Aggregation of Energy

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Glossary

Divisia index A method of aggregation used in economics that permits variable substitution among material types without imposing a priori restrictions on the degree of substitution.

emergy The quantity of solar energy used directly and indirectly to produce a natural resource, good, or service.

energy quality The relative economic usefulness per heat equivalent unit of different fuels and electricity.

energy/real gross domestic product (GDP) ratio (E/GDP ratio) The ratio of total energy use to total economic activity; a common measure of macroeconomic energy efficiency.

energy return on investment (EROI) The ratio of energy delivered to energy costs.

exergy The useful work obtainable from an energy source or material is based on the chemical energy embodied in the material or energy based on its physical organization relative to a reference state. Exergy measures the degree to which a material is organized relative to a random assemblage of material found at an average concentration in the crust, ocean, or atmosphere.

Granger causality A statistical procedure that tests whether (i) one variable in a relation can be meaningfully described as a dependent variable and the other variable as an independent variable, (ii) the relation is bidirectional, or (ii) no meaningful relation exists. This is usually done by testing whether lagged values of one of the variables add significant explanatory power to a model that already includes lagged values of the dependent variable and perhaps also lagged values of other variables.

marginal product of energy 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.

net energy analysis Technique that compares the quantity of energy delivered to society by an energy system to the energy used directly and indirectly in the delivery process.

Investigating the role of energy in the economy involves aggregating different energy flows. A variety of methods have been proposed, but none is accepted universally. This article shows that the method of aggregation affects analytical results. We review the principal assumptions and methods for aggregating energy flows: the basic heat equivalents approach, economic approaches using prices or marginal product for aggregation, emergy analysis, and thermodynamic approaches such as exergy analysis. We argue that economic approaches such as the index or marginal product method are superior because they account for differences in quality among different fuels. We apply economic approaches to three case studies of the U.S. economy. In the first, we account for energy quality to assess changes in the energy surplus delivered by the extraction of fossil fuels from 1954 to 1992. The second and third case studies examine the effect of energy quality on statistical analyses of the relation between energy use and gross domestic product

(GDP). First, a quality-adjusted index of energy consumption is used in an econometric analysis of the causal relation between energy use and GDP from 1947 to 1996. Second, we account for energy quality in an econometric analysis of the factors that determined changes in the energy/GDP ratio from 1947 to 1996. Without adjusting for energy quality, the results imply that the energy surplus from petroleum extraction is increasing, that changes in GDP drive changes in energy use, and that GDP has been decoupled from aggregate energy. These conclusions are reversed when we account for changes in energy quality.

1. ENERGY AGGREGATION AND ENERGY QUALITY

Aggregation of primary-level economic data has received substantial attention from economists for a number of reasons. Aggregating the vast number of inputs and outputs in the economy makes it easier for analysts to discern patterns in the data. Some aggregate quantities are of theoretical interest in macroeconomics. Measurement of productivity, for example, requires a method to aggregate goods produced and factors of production that have diverse and distinct qualities. For example, the post-World War II shift toward a more educated workforce and from nonresidential structures to producers' durable equipment requires adjustments to methods used to measure labor hours and capital inputs. Econometric and other forms of quantitative analysis may restrict the number of variables that can be considered in a specific application, again requiring aggregation. Many indexes are possible, so economists have focused on the implicit assumptions made by the choice of an index in regard to returns to scale, substitutability, and other factors. These general considerations also apply to energy.

The simplest form of aggregation, assuming that each variable is in the same units, is to add up the individual variables according to their thermal equivalents (Btus, joules, etc.). Equation (1) illustrates this approach:

$$E_t = \sum_{i=1}^{N} E_{it}, \qquad (1)$$

where E is the thermal equivalent of fuel i (N types) at time t. The advantages of the thermal equivalent approach are that it uses a simple and well-defined accounting system based on the conservation of energy and the fact that thermal equivalents are easily measured. This approach underlies most methods of energy aggregation in economics and ecology, such as trophic dynamics national energy accounting, energy input–output modeling in economies and ecosystems, most analyses of the energy/gross domestic product (GDP) relationship and energy efficiency, and most net energy analyses.

Despite its widespread use, aggregating different energy types by their heat units embodies a serious flaw: It ignores qualitative differences among energy vectors. We define energy quality as the relative economic usefulness per heat equivalent unit of different fuels and electricity. Given that the composition of energy use changes significantly over time (Fig. 1), it is reasonable to assume that energy quality has been an important economic driving force. 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. Less attention has been paid to the quality of other fuels, and few studies use a quality-weighting scheme in empirical analysis of energy use.

The concept of energy quality needs to be distinguished from that of resource quality. Petroleum and coal deposits may be identified as high-quality energy sources because they provide a very high energy surplus relative to the amount of energy required to extract the fuel. On the other hand, some forms of solar electricity may be characterized as a

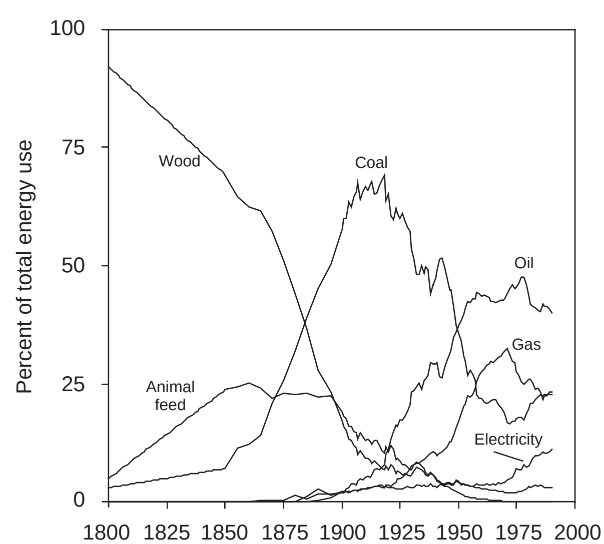

FIGURE 1 Composition of primary energy use in the United States. Electricity includes only primary sources (hydropower, nuclear, geothermal, and solar).

low-quality source because they have a lower energy return on investment (EROI). However, the latter energy vector may have higher energy quality because it can be used to generate more useful economic work than one heat unit of petroleum or coal.

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:

$$E_t^* = \sum_{i=1}^{N} \lambda_{it} E_{it}, \quad (2)$$

where λ represents quality factors that may vary among fuels and over time for individual fuels. In the most general case that we consider, an aggregate index can be represented as

$$f(E_t) = \sum_{i=1}^{N} \lambda_{it} g(E_{it}), \quad (3)$$

where $f(\,)$ and $g(\,)$ are functions, λ_{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 later.

2. 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, the capacity to do useful work, energy density, cleanliness, amenability to storage, safety, flexibility of use, and cost of conversion. However, 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; thus, it cannot explain, for example, why a thermal equivalent of oil is more useful in many tasks than is a heat equivalent of coal. 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 I). The different prices demonstrate that end users are concerned with attributes other than heat content. Ernst Berndt, an economist at MIT, noted that because of the variation in attributes among energy types, the various fuels and electricity are less than perfectly substitutable, either in production or in consumption. For example, from the point of view of the end user, 1 Btu of coal is not perfectly substitutable with 1 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 because 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.

Do market signals (i.e., prices) accurately reflect the marginal product of inputs? Empirical analysis of the relation between relative marginal product and price in U.S. energy markets suggests that this is

TABLE I

U.S. Market Price for Various Energy Types[a]

Energy type	Market price ($\$/10^6$ btu)
Coal	
Bituminous	
Mine-mouth	
Consumer cost	
Anthracite	
Mine-mouth	
Oil	
Wellhead	2.97
Distillate oil	7.70
Jet fuel	4.53
LPG	7.42
Motor gasoline	9.73
Residual fuel oil	2.83
Biofuels	
Consumer cost	
Natural gas	
Wellhead	2.10
Consumer cost	20.34

[a] *Source*. Department of Energy (1997). Values are 1994 prices.

TABLE II

Marginal Product of Coal, Oil, Natural Gas, and Electricity Relative to One Another

	Minimum	Year	Maximum	Year
Oil : coal	1.83	1973	3.45	1990
Gas : coal	1.43	1973	2.76	1944
Electricity : coal	4.28	1986	16.42	1944
Oil : gas	0.97	1933	1.45	1992
Electricity : oil	1.75	1991	6.37	1930
Electricity : gas	2.32	1986	6.32	1930

indeed the case. In the case of the United States, there is a long-term relation between relative marginal product and relative price, and several years of adjustment are needed to bring this relation into equilibrium. The results are summarized in Table II and suggest that over time prices do reflect the marginal product, and hence the economic usefulness, of fuels.

Other analysts have calculated the average product of fuels, which is a close proxy for marginal products. Studies indicate that petroleum is 1.6–2.7 times more productive than coal in producing industrial output, and that electricity is 2.7–18.3 times more productive than coal.

2.1 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 (λ) in Eq. (2) as

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

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.

The quality index in Eq. (4) embodies a restrictive assumption—that fuels are perfect substitutes—and the index is sensitive to the choice of numeraire. Because fuels are not perfect substitutes, an increase 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 increase in oil prices in 1979–1980 would cause an aggregate energy index that uses oil as the numeraire to decline dramatically. An index that uses coal as the numeraire would show a large decline in 1968–1974, one not indicated by the oil-based index.

To avoid dependence on a numeraire, a discrete approximation to the Divisia index can be used to aggregate energy. The formula for constructing the discrete Divisia index E^* is

$$\ln E_t^* - \ln E_{t-1}^* = \sum_{i=1}^{n} \left(\left(\frac{P_{it}E_{it}}{2\sum_{i=1}^{n} P_{it}E_{it}} + \frac{P_{it-1}E_{it-1}}{2\sum_{i=1}^{n} P_{it-1}E_{it-1}} \right) \times (\ln E_{it} - \ln E_{it-1}) \right) \tag{5}$$

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. 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 Eq. (3), $f(\,) = g(\,) = \Delta\ln(\,)$, whereas λ_{it} is given by the average cost share over the two periods of the differencing operation.

2.2 Discussion

Aggregation using price has its shortcomings. 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 nonfuel 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.

Another limit on the use of prices is that they generally do not exist for wastes. Thus, an economic index of waste flows is impossible to construct.

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. However, with or without externalities, prices should reflect productivities. Internalizing externalities will shift energy use, which in turn will change marginal products.

Moreover, prices produce a ranking of fuels (Table I) that is consistent with our intuition and with previous empirical research. 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, and cost of conversion. Eliminate 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.

3. ALTERNATIVE APPROACHES TO ENERGY AGGREGATION

Although we argue that the more advanced 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. We review two of these methods in this section and assess limits on their ability to aggregate energy use.

3.1 Exergy

Other scientists propose a system of aggregating energy and materials based on exergy. Exergy measures the useful work obtainable from an energy source or material, and it 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.

Proponents argue 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 and secondary studies. 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 an 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. Some 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.

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. However, like enthalpy, exergy should not be used to aggregate energy and material inputs aggregation 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, and cost of conversion. 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 natural gas. 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.

3.2 Emergy

The ecologist Howard Odum analyzes 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 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. 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, and 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 and material inputs to the economy, and their use in the construction of indicators of sustainability. Odum measures, values, and aggregates energy of different types by their transformities. Transformities are calculated as 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, the quantity of solar energy used to produce another type of energy. Fuels and materials with higher transformities require larger amounts of sunlight to produce and therefore are considered more economically useful.

Several aspects of the emergy methodology reduce its usefulness as a method for aggregating energy and/or material flows. First, like enthalpy and exergy, emergy is one-dimensional because energy sources are evaluated based on the quantity of embodied solar energy and crustal heat. However, 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 difficult to imagine how this set of attributes is in general related to, much less determined by, the amount of solar energy required to produce coal. Second, the emergy methodology is inconsistent with its own basic tenant, namely that quality varies with embodied energy or emergy. Coal deposits that we currently extract were laid down over many geological periods that span half a billion years. Coals thus have vastly different embodied emergy, but only a single transformity for coal is normally used. Third, the emergy methodology depends on plausible but arbitrary choices of conversion technologies (e.g., boiler efficiencies) that assume users choose one fuel relative to another and other fuels based principally on their relative conversion efficiencies in a particular application. Finally, the emergy methodology relies on long series of calculations with data that vary in quality. However, little attention is paid to the sensitivity of the results to data quality and uncertainty, leaving the reader with little or no sense of the precision or reliability of the emergy calculations.

4. CASE STUDY 1: NET ENERGY FROM FOSSIL FUEL EXTRACTION IN THE UNITED STATES

One technique for evaluating the productivity 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. EROI is the ratio of energy delivered to energy costs. There is a long debate about the relative strengths and weaknesses of net energy analysis. One restriction on net energy analysis' ability 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. This case study illustrates how accounting for energy quality affected calculations for the EROI of the U.S. petroleum sector from 1954 to 1992.

4.1 Methods and Data

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

$$\mathrm{EROI}_t^* = \frac{\sum_{i=1}^{n} \lambda_{i,t} E_{i,t}^{\mathrm{o}}}{\sum_{i=1}^{n} \lambda_{i,t} E_{i,t}^{\mathrm{c}}}, \qquad (6)$$

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

Energy inputs include only industrial energies: the fossil fuel and electricity used directly and indirectly to extract petroleum. The costs include only those energies used to locate and extract oil and natural gas and prepare them for shipment from the wellhead. Transportation and refining costs are excluded from this analysis. Output in the petroleum industry is the sum of the marketed production of crude oil, natural gas, and natural gas liquids.

The direct energy cost of petroleum is the fuel and electricity used in oil and gas fields. Indirect energy costs include the energy used to produce material inputs and to produce and maintain the capital used to extract petroleum. The indirect energy cost of materials and capital is calculated from data for the dollar cost of those inputs to petroleum extraction processes. Energy cost of capital and materials is defined as the dollar cost of capital depreciation and materials multiplied by 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. That quantity is the ratio of fossil fuel and electricity use to real GDP produced by industry.

4.2 Results and Conclusions

The thermal equivalent and Divisia EROI for petroleum extraction show significant differences

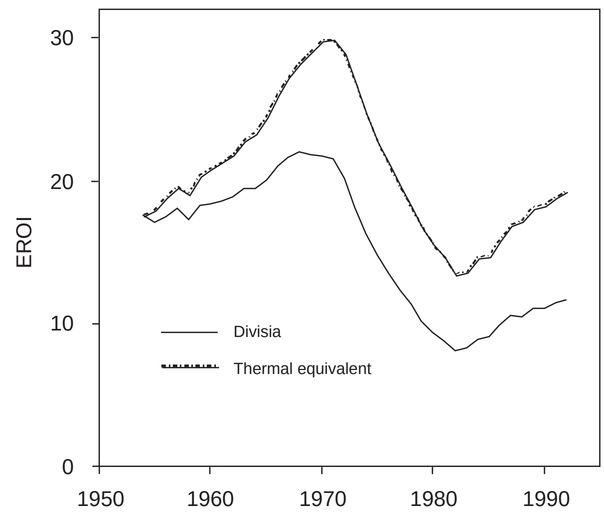

FIGURE 2 Energy return on investment (EROI) for petroleum extraction in the United States, with energy inputs and outputs measured in heat equivalents and a Divisia index.

(Fig. 2). The quality-corrected EROI declines faster than the thermal-equivalent EROI. The thermal-equivalent EROI increased by 60% relative to the Divisia EROI between 1954 and 1992. This difference was driven largely by changes in the mix of fuel qualities in energy inputs. Electricity, the highest quality fuel, is an energy input but not an energy output. Its share of total energy use increased from 2 to 12% during the period; its cost share increased from 20 to 30%. Thus, in absolute terms the denominator in the Divisia EROI is weighted more heavily than in the thermal-equivalent EROI. The Divisia-weighted quantity of refined oil products is larger than that for gas and coal. Thus, the two highest quality fuels, electricity and refined oil products, comprise a large and growing fraction of the denominator in the Divisia EROI compared to the thermal-equivalent EROI. Therefore, the Divisia denominator increases faster than the heat-equivalent denominator, causing EROI to decline faster in the former case.

5. CASE STUDY 2: CAUSALITY IN THE ENERGY/GDP RELATIONSHIP

One of the most important questions about the environment–economy relationship regards the strength of the linkage between economic growth and energy use. With a few exceptions, most analyses ignore the effect of energy quality in the assessment of this relationship. One statistical approach to address this question is Granger causality and/or cointegration analysis. Granger causality tests whether (i) one variable in a relation can be meaningfully described as a dependent variable and the other variable as an independent variable, (ii) the relation is bidirectional, or (iii) no meaningful relation exists. This is usually done by testing whether lagged values of one of the variables add significant explanatory power to a model that already includes lagged values of the dependent variable and perhaps also lagged values of other variables.

Although Granger causality can be applied to both stationary and integrated time series (time series that follow a random walk), cointegration applies only to linear models of integrated time series. The irregular trend in integrated series is known as a stochastic trend, as opposed to a simple linear deterministic time trend. Time series of GDP and energy use are usually integrated. Cointegration analysis aims to uncover causal relations among variables by determining if the stochastic trends in a group of variables are shared by the series so that the total number of unique trends is less than the number of variables. It can also be used to test if there are residual stochastic trends that are not shared by any other variables. This may be an indication that important variables have been omitted from the regression model or that the variable with the residual trend does not have long-term interactions with the other variables.

Either of these conclusions could be true should there be no cointegration. The presence of cointegration can also be interpreted as the presence of a long-term equilibrium relationship between the variables in question. The parameters of an estimated cointegrating relation are called the cointegrating vector. In multivariate models, there may be more than one such cointegrating vector.

5.1 Granger Causality and the Energy GDP Relation

A series of analyses use statistical tests to evaluate whether energy use or energy prices determine economic growth, or whether the level of output in the United States and other economics determine energy use or energy prices. Generally, the results are inconclusive. Where significant results are obtained, they indicate causality from output to energy use.

One analysis tests U.S. data (1947–1990) for Granger causality in a multivariate setting using a vector autoregression model of GDP, energy use, capital, and labor inputs. The study measures energy use by its thermal equivalents and the Divisia aggregation method discussed previously. The relation among GDP, the thermal equivalent of energy use, and the Divisia energy use indicates that there is less "decoupling" between GDP and energy use when the aggregate measure for energy use accounts for qualitative differences (Fig. 3). The multivariate methodology is important because changes in energy use are frequently countered by substitution with labor and/or capital and thereby mitigate the effect of changes in energy use on output. Weighting energy use for changes in the composition of the energy input is important because a large portion of the growth effects of energy is due to substitution of higher quality energy sources such as electricity for lower quality energy sources such as coal (Fig. 1).

Bivariate tests of Granger causality show no causal order in the relation between energy and GDP in either direction, regardless of the measure used to qualify energy use (Table III). In the multivariate model with energy measured in primary Btus, GDP was found to "Granger cause" energy use. However, when both innovations—a multivariate model and energy use adjusted for quality—are employed, energy Granger causes GDP. These results show that adjusting energy for quality is important, as is considering the context within which energy use is occurring. The conclusion that energy use plays an important role in determining the level of economic

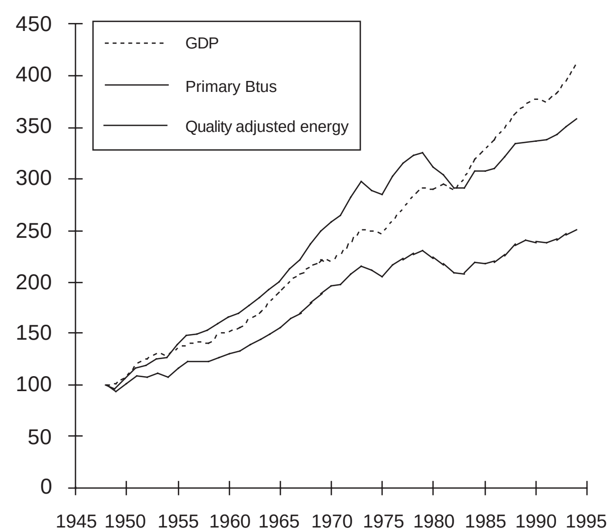

FIGURE 3 Energy use and GDP in the United States, with energy use measured in heat equivalents and a Divisia index. From Stern (1993).

TABLE III

Energy GDP Causality Tests for the United States, 1947–1990[a]

	Bivariate model		Multivariate model	
	Primary Btus	Quality-adjusted energy	Primary Btus	Quality-adjusted energy
Energy causes GDP	0.8328	0.9657	0.5850	3.1902
	0.4428	0.4402	0.5628	0.3188E−01
GDP causes Energy	0.3421	0.7154	9.0908	0.8458
	0.7125	0.5878	0.7163E−03	0.5106

[a]The test statistic is an *F* statistic. Significance levels in italics. A significant statistic indicates that there is Granger causality in the direction indicated.

activity is consistent with results of price-based studies of other energy economists.

6. CASE STUDY 3: THE DETERMINANTS OF THE ENERGY/GDP RELATIONSHIP

One of the most widely cited macroeconomic indicators of sustainability is the ratio of total energy use to total economic activity, or the energy/real GDP ratio (E/GDP ratio). This ratio has declined since 1950 in many industrial nations. There is controversy regarding the interpretation of this decline. Many economists and energy analysts argue that the decline indicates that the relation between energy use and economic activity is relatively weak. This interpretation is disputed by many biophysical economists, who argue that the decline in the E/GDP ratio overstates the ability to decouple energy use and economic activity because many analyses of the E/GDP ratio ignore the effect of changes in energy quality (Fig. 1).

The effect of changes in energy quality (and changes in energy prices and types of goods and services produced and consumed) on the E/GDP ratio can be estimated using Eq. (7):

$$\frac{E}{\mathrm{GDP}} = \alpha + \beta_1 \ln\left(\frac{\text{natural gas}}{\mathrm{E}}\right) + \beta_2 \ln\left(\frac{\text{oil}}{\mathrm{E}}\right) + \beta_3 \ln\left(\frac{\text{primary electricity}}{\mathrm{E}}\right) + \beta_4\left(\frac{\mathrm{PCE}}{\mathrm{GDP}}\right) + \beta_5(\text{product mix}) + \beta_6 \ln(\text{price}) + \varepsilon, \qquad (7)$$

where *E* is the total primary energy consumption (measured in heat units); GDP is real GDP; primary electricity is electricity generated from hydro, nuclear, solar, or geothermal sources; PCE is real personal consumption expenditures spent directly on energy by households; product mix measures the fraction of GDP that originates in energy-intensive sectors (e.g., chemicals) or non-energy-intensive sectors (e.g., services); and price is a measure of real energy prices.

The effect of energy quality on the E/GDP ratio is measured by the fraction of total energy consumption from individual fuels. The sign on the regression coefficients β_1–β_3 is expected to be negative because natural gas, oil, and primary electricity can do more useful work (and therefore generate more economic output) per heat unit than coal. The rate at which an increase in the use of natural gas, oil, or primary electricity reduces the E/GDP ratio is not constant. Engineering studies indicate that the efficiency with which energies of different types are converted to useful work depends on their use. Petroleum can provide more motive power per heat unit of coal, but this advantage nearly disappears if petroleum is used as a source of heat. From an economic perspective, the law of diminishing returns implies that the first uses of high-quality energies are directed at tasks that are best able to make use of the physical, technical, and economic aspects of an energy type that combine to determine its high-quality status. As the use of a high-quality energy source expands, it is used for tasks that are less able to make use of the attributes that confer high quality. The combination of physical differences in the use of energy and the economic ordering in which they are applied to these tasks implies that the amount of economic activity generated per heat unit diminishes as the use of a high-quality energy expands. Diminishing returns on energy quality is imposed on the model by specifying the fraction of the energy budget from petroleum, primary electricity, natural gas, or oil in natural logarithms. This specification ensures that the first uses of high-quality energies decrease the energy/GDP ratio faster than the last uses.

The regression results indicate that Eq. (7) can be used to account for most of the variation in the E/GDP ratio for France, Germany, Japan, and the United Kingdom during the post-World War II period and in the United States since 1929. All the variables have the sign expected by economic theory and are statistically significant, and the error terms have the properties assumed by the estimation technique.

Analysis of regression results indicate that changes in energy mix can account for a significant portion of the downward trend in E/GDP ratios. The change from coal to petroleum and petroleum to primary electricity is associated with a general decline in the E/GDP ratio in France, Germany, the United Kingdom, and the United States during the post-World War II period (Fig. 4). The fraction of total energy consumption supplied by petroleum increased steadily for each nation through the early 1970s. After the first oil shock, the fraction of total energy use from petroleum remained steady or declined slightly in these four nations. However, energy mix continued to reduce the E/real GDP ratio after the first oil shock because the fraction of total energy use from primary electricity increased steadily. The effect of changes in energy mix on the E/GDP ratio shows no trend over time in Japan, where the fraction of total energy consumption supplied by primary electricity declined through the early 1970s and increased steadily thereafter. This U shape offsets the steady increase in the fraction of total energy use from petroleum that occurred prior to 1973.

These regression results indicate that the historical reduction in the E/GDP ratio is associated with shifts in the types of energies used and the types of goods and services consumed and produced. Diminishing returns to high-quality energies and the continued consumption of goods from energy-intensive sectors such as manufacturing imply that the ability of changes in the composition of inputs and outputs to reduce the E/real GDP ratio further is limited.

7. CONCLUSIONS AND IMPLICATIONS

Application of the Divisia index to energy use in the U.S. economy illustrates the importance of energy quality in aggregate analysis. The quality-corrected index for EROI indicates that the energy surplus delivered by petroleum extraction in the United States is smaller than indicated by unadjusted EROI. The trend over time in a quality-adjusted index of total primary energy use in the U.S. economy is significantly different, and declines faster, than the standard heat-equivalent index. Analysis of Granger causality and cointegration indicates a causal relationship running from quality-adjusted energy to GDP but not from the unadjusted energy index. The econometric analysis of the E/real GDP ratio indicates that the decline in industrial economies has been driven in part by the shift from coal to oil, gas, and primary electricity. Together, these results suggest that accounting for energy quality reveals a relatively strong relationship between energy use and economic output. This runs counter to much of the conventional wisdom that technical improvements and structural change have decoupled energy use from economic performance. To a large degree, technical change and substitution have increased the use of higher quality energy and reduced the use of lower quality energy. In economic terms, this means that technical change has been "embodied" in the fuels and their associated energy converters. These changes have increased energy efficiency in energy extraction processes, allowed an apparent decoupling between energy use and economic output, and increased energy efficiency in the production of output.

The manner in which these improvements have been largely achieved should give pause for thought. If decoupling is largely illusory, any increase in the cost of producing high-quality energy vectors could have important economic impacts. Such an increase might occur if use of low-cost coal to generate electricity is restricted on environmental grounds, particularly climate change. If the substitution process cannot continue, further reductions in the E/GDP ratio would slow. Three factors might limit future substitution to higher quality energy. First, there are limits to the substitution process. Eventually, all energy used would be of the highest quality variety—electricity—and no further substitution could occur. Future discovery of a higher quality energy source might mitigate this situation, but it would be unwise to rely on the discovery of new physical principles. Second, because different energy sources are not perfect substitutes, the substitution process could have economic limits that will prevent full substitution. For example, it is difficult to imagine an airliner running on electricity. Third, it is likely that supplies of petroleum, which is of higher quality than coal, will decline fairly early in the 21st century.

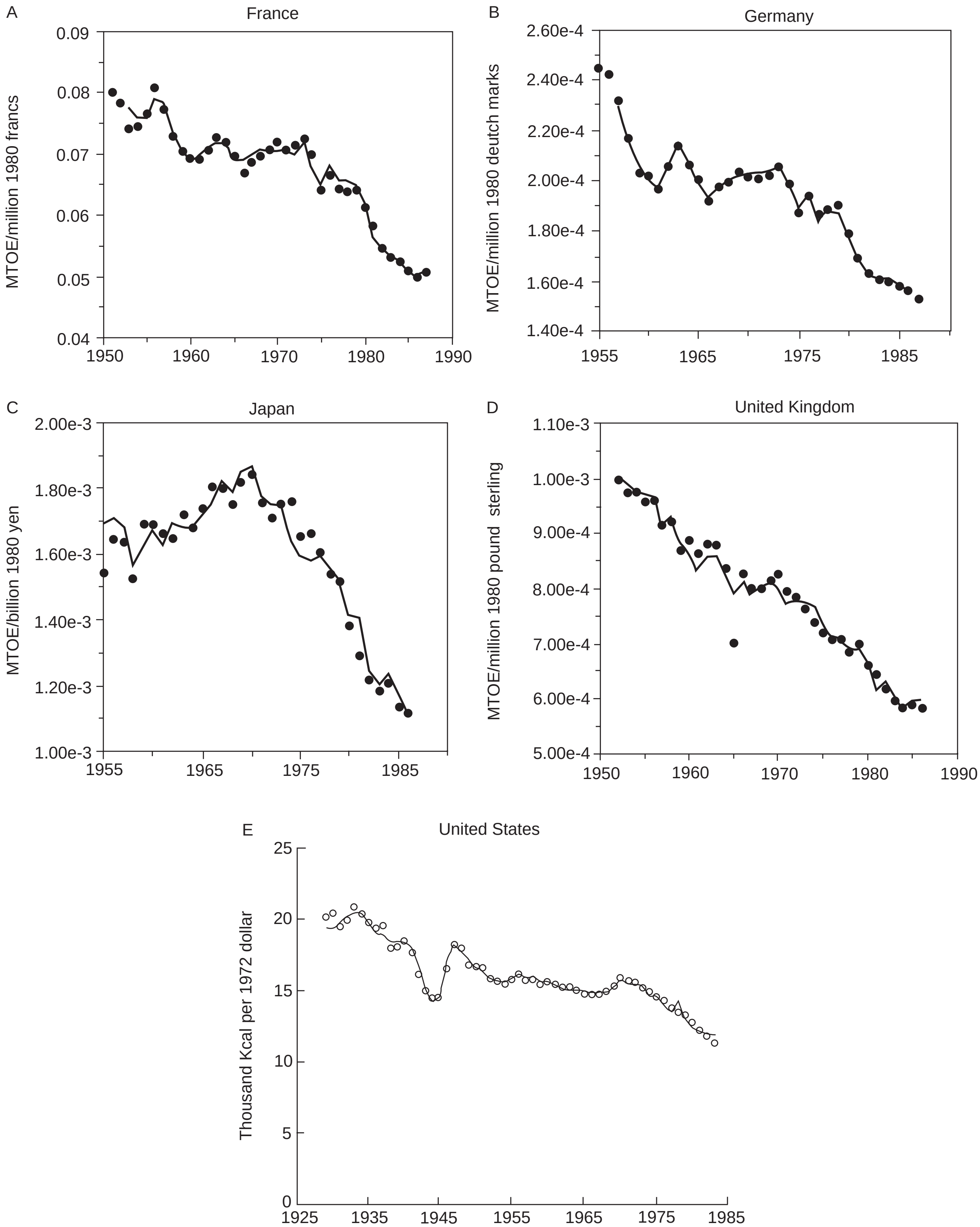

FIGURE 4 The results of a regression analysis (Eq. (7) that predicts the E/GDP ratio as a function of fuel mix and other variables. •, actual values; solid lines, values predicted from the regression equation; ○, actual values for the United States. From Kaufmann (1992) and Hall *et al.* (1986).

Finally, our conclusions do not imply that one-dimensional and/or physical indicators are universally inferior to the economic indexing approach we endorse. As one reviewer noted, ecologists might raise the problem of Leibig's law of the minimum, in which the growth or sustainability of a system are constrained by the single critical element in least supply. Exergy or mass are appropriate if the object of analysis is a single energy or material flux. Physical units are also necessary to valuate those flows. Integrated assessment of a material cycle within and between the environment and the economy is logical based on physical stocks and flows. However, when the question being asked requires the aggregation of energy flows in an economic system, an economic approach such as Divisa aggregation or a direct measure of marginal product embody a more tenable set of assumptions than does aggregation by one-dimensional approaches.

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