percent of the energy produced, yet oil products account for just 15 percent of energy used in the extraction process. Furthermore, the oil products used in the extraction process (gasoline, distillate and residual fuels) have been refined, making them qualitatively very different from crude oil. Another important difference is that electricity and coal are used in extraction, but are absent from the outputs of the oil and gas industry.

This approach demonstrates the simplest and most common form of aggregation, i.e., addition by thermal equivalents (BTUs, joules etc.). Equation 1 illustrates this approach:

$$E_t = \sum_{i=1}^{N} E_{it}$$

(1)

where *E* represents the thermal equivalent of fuel *i* (*N* types) at time *t*. The advantage of the thermal equivalent approach is that it uses a simple and well-defined accounting system based on the conservation of energy, and the fact that thermal equivalents are easily and uncontroversially measured. This approach underlies most methods of energy aggregation in economics and ecology, such as trophic dynamics (Odum, 1957), national energy accounting (USDOE, 2000), energy input-output modeling in economies (Bullard *et al.*, 1978) and ecosystems (Hannon, 1973), most analyses of the energy/GDP relationship (e.g. Kraft and Kraft, 1978) and energy efficiency, and most net energy analyses (Chambers *et al.*, 1979).

Despite its widespread use, aggregating different energy types by their heat units embodies a serious flaw: it ignores qualitative differences among energy vectors. Cleveland et al. (2000) define energy quality as the relative economic usefulness per heat equivalent unit of different fuels and electricity. Schurr and Netschert (1960) were among the first to recognize the economic importance of energy quality. Noting that the composition of energy use changes significantly over time Schurr and Netschert argue that the general shift to higher quality fuels affects how much energy is required to produce GNP.

Since Schurr and Netschert, the issue of energy quality has continued to receive attention from energy analysts. The quality of electricity has received considerable attention in terms of its effect on the productivity of labor and capital and on the quantity of energy required to produce a unit of GDP (Schurr and Netschert, 1960; Jorgenson, 1986; Devine, 1986; Rosenberg, 1998). Berndt (1978, 1990) and Zarnikau et al (1996) discussed energy quality in the context of aggregation schemes, and suggested that economic methods of energy aggregation were the most appropriate. Yet empirical studies that actually account for energy quality are few in number (Turvey and Nobay, Cleveland et al, 1984, 2000 Kaufmann, 1994; Stern, 1993; Zarnikau et al., 1996; Hong, 1983; Nguyen and Andrews, 1989).

Taking energy quality into account in energy aggregation requires more advanced forms of aggregation. Some of these forms are based on concepts developed in the energy analysis literature such as exergy or emergy analysis. These methods take the following form:

$$E^{*}_{t} = \overset{N}{\underset{i=1}{\square}} \square_{it} E_{it}$$

(2)

where the □'s are quality factors that may vary among fuels and over time for individual fuels. In the most general case that, an aggregate index can be represented as:

$$f(E_t) = \overset{N}{\underset{i\square\square\square}{\square}} \square_{it}\, g\,(E_{it})$$

(3)

where f() and g() are functions, $\square_{it}$ are weights, the E_i are the N different energy vectors and E_t is the aggregate energy index in period t. An example of this type of indexing is the discrete Divisia Index or Tornquist-Theil Index described below.

Economic Approaches to Energy Quality

From an economic perspective, the value of a heat equivalent of fuel is determined by its price. Price-taking consumers and producers set marginal utilities and products of the different energy vectors equal to their market prices. These prices and their marginal productivities and utilities are set simultaneously in general equilibrium. The value marginal product of a fuel in production is the marginal increase in the quantity of a good or service produced by the use of one additional heat unit of fuel multiplied by the price of that good or service. We can also think of the value of the marginal product of a fuel in household production.

The marginal product of a fuel is determined *in part* by a complex set of attributes unique to each fuel such as physical scarcity, capacity to do useful work, energy density, cleanliness, amenability to storage, safety, flexibility of use, cost of conversion, and so on. Zarnikaue et al. refer to this set of attributes as *form-value*. But the marginal product is not uniquely fixed by these attributes. Rather, the energy vector's marginal product varies according to the activities in which it is used, how much and what form of capital, labor, and materials it is used in conjunction with, and how much energy is used in each application. As the price rises due to changes on the supply-side, users can reduce their use of that form of energy in each activity, increase the amount and sophistication of capital or labor used in conjunction with the fuel, or stop using that form of energy for lower value activities. All these actions raise the marginal productivity of the fuel. When capital stocks have to be adjusted, this response may be somewhat sluggish and lead to lags between price changes and changes in the value marginal product.

The heat equivalent of a fuel is just one of the attributes of the fuel and ignores the context in which the fuel is used, and thus cannot explain, for example, why a thermal equivalent of oil is more useful in many tasks than is a heat equivalent of coal (Adams and Miovic, 1968; Mitchell, 1974; Webb and Pearce, 1975). Zarnikau et al. cite some specific technologiers that demonstrate why electricity is a higher quality energy than gas or oil in many applications. In addition to attributes of the fuel, marginal product also depends on the state of technology, the level of other inputs, and other factors. According to neoclassical theory, the price per heat equivalent of fuel should equal its value marginal product, and, therefore, represent its economic usefulness. In theory, 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.

Consistent with this perspective, 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).

Do market signals (i.e. prices) accurately reflect the marginal product of inputs? Kaufmann (1994) investigates this question in an empirical analysis of the relation between relative marginal product and price in US energy markets. To do so, he estimates a reduced form of a production function that represents how the fraction of total energy use from coal, oil, natural gas, and primary electricity (electricity from hydro and nuclear sources) affects the quantity of energy required to produce a given level of output .The partial derivatives of the production function with respect to each of the fuels gives the marginal product of individual fuels, in which marginal product is defined as the change in economic output given a change in the use of a heat unit of an individual fuel. The equations are used to calculate the marginal product for each fuel type for each year between 1955 and 1992. The time series for marginal products are compared among fuels, and these ratios are related to relative prices using a partial adjustment model. The results indicate that there is a long run relation between relative marginal product and relative price, and that several years of adjustment are needed to bring this relation into equilibrium. In other words, prices do reflect the marginal product - and hence the economic usefulness - of fuels.

Other analysts calculate the average product of fuels, which is a close proxy for marginal products. Adams and Miovic (1968) estimate 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 indicate that petroleum is 1.6 to 2.7 times more productive than coal in producing industrial output. Electricity is 2.7 to 14.3 times more productive than coal. Using a regression model of the energy/GDP ratio in the U.S., Cleveland *et al.* (1984) find that the quality factors of petroleum and electricity relative to coal were 1.9 and 18.3, respectively.

Price-Based Aggregation

If marginal product is related to its price, energy quality can be measured by using the price of fuels to weight their heat equivalents. The simplest approach defines the weighting factor (□'s) in equation (2) as:

$$\square_{it} = \frac{P_{it}}{P_{1t}} \tag{4}$$

where P_{it} is the price per Btu of fuel. In this case, the price of each fuel is measured relative to the price of fuel type 1. Turvey and Nobay (1965) use equation 3 to aggregate fuel use in the UK.

The quality index in equation 4 embodies a restrictive assumption□ that fuels are perfect substitutes□ and the index is sensitive to the choice of numeraire (Berndt, 1978; Stern, 1993). Because fuels are not perfect substitutes, a rise in the price of one fuel relative to the price of output will not be matched by equal changes in the prices of the other fuels relative to the price of output. For example, the rise in oil prices in 1979-80 would cause an aggregate energy index which uses oil as the numeraire to fall dramatically. An index that uses coal as the numeraire would show a large fall in 1968-74, one not indicated by the oil-based index.

To avoid dependence on a numeraire, Berndt (1978, 1990) proposed a discrete approximation to the Divisia index to aggregate energy. The formula for constructing the discrete Divisia index E^* is :

$$\ln E^*_t - \ln E^*_{t-1} = \sum_{i=1}^{n} \left[\left(\frac{P_{it}E_{it}}{2\sum_{i=1}^{n} P_{it}E_{it}} + \frac{P_{it-1}E_{it-1}}{2\sum_{i=1}^{n} P_{it-1}E_{it-1}} \right) \left(\ln E_{it} - \ln E_{it-1} \right) \right] \quad (5)$$

where P are the prices of the n fuels, and E are the quantities of BTU for each fuel in final energy use. Note that prices enter the Divisia index via cost or expenditure shares. The Divisia index permits variable substitution among material types without imposing a priori restrictions on the degree of substitution (Diewert, 1976). Diewert (1976) shows that this index is an exact index number representation of the linear homogeneous translog production function where fuels are homothetically weakly separable as a group from the other factors of production. With reference to equation (3) f() = g() = □ln(), while $□_{it}$ is given by the average cost share over the two periods of the differencing operation.

Aggregation using price has its shortcomings. Lau (1982) suggests that prices provide a reasonable method of aggregation if the aggregate cost function is homothetically separable in the raw material input prices. This means that the elasticity of substitution between different fuels is not a function of the quantities of non-fuel inputs used. This may be an unrealistic assumption in some cases. Also, the Divisia index assumes that the substitution possibilities among all fuel types and output are equal.

It is well-known that energy prices do not reflect their full social cost due to a number of market imperfections. This is particularly true for the environmental impact caused by their extraction and use. These problems lead some to doubt the usefulness of price as the basis for any indicator of sustainability (Hall, 1990; Odum, 1996). But with or without externalities, prices should reflect productivities. Internalizing externalities will shift energy use, which, in turn, will then change marginal products.

Moreover, prices produce a ranking of fuels (Table 1) that is consistent with our intuition and with previous empirical research (Schurr and Netschert, 1960; Adams and Miovic, 1968; Cleveland *et al.*, 1984; Kaufmann, 1991). One can conclude that government policy, regulations, cartels and externalities explain some of the price differentials among fuels, but certainly not the substantial ranges that exist. More fundamentally, price differentials are explained by differences in attributes such as physical scarcity, capacity to do useful work, energy density, cleanliness, amenability to storage, safety, flexibility of use, cost of conversion, and so on. Wipe away the market imperfections and the price per BTU of different energies would vary due to the different combinations of attributes that determine their economic usefulness. The different prices per BTU indicate that users are interested in attributes other than heat content.

Alternative Approaches to Energy Aggregation

While economic indexing methods such as Divisia aggregation are the most appropriate way to aggregate energy use for investigating its role in the economy, the ecological economics literature proposes other methods of aggregation. These methods rely on physical criteria such as exergy (Ayres et al., 1996; Ayres and Martiñas, 1995) or emergy (Odum, 1996).

The eMergy Approach to Aggregation

Odum (1996) and his colleagues analyze energy and materials with a system that traces their flows within and between society and the environment. It is important to differentiate between two aspects of Odum's contribution. The first is his development of a biophysically-based, systems-oriented model of the relationship between society and the environment. Here Odum's (1971; Odum and Odum, 1976) early contributions helped lay the foundation for the biophysical analysis of energy and material flows, an area of research that forms part of the intellectual backbone of ecological economics (Martinez-Alier, 1987; Krishnan, *et al.*, 1995; Costanza *et al*, 1997). The insight from this part of Odum's work is illustrated by the fact that ideas he emphasized- energy and material flows, feedbacks, hierarchies, thresholds, time lags-are key concepts of the analysis of sustainability in a variety of disciplines.

The second aspect of Odum's work, which we are concerned with here, is a specific empirical issue: the identification, measurement, and aggregation of energy inputs to the economy. Emergy (with an "m") 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's method of calculating transformities assesses the efficiency of the sequence of energy conversions that produce 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*104 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*105 SEJ. The transformities for coal, oil, and natural gas are based on a series of calculations that assess 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.

This approach raises a fundamental question about the appropriateness of transformities to reflect energy quality: Is the usefulness of a fuel as an input to production related to its transformity? Probably not. Users value coal based on it heat content, sulfur content, cost of transportation and other factors that form the complex set of attributes that determine its usefulness relative to other fuels. It is hard to imagine how this set of attributes is in general related to-much less determined by-the amount of embodied emergy. Similarly, any differences in the economically useful attributes of coals laid down 500 or 100 million years ago are not determined by the enormous differences in their embodied emergies. Thus, while Odum's method provides a useful framework for highlighting he important role the environment plays in generating energy and material resources, it is of dubious value in comparing and aggregating energy flows in economic applications.

In addition to this conceptual issue, there are computational problems with emergy analysis that make transformities incomplete indicators of energy quality. 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 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 have 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. 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 percent 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 Exergy Approach to Aggregation

Exergy analysis is based on the second law of thermodynamics that 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 $[1-(T_a/T_o)]$, where T_a and T_o 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 percent 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).

Ayres *et al.* (1996) and Ayres and Martiñas (1995) propose a system of aggregating energy and materials based on exergy. Exergy measures the useful work obtainable from an energy source or material, and is based on the chemical energy embodied in the material or energy based on its physical organization relative to a reference state. Thus, exergy measures the degree to which a material is organized relative a random assemblage of material found at an average concentration in the crust, ocean or atmosphere. The higher the degree of concentration, the higher the exergy content. The physical units for exergy are the same as for energy or heat, namely kilocalories, joules, BTUs, etc. For fossil fuels, exergy is nearly equivalent to the standard heat of combustion; for other materials specific calculations are needed that depend on the details of the assumed conversion process.

Ayres argues that exergy has a number of useful attributes for aggregating heterogeneous energy and materials. Exergy is a property of all energy and materials and in principle can be calculated from information in handbooks of chemistry and physics (e.g. Linde 1991-1992) and secondary studies (e.g. Szargut *et al.* 1988). Thus, exergy can be used to measure and aggregate natural resource inputs as well as wastes. For these reasons, Ayres argues that exergy forms the basis for a comprehensive resource accounting framework that could "provide policy-makers with a valuable set of indicators." One such indicator is a general measure of "technical efficiency," the efficiency with which "raw" exergy from animals or inanimate source is converted into final services. A low exergy efficiency implies potential for efficiency gains for converting energy and materials into goods and services. Similarly, the ratio of exergy embodied in material wastes to exergy embodied in resource inputs is the "most general measure of pollution" (Ayres, *et al.* 1996). Ayres and Martiñas (1995) also argue that the exergy of waste streams is a proxy for their potential ecotoxicity or harm to the environment, at least in general terms.

Cleveland and Herendeen (1988) used exergy in their EROI calculations for solar parabolic trough energy systems that produce heat at temperatures ranging from 50° to 350° C. A standard EROI calculation treats heat produced at the lower temperature as qualitatively the same as heat at higher temperatures, despite the fact that higher temperature heat has greater potential to do work. Cleveland and Herendeen corrected for this quality difference by multiplying the EROI by a Carnot factor which incorporates thermodynamic quality. While the correction procedure was crude, it did demonstrate how fuel quality differences can be incorporated into an EROI analysis.

From an accounting perspective, exergy is appealing because it is based on the science and laws of thermodynamics and thus has a well-established system of concepts, rules, and information that are available widely. It also has wide and useful applications in exergy analyses that popint to the energy, environmental, and economic issues associated with the thermynamic efficency of energy conversion. But like enthalpy, exergy should not be used to aggregate energy and material inputs in economic analysis because it is one-dimensional. Like enthalpy, exergy does not vary with, and hence does not necessarily reflect attributes of fuels that determine their economic usefulness, such as energy density, cleanliness, cost of conversion, and so on. The same is true for materials. Exergy cannot explain, for example, impact resistance, heat resistance, corrosion resistance, stiffness, space maintenance, conductivity, strength, ductility, or other properties of metals that determine their usefulness. Like prices, exergy does not reflect all the environmental costs of fuel use. The exergy of coal, for example, does not reflect coal's contribution to global warming or its impact on human health relative to, say, natural gas. As Ayres (1997) himself notes, the exergy of wastes is at best a rough first-order approximation of environmental impact because it does not vary with the specific attributes of a waste material and its receiving environment that cause harm to organisms or that disrupt biogeochemical cycles. In theory exergy can be calculated for any energy or material, but in practice, the task of assessing the hundreds (thousands?) of primary and intermediate energy and material flows in an economy is daunting.

To summarize, emergy and exergy are not appropriate to aggregate energy in an economic analysis because they are one-dimensional. Like enthalpy, exergy and emergy do not vary with, and hence do not necessarily reflect attributes of fuels that determine their economic usefulness, such as energy density, cleanliness, cost of conversion, and so on.

Methods and Data

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 petroleum. The costs include only those energies used to locate and extract petroleum and prepare it for shipment from the lease. Transportation and refining costs are excluded from 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.

Direct Energy Costs

The direct energy cost of extracting petroleum is the fuel and electricity used in oil and gas fields. These data are from the *Census of Mineral Industries* which reports the quantities of fuel and electricity used in the petroleum sector at five year intervals from 1954 to 1997. 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 non-Census years. Fuel use in non-Census years is estimated by multiplying the estimated energy intensity times real GDP.

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. 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 depreciation in SIC sector 13. Capital depreciation is not an ideal measure of capital input because it reflects financial variables in addition to actual physical depreciation. However, capital depreciation is the only aggregate measure of capital input for the petroleum industry, 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 in the industrial sector of the U.S. economy.[1] That quantity is the ratio of fossil fuel and electricity use to real GNP produced by industry (Department of Energy, 2000; 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.

Construction of the EROI

Two indexes are constructed for the EROI from petroleum extraction. The first is the thermal equivalent EROI, which defined as:

$$EROI_t = \sum_{i=1}^{n} E_{i,t}^{o} \Bigg/ \sum_{i=1}^{n} E_{i,t}^{c}$$

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[1] As defined by the Department of Energy (2000), the industrial sector includes agriculture, forestry, fisheries, mining, construction, and all manufacturing industries.

where E^o and E^c are the energy output and input, respectively, of energy type *n* at time *t*, measured in thermal equivalents. The quantity E^c is the sum of direct and indirect energy inputs to the energy system. Equation 6 is the technique used in the vast majority of net energy analyses.

Following the definitions in equation (2), a quality-corrected EROI* is defined by:

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

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 outputs and energy inputs, respectively. Divisia indices are constructed for energy inputs and outputs to account for energy quality in the numerator and denominator. The prices for energy outputs (oil, natural gas, natural gas liquids) and energy inputs (natural gas, gasoline, distillate fuels, coal, electricity) are the prices paid by industrial end-users for each energy type (Department of Energy, 2000).

Results

The thermal equivalent and Divisia EROI for petroleum extraction show the same general pattern: a rise to a maximum in the early 1970s, a sharp decline throughout the 1970s, a recovery in the 1980s, and then another modest decline in the 1990s (Figure 8).

Beyond this, there are important differences between the two indexes. The Divisia EROI is consistently much lower than the thermal equivalent EROI. The principal reason for this is the difference in the fuel mix, and hence fuel quality, between the numerator and denominator of the EROI. The outputs are the crude, unprocessed forms of oil and natural gas. The inputs are electricity and refined fuels such as gasoline and other distillate fuels. The latter are higher quality than the former, and have higher prices. Refined fuels and electricity are, therefore, weighted more heavily in the Divisia formulation.

The Divisia EROI declines faster and to a greater extent than the thermal-equivalent EROI. In 1997 the Divisia ERIO is 42 percent lower than its maximum in 1972; the thermal equivalent EROI is 28 percent lower than its maximum. In 1997 the thermal-equivalent EROI is 1.6 times the Divisia EROI than it was in 1954. Again this is due to largely by changes in the mix of fuels qualities in energy inputs and energy outputs. Electricity, the highest quality fuel, is an energy inputs but not an energy output. Its share of total energy use rises from 2 to 12 percent over the period; its cost share increases from 20 to 30 percent. Thus, in absolute terms the denominator in the Divisia EROI is weighted more heavily than in the thermal equivalent EROI. On the output side, crude oil is a higher quality fuel than natural gas, as reflected in its higher price per Btu. However, on a thermal equivalent basis, the share of oil in the output of the industry steadily falls from about 56 percent in 1954 to about 38 percent in 1997.

Discussion

The overall decline in the EROI for petroleum extraction in the U.S. suggests that depletion has raised the energy costs of extraction. This is generally consistent with the overall pattern of oil extraction, i.e., both extraction and the EROI for extraction show a decline since the early 1970s. There is no single measure of the quality of the oil and gas resource, but a number of such indicators describe its physical deterioration. These include a decline in field size, depletion of natural drive mechanisms, and more enhanced oil recovery that is extremely energy intensive.

To the extent that the EROI does reflect the scarcity of petroleum in some meaningful way, then energy quality is an important consideration. The ultimate limit to an energy resource's usefulness to society is the energy break-even point, i.e., where the energy delivered to society is equaled by the energy used in the delivery process. But not all "units" of energy are equally useful to society, particularly in regards to their ability to perform specific tasks in the production of goods and services. A more appropriate indicator is a quality-corrected EROI that reflects the net availability of energy to actually produce goods and services that reflects choices people make about how to use energy. These choices are based on perceived differences in what Zirnkau et al. call the form-value of different energy types. The quality-corrected EROI is consistently lower than the uncorrected version. This suggests that in a more meaningful economic sense, petroleum I more scare than we might otherwise think. It also suggests that the transition to alternative energy sources, which is driven in part by the scarcity of conventional fuels, may be triggered sooner than is suggested by conventional net energy analyses .

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